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ACCUMULATION OF MINERAL ELEMENTS IN THE *LONGISSIMUS DORSI* MUSCLE OF BULLS OF DIFFERENT AGES AND BREEDS

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Background. In the context of growing demand for higher-quality food, it is imperative to determine the biological value and safety of beef based on the level of vital trace elements. There is limited knowledge about the course of their formation, which underscores the need for further in-depth research in this area.

Materials and Methods. The object of the research was samples of the *Longissimus dorsi* muscle of bulls of six breeds of cattle of dairy and combined productivity. The calcium content in the samples was determined by the complexometric method. The phosphorus content was determined by the colorimetric method using a photoelectric colorimeter. The content of other trace elements was determined by the standardized atomic absorption method using an AAS-30 spectrophotometer (Sagle Zeiss, Germany) at the research base of the Testing Center of the Institute of Animal Science of the NAAS, accredited by the National Accreditation Agency of Ukraine, in accordance with the requirements of DSTU EN ISO/IEC 17025:2019.

Results. The findings indicate that the age factor is associated with the accumulation of mineral elements in muscle tissue, while breed plays a key role in regulating overall mineral metabolism. Studies of the mineral composition of the *Longissimus dorsi* muscle of bulls at different growth stages identified 12 elements, five of which were classified as macroelements (Ca, P, Mg, K, and Na), and seven as trace elements (Cu, Co, Mn, Zn, Fe, Pb, and Cd). The concentrations of these elements varied within a fairly wide range but did not exceed the maximum permissible levels established for cattle meat. The content of such heavy metals as lead and cadmium in the meat of mature, intensively raised 21-month-old steers was significantly lower than in the veal of 3-month-old steers.

Conclusion. The results of the study indicate the absence of natural changes in the content of all trace elements during different growth periods. Only specific features of accumulation for each trace element and growth period were revealed, which does not contradict the general trend of similarity of the mineral composition of the meat of dairy and combined bulls. The content of lead and cadmium in the meat of mature, intensively raised 21-month-old steers was significantly lower than in the veal of 3-month-old steers.

Keywords: mineral elements, *Longissimus dorsi* muscle, beef, bulls, breed, age

INTRODUCTION

The primary responsibility of the livestock sector is to provide the population with safe, high-quality products. This is only possible through the implementation of innovative technologies for maintenance, feeding, breeding, and utilization (Paliy *et al*., 2020; Rueda García *et al*., 2024). Studies of the biological value of beef in terms of mineral elements are becoming extremely important today because mineral elements are key to metabolic, synthetic, and immunobiological processes in animals (Juárez *et al*., 2021; Stadnik, 2024). This is due to the expansion of dietary, therapeutic, and prophylactic products in Ukraine, especially in the context of environmental impact. Mineral elements are minerals present in cattle (Hussein *et al*., 2022; Fernández-Villa *et al.,* 2025). Although they are not primary structural components of the diet, they play a crucial and multifaceted role in ensuring animals' vital activity (Arthington & Ranches, 2021; Silva *et al*., 2022; Cheek *et al.,* 2024). Calcium, for example, is the main structural element of bone tissue (Meng *et al.*, 2024). A calcium deficiency in the diet leads to impaired bone mineralization, stunted growth, and reduced live weight gain, particularly in young animals (Wilkens *et al*., 2020; Neves, 2023). In turn, phosphorus is responsible for maintaining bone integrity, muscle development, cell differentiation, and the functioning of phosphate buffer systems (Grünberg, 2023). Hypophosphatemia manifests as post-accident hemoglobinuria, hypofertility, decreased appetite, and reduced milk yield (Grünberg *et al*., 2015; van den Brink *et al*., 2023). Magnesium is an important intracellular cation involved in numerous enzymatic reactions, energy metabolism (Feeney *et al*., 2016; Khiaosa-Ard *et al*., 2023), and DNA and protein synthesis. It also affects skeletal metabolism and vascular tone, as well as interacts with other electrolytes (Turgut *et al*., 2008; Kovács *et al*., 2023). Magnesium is essential for fermentation processes in the rumen of ruminants (Arce-Cordero *et al*., 2021). Potassium, primarily in the form of an intracellular cation, regulates water and electrolyte balance, cell excitability, muscle activity, and membrane potential generation (Yamada & Inaba, 2021). Deficiency is often associated with impaired reproductive function, mastitis, hepatic lipidosis, and displacement of abdominal organs (Constable *et al*., 2013, 2014; Plöntzke *et al*., 2022). Sodium maintains acid-base homeostasis and regulates water metabolism. It also forms an optimal environment for enzymatic systems that affect digestion and excretion (Spek *et al*., 2012; Robert *et al*., 2020; Ben Meir *et al*., 2023). Copper is essential for normal bone development, nervous tissue development, and immunocompetent cell development (Mitchell *et al*., 2025). Deficiency manifests as anemia, diarrhea, reduced weight gain, lameness, changes in hair pigmentation, infertility, and immune disorders (Rawson *et al*., 2022; Fulton *et al*., 2023). Cobalt plays an important role in hematopoiesis, vitamin B12 synthesis, fat and protein metabolism, as well as nervous system functioning (Raths *et al*., 2023).

Manganese activates numerous enzymatic systems related to lipid, carbohydrate, and protein metabolism, as well as the immune response (Ji *et al*., 2023; Cha *et al*., 2025). Zinc maintains the structural and functional integrity of cells and regulates enzymatic activity (Oconitrillo *et al.*, 2024); its deficiency disrupts reparative processes (Prasad, 2012). Iron is a component of many enzymes that facilitate oxygen transport, energy metabolism, cell growth regulation, and hormone synthesis and metabolism (Dauncey *et al*., 2004; Sickinger *et al*., 2025). At the same time, the presence of toxic elements, such as lead and cadmium, poses an environmental threat. Lead from feed harms reproductive function (Ebrahimi & Taherianfard, 2011; Yi & Zhang, 2012), while cadmium accumulates in the kidneys, disrupting mineral metabolism, reducing bone calcium levels, and suppressing vitamin metabolism (Venäläinen *et al*., 2005; Bhattacharyya, 2009; Thirumoorthy *et al*., 2011).

Despite the widespread belief that the mineral content of beef is a crucial indicator of its quality and environmental safety (Pilarczyk *et al*., 2014b; Tizioto *et al*., 2014), it should be emphasized that the quality of meat products is influenced by many factors, with the breed and age of the animals being the most significant. For example, the muscle tissue of Charolais bulls was found to contain higher concentrations of potassium, manganese, and iron than that of Hereford and Simmental breeds (Pilarczyk *et al*., 2014a). However, studies (Momot *et al*., 2020) could not determine which breed – Hereford, Limousin, or Charolais – has the greatest impact on the mineral composition of Holstein-Friesian animals' meat. However, the authors believe that the optimal slaughter age for the desired accumulation of trace elements in meat is 21 months. A similar trend was observed in experiments (Giuffrida-Mendoza *et al*., 2007).

The results of other studies confirm the influence of breed on mineral accumulation. For example, samples of the *Longissimus dorsi* muscle of Holstein-Friesian bulls contained less calcium, magnesium, and potassium but more manganese than other breeds (Domaradzki *et al*., 2016). Beef from Polish White Back cattle had an increased calcium, manganese, and copper accumulation but lower sodium content. According to V. Pereira *et al*. (2018). Holstein-Friesian bull meat showed increased levels of copper, iron, manganese, selenium, and zinc compared to Galician breed meat. The Simmental breed had higher levels of sodium, calcium, iron, and zinc, while Charolais meat had more copper, nickel, and barium. The Limousin breed had the lowest mineral composition (Valaitienė *et al*., 2016). Other researchers have provided similar data (Litwinczuk *et al*., 2015).

Thus, despite the significant number of publications on the mineral composition of cattle tissues, the issue of trace element content in beef at different ontogenetic stages, considering the breed of bulls, remains relevant. An analysis of existing scientific literature reveals significant knowledge gaps that must be addressed to develop a comprehensive, science-based domestic concept of meat productivity formation in ontogeny.

This is particularly important for uncastrated bulls of dairy and dual-purpose breeds, as they constitute the primary source of meat production on most farms.

This study aims to determine age- and breed-specific features of micronutrient accumulation in the *Longissimus dorsi* muscle of dairy and combined bulls.

MATERIALS AND METHODS

Principles of group formation, object of research, and feeding conditions of experimental bulls. The experiment was conducted in the production conditions of the basic farm of the Institute of Animal Science of the NAAS in Kharkiv Region, using purebred bulls of Black-and-White (BW), Red Steppe (RS) and Angler (A) dairy breeds and Simmental (S), Lebedyn (L), and Grey Ukrainian (GU) dairy breeds of the combined productivityi. Six groups of 25 bulls were formed and kept untethered in group sections of the same facility until 4 months of age. After that, they were tethered until the end of the intensive growing season.

During the growing period (from 30 days to 21 months of age), the experimental animals were fed diets of the same nutritional value, taking into account detailed feeding standards, which provided for 900–1000 g of average daily gain. The level of feeding during the growing period was high and was designed to identify potential opportunities for increasing meat productivity and achieving a live weight of 550–650 kg by bulls at the age of 18–21 months. The total nutritional value of the feed consumed by the bulls during the growing period in the context of the experimental breeds was 44.9–48.0 c of energy feed units. One energy feed unit accounted for 102–106 g of digestible protein, respectively. The ratio of the main components of the diets (on average by groups) was characterized by the following indicators: the concentration of energy available for metabolism in 1 kg of dry matter – 289 MJ; energy-protein ratio – 13.62 g; calcium to phosphorus ratio 1.84:1; fiber content in dry matter – 22.3 %.

The formation of the meat productivity of bulls was evaluated at 3, 12, and 21 months of age. Three heads were selected from each breed group with a live weight corresponding to the group's average weight for control slaughter. Slaughter was performed under the production conditions of the meat processing plant. After exsanguination, skinning, and entrail removal, a veterinarian first examined the carcasses and then divided them into right and left halves. The halved carcasses were cooled in a refrigerator at 4 °C. To determine changes in mineral substances in the *Longissimus dorsi* muscle depending on breed and age, samples were taken from each right half of the carcass at certain age periods at the level of 9–12 ribs, then they were packed in vacuum bags, labeled and delivered to the laboratory, where they were freed from connective tissue.

Laboratory analysis of micronutrient content in the *Longissimus dorsi* muscle. After drying, the test samples of the *Longissimus dorsi* muscle were ground in laboratory mills. Each sample was burned twice in a muffle furnace at 450–500 °C until ash formed. The ash was then dissolved in acid. The average water samples were first evaporated in porcelain cups in a sand bath and then dried in an oven at 105 °C until they reached a constant weight. The resulting dry residue was burned in a muffle furnace at 450–500 °C until ash formed and the coal particles disappeared completely. Conversion factors for dry matter concentrations of trace elements, determined in an ash hood, were calculated by weighing the sample before ashing and its ash residue after combustion in a muffle furnace on an electronic balance. The calcium content of the samples was determined using the complexometric method, which is based on the ability of Trilon B to form a stable, colorless complex compound with calcium ions. Phosphorus content was determined using the colorimetric method with a photoelectric colorimeter. The content of other trace elements was determined using a standardized atomic absorption method with an AAS-30 spectrophotometer (Sagle Zeiss, Germany). This method is based on quantitative analysis of absorption spectra, which have a functional relationship between the concentration of an element in the absorbing layer and a parameter that characterizes the absorption line.

Statistical analysis. The results were processed by variational statistics methods using the analysis of variance (ANOVA) software package Stat Plus 5 (6.7.0.3) (Analyst Soft Inc., USA). The results are presented as mean ± standard error (x ± SE). Tukey's test was used to compare the difference in mean values between breeds within each row, where differences were considered statistically significant at $p < 0.05$ for all data.

RESULTS AND DISCUSSION

Studies of the mineral composition of the *Longissimus dorsi* muscle in bulls of different ages revealed 12 elements, five of which are macroelements (Ca, P, Mg, K, and Na) and seven of which are trace elements (Cu, Co, Mn, Zn, Fe, Pb, and Cd). The concentrations of these elements varied within a fairly wide range but did not exceed the maximum permissible levels for cattle meat. **Table 1** shows the macroelement content in the *Longissimus dorsi* muscle of bulls.

It was found that among the macroelements, the highest ability of the *Longissimus dorsi* muscle to accumulate calcium at 3 months of age, depending on the breed, was recorded in Lebedyn bulls – 0,014 g/kg, phosphorus – Red Steppe (0.064 g/kg), magnesium – Black-and-White and Simmental (0.080 g/kg each), potassium – Black-and-White (0.189 g/kg), sodium – Lebedyn and Black-and-White (0.030 g/kg each); trace elements: copper – Lebedyn (0.363 mg/kg), cobalt – Red Steppe (0.029 mg/kg), manganese and zinc – Angler (0.190 and 1.990 mg/kg), iron – Simmental (9.947 mg/kg), plumbum – Lebedyn (0.450 mg/kg), cadmium – Red Steppe (0.099 mg/kg) rocks. The formation of the mineral composition of the *Longissimus dorsi* muscle of bulls of different breeds in ontogeny is illustrated in **Table 2.**

The total content of macroelements on average for the studied breeds during this period of bulls' growth was 0.317 g/kg, and trace elements – 11.409 mg/kg. Among the macroelements in the samples of the *Longissimus dorsi* muscle of the six studied breeds, potassium was identified as the most abundant (48.3 % of the total determined). Its content, depending on the age period of growth of bulls, varied from 0.021 g/kg at 21 months to 0.153 g/kg at 3 months of age. The predominant amount of trace elements was represented by iron (74.2 % of the total determined), with a concentration range of 7.386 mg/kg at 21 months of age to 8.460 mg/kg at 3 months of age.

Considering the main trends in the deposition of macroelements in the flesh of carcasses, it is important to emphasise the presence of statistically significant differences between breeds at different ages. Notably, at 3 months of age, differences in magnesium content were observed between bulls of the following breeds: Black-and-White and Angler ($p < 0.05$), Simmental and Angler ($p < 0.05$), Black-and-White and Grey Ukrainian ($p < 0.01$), Simmental and Grey Ukrainian ($p < 0.01$), Black-and-White and Red Steppe ($p < 0.01$), Simmental and Red Steppe ($p < 0.01$) and Lebedyn and Red

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Table 1. **Macroelement content in the *Longissimus dorsi* muscle of bulls in ontogeny, g/kg (x ± SE, n = 3)**

Name of the macro-element	The period, months	Breed						On average
		L	BW	RS	S	A	GU	
Ca	3	0.014±0.001^{a}	0.012±0.001^{a}	0.011±0.001^{a}	0.012±0.001^{a}	0.011±0.001^{a}	0.011±0.001^{a}	0.012±0.001
P		0.057±0.005^{a}	0.049±0.010^{a}	0.064± 0.004^{a}	0.061±0.008^{a}	0.051±0.009^{a}	0.053±0.010^{a}	0.056±0.080
Mg		0.075±0.004^{ac}	0.080±0.003^{c}	0.062± 0.001^{b}	0.080±0.002^{c}	0.066±0.001^{ab}	0.065±0.002^{ab}	0.071±0.002
K		0.163±0.005^{a}	0.189±0.014^{b}	0.156± 0.001^{a}	0.142±0.001^{a}	0.129±0.002^{c}	0.140±0.010^{bc}	0.153±0.006
Na		0.030±0.001^{a}	0.030±0.001^{a}	0.022± 0.001^{a}	0.024±0.001^{a}	0.021±0.001^{b}	0.024± 0.001^{a}	0.025±0.001
Ca	12	0.008±0.001^{a}	0.008±0.001^{a}	0.008±0.001^{a}	0.009±0.001^{a}	0.009±0.001^{a}	0.008±0.001^{a}	0.008±0.001
P		0.049±0.004^{a}	0.056±0.005^{a}	0.029±0.003^{b}	0.036±0.006^{ab}	0.044±0.007^{ab}	0.032±0.002^{b}	0.041±0.005
Mg		0.033±0.003^{a}	0.028±0.004^{a}	0.042±0.007^{a}	0.044±0.021^{a}	0.036±0.012^{a}	0.033±0.004^{a}	0.036±0.013
K		0.045±0.007^{a}	0.046±0.003^{a}	0.048±0.002^{a}	0.045±0.006^{a}	0.043±0.005^{a}	0.044±0.012^{a}	0.045±0.006
Na		0.008±0.002^{a}	0.007±0.004^{a}	0.006±0.004^{a}	0.005±0.002^{a}	0.004±0.001^{a}	0.005±0.001^{a}	0.006±0.003
Ca	21	0.008±0.001^{a}	0.007±0.001^{a}	0.007± 0.001^{a}	0.007±0.001^{a}	0.006±0.001^{a}	0.007±0.001^{a}	0.007±0.001
P		0.013±0.001^{a}	0.016±0.001^{a}	0.013± 0.001^{a}	0.013±0.001^{a}	0.012±0.002^{a}	0.013±0.001^{a}	0.013±0.001
Mg		0.033±0.002^{a}	0.030±0.012^{a}	0.038±0.010^{a}	0.036±0.020^{a}	0.031±0.017^{a}	0.033±0.015^{a}	0.034±0.015^{a}
K		0.020±0.003^{a}	0.024±0.002^{a}	0.024± 0.002^{a}	0.025±0.004^{a}	0.018±0.003^{a}	0.020±0.002^{a}	0.021±0.003
Na		0.004±0.001^{a}	0.004±0.001^{a}	0.003±0.001^{a}	0.004±0.001^{a}	0.004±0.001^{a}	0.004±0.001^{a}	0.004±0.001

Note: L – Lebedyn; BW – Black-and-White; RS – Red Steppe; S – Simmental; A – Angler; GU – Grey Ukrainian breeds. Different letters indicate significant differences between breeds within each row, as determined by the Tukey test

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Table 2. **Dynamics of microelement composition of the *Longissimus dorsi* muscle of bulls, mg/kg (x ± SE, n = 3)**

Name of the microelement	Period, months	Breed						On average
		L	BW	RS	S	A	GU	
Cu	3	0.363±0.097[a]	0.215±0.006[a]	0.258±0.042[a]	0.318±0.091[a]	0.253±0.022[a]	0.282±0.013[a]	0.282±0.045
Co		0.020±0.001[a]	0.022±0.002[a]	0.029±0.002[a]	0.016±0.005[ab]	0.011±0.001[b]	0.018±0.004[ab]	0.019±0.003
Mn		0.148±0.010[a]	0.130±0.006[a]	0.150±0.008[a]	0.180±0.023[ab]	0.190±0.009[b]	0.173±0.022[ab]	0.162±0.013
Zn		1.980±0.017[a]	1.967±0.009[a]	1.957±0.032[a]	1.970±0.006[a]	1.990±0.035[a]	1.970±0.035[a]	1.972±0.022
Fe		7.760±0.064[a]	7.077±0.505[a]	7.747±0.072[a]	9.947±1.100[ab]	9.857±0.118[b]	8.370±0.930[ab]	8.460±0.464
Pb		0.450±0.027[ab]	0.405±0.001[a]	0.433±0.008[ab]	0.445±0.001[b]	0.390±0.013[a]	0.430±0.011[ab]	0.426±0.012
Cd		0.076±0.002[a]	0.086±0.018[a]	0.099±0.029[a]	0.092±0.023[a]	0.083±0.001[a]	0.089±0.027[a]	0.088±0.017
Cu	12	0.092±0.006[a]	0.096±0.020[a]	0.088±0.006[a]	0.114±0.009[a]	0.067±0.002[a]	0.113±0.007[a]	0.095±0.008
Co		0.064±0.006[ab]	0.044±0.004[a]	0.083±0.019[ab]	0.064±0.005[b]	0.054±0.004[ab]	0.047±0.003[a]	0.059±0.007
Mn		0.088±0.006[ab]	0.098±0.008[a]	0.073±0.003[b]	0.084±0.012[ab]	0.072±0.005[ab]	0.079±0.009[ab]	0.082±0.007
Zn		3.504±0.054[ab]	3.299±0.013[a]	3.617±0.205[ab]	3.425±0.029[ab]	3.685±0.050[ab]	3.795±0.141[b]	3.554±0.082
Fe		9.650±1.423[a]	9.222±1.389[a]	10.727±0.749[a]	8.845±0.699[a]	10.117±0.844[a]	9.385± 0.518[a]	9.657±1.087
Pb		0.372±0.010[a]	0.315±0.009[a]	0.256±0.015[c]	0.336±0.007[a]	0.303±0.008[bc]	0.286±0.020[bc]	0.311±0.012
Cd		0.029±0.008[a]	0.036±0.010[a]	0.037±0.008[a]	0.049±0.006[a]	0.038±0.015[a]	0.040±0.013[a]	0.038±0.010
Cu	21	0.043±0.007[a]	0.028± 0.004[a]	0.034±0.002[a]	0.038±0.005[a]	0.027±0.006[a]	0.036±0.003[a]	0.034±0.005
Co		0.063±0.008[a]	0.057±0.006[ab]	0.052±0.005[a]	0.040±0.002[b]	0.039±0.007[ab]	0.049±0.007[ab]	0.050±0.006
Mn		0.061±0.009[a]	0.043±0.004[a]	0.054±0.004[a]	0.071±0.016[a]	0.046±0.003[a]	0.048±0.006[a]	0.054±0.007
Zn		7.122±0.018[a]	6.827±0.032[ab]	7.078±0.042[a]	6.803±0.022[b]	5.985±0.040[c]	6.706±0.065[b]	6.754±0.037
Fe		7.653±1.402[a]	8.326±2.305[a]	6.897±1.202[a]	7.802±2.360[a]	6.861±0.920[a]	6.775±1.070[a]	7.386±1.543
Pb		0.144±0.008[a]	0.134±0.008[a]	0.142±0.015[a]	0.140±0.012[a]	0.130±0.005[a]	0.142±0.007[a]	0.139± 0.009
Cd		0.021±0.001[a]	0.018±0.010[a]	0.018±0.011[a]	0.019±0.003[a]	0.021±0.001[a]	0.019±0.003[a]	0.019± 0.007

Note: L – Lebedyn; BW – Black-and-White; RS – Red Steppe; S – Simmental; A – Angler; GU – Grey Ukrainian breeds. Different letters indicate significant differences between breeds within each row, as determined by the Tukey test

Steppe ($p < 0.01$). Regarding the potassium content, statistically significant differences were recorded between the following breeds: Black-and-White and Lebedyn ($p < 0.01$), Black-and-White and Red Steppe ($p < 0.05$), Black-and-White and Simmental ($p < 0.01$), Black-and-White and Grey Ukrainian ($p < 0.05$), Lebedyn and Grey Ukrainian ($p < 0.05$), Black-and-White and Angler ($p < 0.001$), Lebedyn and Angler ($p < 0.01$), Red Steppe and Simmental ($p < 0.001$), Red Steppe and Angler ($p < 0.001$) and Simmental and Angler ($p < 0.01$). Statistically significant differences were observed in the sodium concentration between the Lebedyn and Red Steppe bulls ($p < 0.001$), the Simmental and Red Steppe bulls ($p < 0.01$), the Grey Ukrainian and Red Steppe bulls ($p < 0.01$), the Black-and-White and Red Steppe bulls ($p < 0.01$), Lebedyn and Simmental ($p < 0.05$), Lebedyn and Grey Ukrainian ($p < 0.05$), Black-and-White and Simmental ($p < 0.01$), Black-and-White and Grey Ukrainian ($p < 0.01$), Black-and-White and Angler ($p < 0.01$) and Lebedyn and Angler ($p < 0.01$).

Statistical processing of the data obtained on the content of trace elements in samples of bull beef in this age period made it possible to identify a statistically significant difference in the accumulation of cobalt between Black-and-White and Angler ($p < 0.01$), Red Steppe and Angler ($p < 0.01$) breeds; manganese – Angler and Black-and-White ($p < 0.01$), Angler and Lebedyn ($p < 0.05$), Angler and Red Steppe ($p < 0.05$) breeds; iron – Angler and Lebedyn ($p < 0.01$), Angler and Red Steppe ($p < 0.01$), Angler and Black-and-White ($p < 0.01$) breeds; plumbum – Simmental and Black-and-White ($p < 0.05$), Simmental and Angler ($p < 0.01$) breeds.

It is noteworthy that when bulls reach the age of one year, there is a gradual decrease in the content of minerals in the carcass flesh compared to the age of 3 months. In particular, the average content of macroelements by breed was: calcium – 0.008 (-0.004) g/kg, phosphorus – 0.041 (-0.015) g/kg, magnesium – 0.036 (-0.035) g/kg, potassium – 0.045 (-0.108) g/kg, sodium – 0.006 (-0.019) g/kg. The total content of macroelements in the studied breeds was 0.136 g/kg, with the highest concentration of potassium accounting for 33.1% of the total amount determined. During this period, the highest phosphorus content was found in the samples of the *Longissimus dorsi* muscle of Black-and-White bulls (0.056 g/kg), magnesium – Simmental (0.044 g/kg), and Bsodium – Lebedyn (0.008 g/kg), while the calcium concentration was relatively stable.

At the same time, statistical differences between breeds at 12 months of age were only proven by phosphorus content in bulls of the Lebedyn and Grey Ukrainian breeds ($p < 0.05$), the Black-and-White and Grey Ukrainian breeds ($p < 0.05$), the Lebedyn and Red Steppe breeds ($p < 0.01$) and the Black-and-White and Red Steppe breeds ($p < 0.05$).

In contrast to macroelements, the distribution of microelements in the samples of the *Longissimus dorsi* muscle of bulls during this period revealed different results. In particular, the accumulation of copper decreased by 0.187 mg/kg, manganese by 0.080 mg/kg, lead by 0.115 mg/kg, and cadmium by 0.048 mg/kg. Conversely, cobalt increased by 0.040 mg/kg, zinc by 1.582 mg/kg, and iron by 1.197 mg/kg; the latter microelement was dominant (70.0%) of those determined.

Along with this, the maximum content of copper was characteristic of the samples of the *Longissimus dorsi* muscle of yearling Simmental bulls (0.114 kg/kg), cobalt – Red Steppe bulls (0.083 mg/kg), manganese – Black -and-White bulls (0.098 mg/kg), iron – Angler bulls (10.117 mg/kg), magnesium – Simmental bulls (0.044 mg/kg), plumbum – Simmental bulls (0.336 mg/kg) and cadmium (0.049 mg/kg), while the content of other microelements fluctuated within insignificant limits.

Similarly, in the concentration of cobalt, statistically reliable significance was observed during this period of growth between animals of Simmental and Black-and-White ($p < 0.05$), Simmental and Grey Ukrainian ($p < 0.05$) breeds; manganese – Black-and-White and Red Steppe ($p < 0.05$) breeds; zinc – Grey Ukrainian and Black-and-White ($p < 0.05$) breeds; plumbum – Lebedyn and Simmental ($p < 0.01$), Lebedyn and Black-and-White ($p < 0.01$), Lebedyn and Grey Ukrainian ($p < 0.01$), Lebedyn and Angler ($p < 0.01$), Lebedyn and Red Steppe ($p < 0.01$), Simmental and Black-and-White ($p < 0.05$), Simmental and Red Steppe ($p < 0.01$), Black-and-White and Red Steppe ($p < 0.05$) breeds.

It should be emphasized that in the process of growth of bulls up to 21 months of age, a further decrease in the concentration of macroelements in the *Longissimus dorsi* muscle was noted: calcium by 0.001 g/kg, phosphorus by 0.028 g/kg, magnesium by 0.002 g/kg, potassium by 0.024 g/kg, sodium by 0.002 g/kg, compared to 3 months of age. With a total macroelement content of 0.079 g/kg, magnesium (43.0 %) accounted for the largest share of macroelements. The similar age-related ability to reduce the content of mineral elements in the beef of 21-month-old bulls is confirmed by the findings of M. Momot *et al*. (2020).

Muscle tissue of Black-and-White bulls was most enriched in phosphorus and potassium (0.016 and 0.024 g/kg). Meanwhile, other macronutrients were deposited in the *Longissimus dorsi* muscle of each studied breed quite evenly.

During this period, no statistically significant differences were recorded in the *Longissimus dorsi* muscle for any of the identified macroelements between the studied breeds.

The dynamics of microelement levels in bulls at this stage of growth were expressed as follows in absolute values: copper decreased from 0.095 to 0.034 mg/kg (-0.061); cobalt decreased from 0.059 to 0.050 mg/kg (-0.009); and manganese decreased from 0.082 to 0.054 mg/kg (-0.028 mg/kg; iron decreased from 9.657 to 7.386 mg/kg (-2.271); lead decreased from 0.311 to 0.139 mg/kg (-0.172); and cadmium decreased from 0.038 to 0.019 mg/kg (-0.019). Meanwhile, the concentration of zinc increased from 3.554 to 6.754 mg/kg (+3.200).

During this growth period, the total content of microelements in the beef samples was 14.436 mg/kg, with iron accounting for 51.2% of the total. Lebedyn beef had the highest concentrations of copper (0.043 mg/kg), cobalt (0.063 mg/kg), manganese (7.122 mg/kg), and lead (0.144 mg/kg). Simmental beef had the highest concentration of manganese (0.071 mg/kg), Black-and-White beef had the highest concentration of iron (8.326 mg/kg), and Lebedyn and Angler beef had the highest concentration of cadmium (0.021 mg/kg each).

The statistically significant interbreed difference in the content of cobalt in the carcass flesh was found only between bulls of Lebedyn and Simmental ($p < 0.001$) breeds. On the other hand, zinc concentration revealed a wider range of statistically significant interbreed differences, namely between bulls of Lebedyn and Simmental ($p < 0.01$), Lebedyn and Grey Ukrainian ($p < 0.01$), Red Steppe and Grey Ukrainian ($p < 0.01$), Lebedyn and Angler ($p < 0.001$), Red Steppe and Angler ($p < 0.001$), Black-and-White and Angler ($p < 0.001$), Simmental and Angler ($p < 0.001$), and Grey Ukrainian and Angler ($p < 0.001$) breeds.

The results of the study convincingly prove that the intensive rearing of bulls of all breeds for meat from 3 to 21 months of age naturally decreases the average concentration of macronutrients in beef: calcium – from 0.012 to 0.007 (-0.005) g/kg, phosphorus –

from 0.056 to 0.013 (-0.043) g/kg, magnesium – from 0.071 to 0.034 (-0.037) g/kg, potassium – from 0.153 to 0.021 (-0.132) g/kg, sodium – from 0.025 to 0.004 (-0.021) g/kg.

Characterizing the content of microelements in the period from 3 to 21 months of age in the *Longissimus dorsi* muscle, it is necessary to note a similar trend of decrease in the average concentration of copper by 0.248 mg/kg, manganese – by 0.108 mg/kg, iron – by 1.074 mg/kg, plumbum – by 0.287 mg/kg and cadmium – by 0.69 mg/kg, while the content of cobalt and zinc increases by 0.031 and 4.782 mg/kg, respectively. Other scientists have also observed a decrease in the content of mineral elements in beef during animal growth (Giuffrida-Mendoza *et al*., 2007).

It is important to note that in 3-month-old bull calves, rapid growth is associated with an increased demand for copper, manganese, and iron. These nutrients are essential for hemoglobin synthesis, the functioning of enzyme systems, and maintaining an active metabolism, which contributes to their greater accumulation in muscle tissue. In 21-month-old animals, growth rates slow down, and the absorption of trace elements from feed and water decreases due to lower body requirements, reduced intestinal absorption efficiency, and age-related changes in microbiota, digestive juice secretion, and medium acidity. Some copper, iron, and manganese likely redistribute from muscle tissue to the liver or bind to myoglobin with age. At the same time, the morphological structure of muscles changes with increasing age – the content of fat deposits and connective tissue increases, which contributes to a decrease in the concentration of these trace elements in muscle fibers. Other scientists have also noted similar changes in mineral composition (Giuffrida-Mendoza *et al*., 2007; Polidori *et al*., 2017).

It is also worth noting that some researchers have observed a tendency for the concentration of copper and/or zinc to decrease in animal tissues when cadmium accumulates in their bodies (Zasadowski *et al*., 1999). This is precisely what we have observed in our studies.

Changes in the zinc and cobalt content of 21-month-old bulls reflect the specific biological roles of these trace elements. As the age of the bulls increases, the concentration of these trace elements in their muscles grows while their excretion decreases. This is due to an increased feed consumption, which leads to higher accumulation of these minerals, as well as changes in metabolic balance caused by an increased copper and iron content, which activate metabolic processes involving these elements. At three months of age, intensive growth and hair formation, as well as significant losses through urine, contribute to an enhanced excretion of these elements from the body. In 21-month-old animals, however, these processes slow down, ensuring the accumulation of zinc and cobalt in muscle tissue. Similar evidence regarding the age-related redistribution of these minerals is presented in the study of P. Barge *et al*. (2006).

However, in bulls aged 12 and 21 months, the decrease in the level of accumulation of individual mineral elements in samples of the *Longissimus dorsi* muscle was uneven, with varying degrees of statistical significance depending on the breed and specific mineral element ($p < 0.05$ – $p < 0.001$).

A comparative analysis of the heavy metal content in the meat of six breeds of bulls at various ages did not reveal concentrations exceeding the maximum permissible concentrations (MPCs): 5.0 mg/kg for copper; 70 mg/kg for zinc; 0.5 mg/kg for lead; and 0.05 mg/kg for cadmium. However, the cadmium content in the *Longissimus dorsi* muscle of 21-month-old bulls was 2.6 times lower than the permissible level. At three months of age, it was 1.8 times higher. The lead concentration in beef from three- and

12-month-old bulls approached the upper limit of the maximum permissible concentration of this micronutrient in meat. The importance of minerals in beef as indicators of quality and environmental safety has been emphasised (Reykdal *et al*., 2011; Pilarczyk *et al*., 2014b; Tizioto *et al*., 2014; Özlü & Atasever, 2018; Patel *et al*., 2020).

We believe that the elevated cadmium levels found in the longissimus dorsi (back muscle) of 3-month-old bull calves can be attributed to their higher intestinal permeability and weaker barrier function. This allows a more intensive absorption of cadmium from feed and water compared to 21-month-old bulls. Additionally, the less developed muscle tissue in these younger bulls, which has a lower protein content and higher moisture content, exacerbates this effect. As a result, even a small amount of cadmium intake can lead to a significant increase in its concentration per unit of meat mass. In young animals, cadmium accumulation processes prevail over excretion. In 21-month-old bulls, however, a balance is established, resulting in lower cadmium levels in the muscles. Similar findings regarding the increased cadmium accumulation in young animals have been reported by Bazargani-Gilani *et al*. (2016) and Hashemi (2018). However, other researchers have not confirmed this trend (Zenad *et al*., 2020; Drapal *et al*., 2021).

CONCLUSION

The results of the study of the mineral composition of beef from six breeds of bulls during ontogeny indicate an absence of natural changes in the content of all mineral elements during different growth periods. Only specific accumulation features for each trace element and growth period were found, which did not contradict the general trend of similarity in the mineral composition of meat from dairy and combined bulls. The content of heavy metals lead and cadmium in the meat of mature, intensively raised 21-month-old steers was significantly lower than in the veal of 3-month-old steers.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Animal studies: the experiments conducted on animals do not contradict the current legislation of Ukraine (Article 26 of the Law of Ukraine 5456-VI of 16.10.2012 „On the Protection of Animals from Cruelty") as amended as of 04.08.2017, and the „General Ethical Principles for Animal Experiments" adopted by the First National Congress on Bioethics (Kyiv, 2001) and international bioethical standards (materials of the IV European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Purposes (Strasbourg, 1985).

AUTHOR CONTRIBUTIONS

Conceptualization, [S.M.; I.K.; A.P.; N.B.] methodology, [S.M.; I.K.; A.P.]; validation, [A.K.; T.H.; O.P.; A.S.]; formal analysis [S.M.; I.K.; N.B.; A.S.]; investigation, [S.M.]; data curation, [I.K.; A.P.; N.B.; K.R.]; writing – original draft preparation, [S.M.; N.B.; N.P.]; writing – review and editing, [S.M.; I.K.; A.P.; N.B.; O.P.]; visualization, [N.B.; A.S.; K.R.]; supervision, [N.B.; A.K.; T.H.]; project administration, [S.M.; I.K.; A.P.]; funding acquisition, [S.M.; I.K.; A.P.; N.B.; T.H.; O.P.; A.S; N.P].

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АКУМУЛЯЦІЯ МІНЕРАЛЬНИХ ЕЛЕМЕНТІВ У М’ЯЗІ *LONGISSIMUS DORSI* БУГАЙЦІВ РІЗНОГО ВІКУ ТА ПОРОДИ

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Вступ. У контексті посилення вимог до якості продуктів харчування набуває особливої значущості визначення біологічної цінності й безпечності яловичини за рівнем життєво необхідних мікроелементів. Знання про перебіг їхнього формування досить обмежені, що й зумовлює актуальність і необхідність подальших ґрунтовних досліджень у цьому напрямі.

Матеріали та методи. Об’єктом дослідження були зразки *Longissimus dorsi* muscle бугайців шести порід великої рогатої худоби молочного та комбінованого напряму продуктивності. Вміст кальцію у зразках ідентифікували, застосовуючи комплексометричний метод. Вміст фосфору досліджували колориметричним методом за допомогою фотоелектричного колориметра. Вміст інших мікроелементів визначали стандартизованим атомно-абсорбційним методом за допомогою спектрофотометра AAS-30 (Sagle Zeiss, Німеччина) на експериментальній базі Випробувального центру Інституту тваринництва НААН, акредитованого Національним агентством з акредитації України, відповідно до вимог ДСТУ EN ISO/IEC 17025:2019.

Результати. Акцентовано увагу на тому, що віковий чинник асоціюється з накопиченням мінеральних елементів у м’язовій тканині, тоді як порода відіграє ключову роль у регуляції загального мінерального обміну. У ході досліджень мінерального складу *Longissimus dorsi* muscle бугайців у різні вікові періоди росту ідентифіковано 12 елементів, серед яких 5 класифікували як макроелементи (Ca, P, Mg, K, Na), а 7 – як мікроелементи (Cu, Co, Mn, Zn, Fe, Pb, Cd). Аргументовано, що концентрації зазначених елементів варіювали в досить широких межах, однак не перевищували гранично допустимих рівнів, встановлених для м'яса великої рогатої худоби. Вміст важких металів плюмбуму і кадмію у м'ясі зрілих, інтенсивно вирощуваних бугайців 21-місячного віку був значно нижчий, ніж у телятині бугайців 3-місячного віку.

Висновок. Результати дослідження свідчать про відсутність загальної для всіх мінеральних елементів закономірної зміни їхнього вмісту в різних вікових періодах росту. Установлено лише специфічні особливості накопичення для кожного мікроелемента й періоду росту, які не порушували загальної тенденції подібності мінерального складу м'яса бугайців молочного і комбінованого напряму продуктивності. Вміст важких металів плюмбуму і кадмію у м'ясі зрілих, інтенсивно вирощуваних бугайців 21-місячного віку був значно нижчий, ніж у м'ясі бугайців 3-місячного віку.

Ключові слова: мінеральні елементи, м'яз *Longissimus dorsi*, яловичина, бугайці, порода, вік

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