DOI https://doi.org/10.30525/978-9934-26-316-3-16

MINERAL ELEMENTS IN SHEEP NUTRITION AND WOOL PROCESSES

Stapay P. V., Stakhiv N. P., Salyha Yu. T.

INTRODUCTION

One of the most important factors in the rational and complete feeding of farm animals is to provide them with the necessary mineral elements in optimal quantities and proportions, since they play an extremely important and multifaceted role, although they themselves have neither plastic nor energy values. Mineral elements are indispensable components of all living organisms. Their content in the animal body is 2,4–4,8%, and they play an extremely important role in metabolism as one of the links in the metabolic pathway in it[1].

Mineral elements are involved in the construction of micro– and macrostructures of various tissues (in the formation of bone tissue and cell membrane construction), in the regulation of osmotic pressure in biological fluids and in maintaining the acid-base balance of the reaction of the environment (pH) at a certain level, due to their participation in the formation of buffer systems of biological fluids and tissues. They affect the permeability of cell membranes and blood vessels, perform important functions in the formation of stability of biological colloidal systems, stimulate the growth and development of symbiotic microflora of the gastrointestinal tract, regulate enzymatic processes and bacterial protein synthesis in ruminant rumen, and also play an important role in the processes of reproduction, immune defense, hematopoiesis and intracellular metabolism, cell respiration, etc. Mineral elements are part of proteins (Se, S), enzymes (Zn, Cu, Ni, Mo, Fe), coenzymes (P, Co), vitamins (Co), hormones (I, Zn) and simply participate in various parts of metabolism[2, 3, 4, 5, 6, 7].

---

[1] Седіло Г. М. Роль мінеральних речовин у процесах вовноутворення. Львів: «Афіша». 2002. – 184 с.

[2] Stewart WC, Scasta JD, Taylor JB, Murphy TW, Julian AAM. Invited Review: Mineral nutririon considerations for extensive sheep production systems. Applied Animal Science. 2021;37 (3): 256–72.

[3] Сологуб, Л. І. Йод в організмі тварин і людини (Біохімічні аспекти). Біологія тварин. – 2005. – 7 (1-2), с. 31-50.

[4]Robin W Warne. The Micro and Macro of Nutrients across Bilogical Scales. Integrative and Comporative Biology. 2014; 54(5): 864-72.

[5] Sunday A Adedokun, Opevemi C Olojede. Optimizing Gastrointestinal Integrity in Poultry: The Role of Nutrients and Feed Additives. Frontiers in Veterinary Science. 2019; 5(348): 1–11.

[6]Zduniak P, Surmacki A, Erciyas K, Yavuz, Chudzińska M, Barałkiewicz D. Are there different requirements for trace elements in eumelanin– and pheomelanin-based color production? A case study of two passerine species. Comp Biochem Physiol A Mol Inegr Physiol. 2019; 175: 96–101.

[7] Rao KR, Padmavathi IJ, Raghunath M. Maternal micronutrient restriction programs the body adiposity, adiposyte function and lipid metabolism in offspring: a review. Rev Endocr Metab. 2012; 13 (2): 103–8.

About 96–98% of dry matter in plant and animal tissues consists of Carbon, Hydrogen, Oxygen and Nitrogen. Animal bodies contain more Carbon and Nitrogen, and plant tissues contain more Oxygen.

Under the influence of high temperature (during combustion) or a mixture of concentrated acids, the organic matter of plant and animal tissues burns out with the release of carbon dioxide, water and ammonia, and the inorganic part remains in the form of a precipitate – ash. The elements found in the ash, purified from impurities, are classified as mineral (inorganic, ash).

Currently, more than 80 mineral elements (macro– and microelements) have been found in the body of animals and in the composition of plants. At the same time, 50 of them are quantified and serve as permanent components of the body.

Pure and dry (devoid of mineral and plant impurities and sweat) wool is almost 97 % composed of keratin protein and only a small amount is represented by non-protein components – lipids, macro-and micronutrients, carbohydrate and protein metabolism products – uric acid, purines, amino acids, urea, glycogen, citric acid, phenols, etc. Like all protein substances, keratin consists of Carbon (49–52%), Hydrogen (5–7%), Oxygen (21–24%), Nitrogen (15–21%). However, one of the features of keratin, that distinguishes it from other protein compounds, is the high content of Sulfur (2–5%). In addition to Sulfur, sheep’s wool contains many other minerals. With the help of new research methods, especially absorption spectrophotometry, it was found that keratin fibers contain about 37 elements. These are calcium, sodium, potassium, phosphorus, magnesium, iron, zinc, copper, silicon and others. One kilogram of dry matter of wool contains 4,2 g of ash, including 2300 mg of Calcium, 305 – Sodium, 185 – Magnesium, 137 – Phosphorus, 115 – Zinc, 60 – Iron, 45 – Potassium, 25 – Manganese and 25 mg of Copper. More than 30 % of wool ash is silicon[8].

Therefore, taking this into account, mineral elements must constantly enter the body with food and thereby ensure normal metabolism and energy, the functioning of enzymes, hormones, vitamins, tissues and products.

The main source of nutrients from which farm animals build their bodies is vegetable feed. The main component of the successful management of any branch of animal husbandry, including sheep breeding, is, first of all, the organization of a stable feed base to ensure balanced feeding of animals according to improved standards[9, 10, 11].

It should be noted that there is no clear boundary between organic and mineral elements, as this division is arbitrary, since the metabolism in the body is only one and the mineral metabolism is one of the links in this

[8] Стапай П.В., Огородник Н.З., Бальковський В.В., Павкович С. Б. Фізіолого-біохімічні основи формування вовнової продуктивності овець. – Новий світ-2000. – 2021. – 150 с.

[9] ARC (Agricultural Research Council). The nutrient requirements of ruminant livestock. The Gresham Press, London. 1980.

[10] National Research Council. Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids. The National Academies Press, Washington. DC. 2007.

[11] SCA (Standing Committee on Agriculture). Feeding Standards for Australian Livestock: Ruminants. 1990.

common chain. An example is the metabolism of Phosphorus, an element that binds all the processes of protein, carbohydrate, lipid, mineral and energy metabolism in the body. This to some extent also applies to S, Mg, Fe, Zn.

In feed, mineral elements are in the form of mineral and organic compounds of various complexity, which are often difficult to digest for the animal organism. Therefore, in order to meet the needs of animals in minerals, it is necessary to know not only their content in feed, but also the degree of assimilation by the body, which varies significantly depending on the species of animals, their physiological state, age and productivity level. It has been found that some minerals are better used by ruminants, others by monogastric ones. The absorption of mineral elements decreases with age. Pregnant animals absorb mineral elements better[12, 13].

The concentration of macroelements in the dry matter of the sheep diet directly depends on the sex and age group, physiological state, live weight and productivity level of animals[14]. Thus, for ewes with twin lambs, due to more intense metabolic processes in the body and the loss of minerals with milk, a higher need for almost all limiting macro– and microelements is characteristic[15, 16]. It is noted that, first of all, for young sheep in intensive breeding and fattening, calcium and phosphorus are needed, which ensure the formation of bone tissue and the growth of animal skeleton.

Many factors influence the digestibility and utilization of feed nutrients, among which the level and ratio of mineral elements in the diet is important. In the complex mechanisms of metabolism, mineral elements are in close connection and interaction not only with each other, but also with organic components. Knowing the features of these connections allows you to direct the metabolic processes in the body in the direction of their most efficient use and obtaining the highest productivity from animals.

---

[12] Науково-практичні основи нормованої годівлі овець та кормовиробництва. – Монографія за ред. Іовенко В.М. – Херсон. – 2022. – ОЛДІ-ПЛЮС. – 700 с.

[13] Masters D G. Practical implications of mineral and vitamin imbalance in grazing sheep. Animal Production Science. 2018; 58 (8): 1438-50.

[14] Кононенко В. К. Мінеральна поживність кормів та балансування раціонів високопродуктивних корів у Київському Поліссі // Матеріали міжнар. науково–практичної конференції, «Актуальні проблеми годівлі с/г тварин і технології кормів». – Київ. – 2003. – С. 20–22.

[15] Khan MJ, Abas A, Ayaz M. Factors affecting wool quality and quantity in sheep. African Journal of Biotechnology. 2012; 11 (73): 13 761–6.

[16] Стапай П. В., Дружина О. С., Ткачук В. М. та ін. Вплив амінокислот лізину, метіоніну та Сульфуру на м’ясну і вовнову продуктивність молодняку овець // Проблеми зооінженерії та ветеринарної медицини. – Збірник наукових праць. – Харків. – 2014. – Вип. 28. – Ч.2. – с.105-108.

1. Biological role of mineral elements in metabolic processes and nutrition of sheep

In recent years, more and more attention has been paid to the important role of mineral elements in the biological functions of the animal organism. Their close relationship with proteins, their influence on the growth, productivity and reproductive functions of animals, tissue respiration, intracellular metabolism, hematopoietic functions, etc. have been established. Trace elements as metal components largely activate or inhibit the action of many enzymes, vitamins, hormones and thus ensure their physiological function and the intensity of metabolic processes. During the life of an organism, mineral elements are excreted in milk, feces, and urine. They cannot be synthesized in the body or replaced by other nutritional components. They enter the body of animals only with food and water.

Numerous studies have established a close relationship between mineral elements and metabolic processes[17, 18]. Elements that influence the body's metabolism in one direction and enhance each other's activity are called synergists, and those that affect the metabolism in the opposite direction are called antagonists. It is important to note that the nature of the interaction between mineral elements is not constant but can change with a deficiency or excess of one or another element. Thus, Cu can be toxic to sheep even at its normal content in the diet (10–11 mg/kg), but on condition that it contains an insufficient amount of Molybdenum[19]. At optimal doses of Mn and I in the diet, the effect of antagonism between them is not manifested. However, at a high level of Mn and a low content of I, the accumulation of the latter in the thyroid gland decreases. Iodine increases the content of Mn, Zn, Cu, Ni and Fe in the animal body. Iodine antagonists include Calcium, Mangan, Cobalt, Plumbum. Sulfur is a Silicium antagonist, and Iodine is a Fluor antagonist. Interactions between mineral elements can also be disturbed with a lack or excess of vitamins, protein, fat, etc. in the feed. Therefore, in this case, it is necessary to note the specifics of the relationship of feed nutrients for different animal species, taking into account their physiological state, productivity, type of feeding, etc.

---

[17] Ткачук В. М., Стапай П. В., Кирилів Я. І. Економічна оцінка підвищених рівнів мінеральних елементів та фільтроперліту у годівлі овець // Науковий вісник Львівського Національного Університету ветеринарної медицини та біотехнологій імені С. З. Гжицького. – Серія «Сільськогосподарські науки». – Львів. – 2014. – Т.16. – № 3 (60). – Ч. 3. – с.193-198.

[18] Дружина О.С., Гавриляк В.В., Стапай П.В. та ін. Показники білкового обміну у крові баранчиків за умов використання у їх раціонах амінокислот лізину, метіоніну та Сульфуру // Вісник Сумського національного аграрного університету. – Серія «Тваринництво». – 2014. – Вип. 2 /1 (24). – с.117-120.

[19] Кліценко Г.Т., Кулик М.Ф., Косенко М.В., Лісовенко В.Т. Мінеральне живлення тварин. К.: Світ. – 2001. – 575 с

The studies have shown a close relationship between mineral elements and protein nutrition[20, 21]. The richer the balanced diet in mineral elements is, the more efficiently nitrogen substances are used. In turn, the protein value of the diet has a positive effect on the use of mineral elements. With a simultaneous increase in the level of feeding and protein content in diets, the absorption and use of Ca, P, Na, Zn in the body improves[22]. For example, the assimilation of S from natural feed by animals ranges from 25–70% and depends on the type of feed, the availability and quality of protein, and the presence of non-protein nitrogen compounds in diets. It has been noted that feeds rich in protein are also high in S. Therefore, balanced diets rich in protein are usually characterized by a sufficient amount of this element. The bioavailability of Sulfur for ruminants from different sources is as follows: methionine – 81–100%, sodium sulfate – 60–80% and ammonium sulfate – 60–80%. There is also a close relationship between easily fermentable carbohydrates and individual mineral elements, especially such as Ca, P, Na, Mg, S, Mn, Zn, Cu, Co[23]. A close relationship has also been established between easily fermenting carbohydrates and individual mineral elements, especially Ca, P, Na, Mg, S, Mn, Zn, Cu, Co[24].

In the processes of intracellular metabolism of fats and their decay products, phosphoric acid compounds are most actively involved. Of the five known fat oxidation reactions, four are associated with Phosphorus. They proceed during absorption, resynthesis and formation of phosphatides.

Mineral metabolism is closely related to water metabolism, therefore water is classified as a mineral substance, since it is the main solvent and participant in all physiological processes of the body. Water is the most important component of various organisms, therefore, it should be considered as an environment in which all biochemical transformations associated with the vital activity of the organism take place. Accordingly, there is a lot of water in the muscles, kidneys, heart (up to 70–80%). Blood passing through the heart has only 3–5% more water than the organ itself. Part of the water is in a bound form (immobile and hydration), which makes it impossible to be mobile. The loss of 10% of water leads to the violation of physiological functions in the body, and 20% causes death[25].

[20] Ібатулін І.І, Мельничук Д.О., Богданов Г.О. та ін. Годівля сільськогосподарських тварин. – Вінниця: Нова книга. – 2007. – 616 с.

[21] Ібатулін І.І., Бащенко М.І., Жукорський О.М. та ін. Довідник з повноцінної годівлі сільськогосподарських тварин. – Київ: Аграрна наука. – 2016. – 336.

[22] Седіло Г. М., Макар І. А., Стапай П. В. та ін. Використання солемінеральних сумішей в годівлі овець у господарствах різних регіонів України. – Львів, 2003. – 16 с.

[23] Стапай П. В., Макар І. А., Гавриляк В. В. Фізіолого-біохімічні основи живлення овець // Львів: Лео-Бланк, – 2007. — 98 с.

[24] Свистула М. Б, Ефремов Д. В., Горб С. В. та ін. Науково-практичні основи нормованої годівлі овець та кормовиробництва. – Херсон: ОЛДІ – Плюс, 2022. – 300с.

[25] Pikhtirova A, Ivchenko V. The elemental composition and microstructure features of sheeps wool in condition of insufficient mineral nutrition. Materials of International scientific and practical conference «Innovationapproaches to the development of science» Dublin, Ireland. Veterinary Science. 2018; 2 (5): 26–9.

The role of mineral elements in the processes of wool formation in sheep

The formation and growth of wool, its structure and physico-chemical parameters are genetically determined. However, factors such as breed, age, individual characteristics of the organism, its physiological state, the effect of the season, the nature of nutrition and housing conditions of animals have a significant impact on wool growth and quality. Not only the general level of nutrition but also the nutritionally balanced diet are of great importance. To function well the animal body needs all the mineral elements, but most of all large quantities of Calcium, Phosphorus, Magnesium, Sodium, Chlorine, Sulfur, Potassium, Cobalt, Iodine, Cuprum, Selenium, Silicium are required. This is due to the production of a specific product – wool[26, 27].

Sheep wool is characterized by a great variety and a set of valuable technological properties. It spins up and felts well, has low thermal conductivity, good electrical and sound resistance, lightness, high strength, hygroscopicity, good permeability to air and ultraviolet rays, is dyed in different shades, and releases heat when wet. In terms of structure and technological properties, it is the most complex substance of all textile fibers both natural and artificial.

Speaking about the mineral composition of wool, it should be emphasized that hair in the broad sense of the word (hair, wool, bristles, etc.) has attracted the attention of a wide range of researchers, especially in terms of its possible use as an indicator of the state of mineral nutrition. In this respect, the hairline is an advantageous object for research. Its unique property is the ability to store data on metabolism both in the body as a whole and in wool-forming structures in particular. The hair itself is characterized by high metabolic inertness, and the minerals in it are firmly fixed with protein structures. Thus, hair analysis is a very informative tool in terms of assessing the intake of minerals into the body and, from this point of view, can be used in both scientific and practical activities.

Currently, there is more and more information about the possibility of establishing the degree of provision of the animal body with minerals by their content in the hair, since the hair is closely related to the metabolism of some mineral elements such as Ca, P, S, Cu, Se, Mg and Fe. Their content in the hair (wool) is a mirror image of the provision of the body with these

[26] John A Rippon, John R Christoe, Ronald J Denning, David J Evans, Mickey G Huson et al. Wool: Structure, Properties, and Processing. 2016.

[27] Jin YQ, Ding X G, Diao SC, Yu SC, Zhao JX, Zhang JX. Net micromineral requirements for maintenance and growth of ewe lambs at the latter fattening period. Asian-Australas. J. Anim. Sci. 2020; 33: 1421–9.

substances[28, 29, 30, 31, 32, 33, 34, 35]. Studies on the composition of the hairline of humans and animals made it possible to conclude that there are species, intraspecific, age, sex, seasonal differences in terms of the mineral content, as well as the differences related to pathology, physiological condition of the body, environmental conditions, topographic location and growth wool. For example, the content of Mg and Cu in sheep wool is lower than in the hair of goats, cows, and especially horses[36, 37, 38, 39, 40, 41].

The relationship between the content of mineral substances in the soil and their content in wool has also been found[42]. Many scientific studies report a deficiency of mineral elements in soils and feed, and therefore it is necessary to additionally introduce them into the diets of sheep[43, 44, 45, 46]. However, there

---

[28] Rippon JA et al. Wool, in Encyclopedia of Polymer Science and Technology, New York : Interscience Publishers. 2003.

[29] Fan Q, Wang Z, Chang S, Peng Z, Wanapat M, Bowatte S, Hou F. Relationship of mineral elements in sheep grazing in the highland agro-ecosystem. Australasian journal of Animal Sciences. 2020; 33 (1): 44–52.

[30] Langbein L, Schweizer J. Keratins of the human hair follicle. International Review of Cytology. 2005;243: 1–78.

[31] McManus CM, Faria DA, Lucci CM, Louvandini H, Pereira SA, Paiva SR. Heat stress effects on sheep: Are hair sheep more heat resistant? Theriogenology. 2020; 155: 157–67.

[32] Hintz HF. Hair analysis as an indicator of nutritional status. Journal of Equine Veterinary Science. 2001; 21(4): A1.

[33] Pereira FS, Carmo ABR, Costa MRGF, Medeiros AN, Oliveira RL, Pinto AP, Carneiro MSS, Lima FWR, Campos ACN, Gomes SP. Mineral requirements of hair sheep in tropical climates. J. Anim. Physiol. Anim. Nutr. 2016; 100: 1090–6.

[34] Sefdeen SM. Effect of dietary iron in presente of sulphur on some liver mineral concentrations and performance of growing lambs. Iraqi Journal of Agricultural Sciences. 2021; 52 (1): 1–9.

[35] Grace ND, Knowles SO, Rounce DM, West DM, Lee J. Effect of increasing pasture copper concentrations on the copper status of grazing Romney sheep. New Zeal. J.Agric. Res. 2012; 41:377–86.

[36] Myros VV, Fominova AS. Sheep and goat breeding: study aid. «Kharkiv», Kharkiv. 2009.

[37] Годівля сільськогосподарських тварин. І.І. Ібатулін, Д.О. Мельничук, Г.О. Богданов та ін. Вінниця : Нова книга, 2007. 616 с.

[38] Довідник з повноцінної годівлі сільськогосподарських тварин / за наук. ред. І.І. Ібатулліна, О.М. Жукорського. Київ : Аграр. наука, 2016. 336 с.

[39] Седіло Г.М. Роль мінеральних речовин у процесах вовноутворення : автореф. дис. д-ра с.-г. наук : 03.00.04. Львів, 2004. 25 с.

[40] Cannas A, Tedeschi LO, Atzori AS, Fox DG. The Small Ruminant Nutrition System: development and evaluation of a goat sub-model. Ital. J. Anim. Sci. 2007; 6: 609–11.

[41] Гавриляк В. В., Макар І.А. Видові особливості фізико-хімічних показників волоса // Наукові записки Тернопільського Національного Педагогічного Університету ім. В. Гнатюка / Серія: Біологія. – 2011. – № 1 (46). – С. 82-86.

[42] Приліпко Т.М. Селен і сірка в раціонах вівцематок асканійської тонкорунної породи. Тваринництво України. 2001. № 2. С. 30–31.

[43] Dove H, Masters DS, Thompson N. New perspectives on the mineral nutrition of liverstock grazing ceral and canola zzops. Animal Production Science. 2016; 56: 1560.

[44] Song C, Shen X. Effect of environmental zinc deficiency on antioxidant system function in Wumeng semi-fine wool sheep. Biol.Trace Elem. Res. 2020; 195: 110–6.

[45] Huo B, Wu T, Song C, Shen X. Studies of selenium deficiency in the Wumeng semi-fine wool sheep. Biol.Trace Elem. Res. 2020; 194: 152–8.

[46] Дзень Є.О., Лучка І.В., Талоха Н.І., Салига Ю.Т. Вміст Купруму у грунтах, воді та рослинних кормах раціону ВРХ у різних біогеохімічних провінціях Західної України. // Біологія тварин. – 2012. – Т.14 . – № 1-2. – с.93-100.

are disagreements on this issue, for example, some researchers believe[47] that the use of Ca in diets is negatively correlated with the content of P and Zn in wool. On the contrary, other data suggest the opposite. In addition, the content of Ca and Mg in wool can be displayed only when there is an excess of them in the diet, and the content of Na – only when it is highly deficient. At present, it is generally recognized that the animal organism should be considered in a close connection with feed factors as the main source of their nutrition. Therefore, the soil, plants and animal organisms are closely related as the only migratory circle. Researchers who have determined the mineral composition of wool note that such elements as Sulfur, Calcium, Phosphorus, Cuprum, Cobalt, Zinc, Selenium and Silicium are among the main indicators of the state of the sheep mineral provision[48].

Australian researchers in the SCA (1996) standards have proposed minimum levels of mineral elements to meet the needs of sheep depending on the productivity level and growth rate[49].

The main source of nutrients from which farm animals build their bodies is plant feed. The main component of successful management of any branch of animal husbandry, including sheep breeding, is, first of all, the organization of a stable forage base to ensure balanced feeding of animals in accordance with improved standards. The mineral composition of feed depends on many factors – the type of plants, the place where they are grown, soil, varieties, fertilizers, etc. It is known that biogenic minerals are necessary to ensure the vital activity of the animal organism. It is noted that according to different systems of sheep nutrition rationing, there are certain differences in the norms of mineral elements for sheep.

Table 1

Comparative characteristics of various mineral nutrition rationing systems for sheep in the dry matter of the diet.

System	Na, g/kg	Ca, g/kg	P, g/kg	S, g/kg	Cu, mg/kg	Co, mg/kg	Se, mg/kg	I, mg/kg	Zn, mg/kg	Mn, mg/kg	Fe, mg/kg
ARC, 1980	0,8 –2,7	1,4 –4,5	1,2 –3,5	–	1–8,6	0,08 – 0,1	0,03 – 0,05	0,15 – 0,5	30	25	30
SCA, 1990	0,7 –0,9	1,5 –2,6	1,3 –2,5	2,0	5	0,11	0,05	0,5	20 – 30	15 – 25	40
NRC, 2007	0,9 –1,8	2– 8,2	1,6 –3,8	1,4 –2,6	7–11	0,1 – 0,2	0,1 – 0,2	0,1 – 0,8	20 – 33	20 – 40	30 – 50

It was shown that samples of New Zealand wool from regions with different soil composition differ markedly in the content of Ca, Mg, Zn, Al, Fe, Mn, Ba, Ti, Ni, Mo, S. By the way, this experiment found a direct

[47] Teixeira IAMDA, Resende KTD, Silva AGS, Härter CJ, Sader APDO. Mineral requirements for growth of wool and hair lambs. Rev. Bras. Zootec. 2013; 42: 347–53.

[48] Oddy VH, Sainz ARD. Nutrition for sheep meat production. In: Freer, M.; Dove, H. (Eds.) Sheep nutrition Wallingford, UK: CABI Publishing. 2002: 237-62.

[49] SCA Feeding Standarts for Australian Lirestoc (SCA). Rumninants Standing Committee on Adriculture (CSIRO; Melbourne). 1990.

correlation between Ca and Mg content in wool, their total content and ash content.

Studying the mineral composition of sheep wool, Fan K. and co-authors found that one kilogram of dry matter contains ash – 4,2 g, Ca – 2300 mg, Na – 305, Mg – 185, P – 137, Zn – 115, Fe – 60, K – 45, Mn – 25, Cu – 25 mg.

A comparative study of the mineral composition of human hair, pig bristles, sheep wool, goat wool, cow hair, horse hair and other animal hair showed that they all have a fairly high content of Ca, Na, K, P, Mg, Fe, Cu, Zn, Si, and especially S. Thus, a more or less comprehensive answer to the question of the role of minerals in wool formation can be given on the basis of analysis of those and some other elements, since they seem to have the most pronounced effect on these processes.

Sheep wool per 1 kg of dry matter contains 16–22 mmol of **Calcium** and 3,2–4,3 mmol of **Phosphorus**. And although there is no direct information about the importance of Calcium in wool formation, some idea of the mechanisms of its action can be formed on the basis of data reflecting the participation of this element in the construction of bone tissue. About 99% of Ca is found in skeletal bones. Thus, it can be assumed that Ca is most likely involved in the process of keratinization of wool fiber, that is, in the final phase of keratin synthesis, just as it occurs during calcification or mineralization of bone. In this case, the formation of bone tissue is presented as a process of organic matter synthesis followed by its calcification occurring in osteoblasts and accompanied by a significant energy consumption. The latter is formed as a result of respiration of these cells and is used for the synthesis of large amounts of mucopolysaccharides and protein-carbohydrate complexes[50, 51, 52].

All Calcium in wool is in an easily dissociated state and after hydrolysis of the protein turns into an ionic form – Ca^{2+}. Therefore, this may indicate that wool Calcium is bound to Phosphorus, specifically to the orthophosphate residue, and apparently forms compounds with the carboxyl groups of aspartic and glutamic acids, and also interacts with glucuronide residues of mucopolysaccharides.

There is an opinion about the possible dependence of the elastic parameters of the fibers on the presence of Ca in them. In particular, it is believed that the higher content of this element in wool is, the less elastic and more fragile it becomes. Good wool is an elastic product up to a certain limit,

[50] Sousa DL, Marcondes MI, Silva LP, Wellington FR, Lima Herbster CJ,
Souza JG, Pacheco JPR, Bezerra LR, Oliveira RL, Pereira ES. Macromineral and trace element requirements for Santa Ines sheep. Sci Rep. 2021; 11: 12329.

[51] Szigeti E, Katài J, Komlósi I, Olàh J, Szabó C. Newly Grown Wool Mineral Content Response to Dietary Supplementation in Sheep. Animals. 2020; 10(8): 1390.

[52] Pedernera M, Mereu A, Villalba JJ. Preference for inorganic sources of magnesium and phosphorus in sheep as a function of need. Journal of animal science. 2021; 99(1): skab010.

which is probably determined by the Ca content in the fiber. Therefore, it is possible that Ca is involved in the formation of wool stiffness, which in turn may be important in the formation of technological properties of wool, in particular, its felting. The higher the stiffness of wool fibers is, the lower its feltness is, and therefore such wool becomes more suitable as a raw material for the manufacture of fur products.

As for the role of Phosphorus in the processes of wool formation, it should be considered, first of all, in terms of the importance of this element in the energy of metabolic reactions, including those related to the synthesis of wool fiber keratin. Thus, the specific value of P for wool formation processes is not yet clear, neither is its role in the formation of physical and mechanical properties of wool fibers. Nevertheless, phosphorylated serine was isolated from wool. Therefore, it is possible to think about the presence of a certain amount of phospholipids in it. However, its amount is so insignificant (less than 3,5 μmol/kg) that we should not talk about the special contribution of this compound to the overall balance of wool Phosphorus.

The content of Calcium and Phosphorus in wool in different periods of its growth is different, which is obviously due to their different intake of sheep with food, seasonal characteristics, their different digestibility, hormonal activity. And importantly, the lack of Ca and P in the diet always leads to a decrease in their content in wool, reducing wool growth and deteriorating its quality. As it turned out, the traditional norms of P and Ca for adult sheep do not always meet their needs, and therefore adding them by 10 and 15% above the norm always gives a noticeable positive effect, which is also biologically justified and economically beneficial. It was found that the total shear of wool was 8,0% higher in animals in which the level of P and Ca was 10% higher[53, 54, 55].

In the processes of wool formation, the most important role belongs to **Sulfur**. This is primarily due to the fact that it is included in proteins containing sulfur-containing amino acids (cystine, cysteine, methionine), and is also a component of vitamins and hormones. The special role of sulfur-containing amino acids in the metabolism of an animal organism is due to the presence in their composition of sulfhydryl and methyl groups used to synthesize a number of important biochemical compounds – adrenaline, choline, creatine, etc. Sheep, unlike other farm animals, are characterized by a more intensive S metabolism and a greater need for it due to the production of such a specific product as wool, the main component of which is solid keratin – a complex protein compound that differs from other proteins by a

[53] Saha SK, Pathak NN. Mineral Nutrition. Fundamentals of Animal Nutrition. Springer, Singapore. 2021: 113–31.

[54] Hynd PI, Masters DG. Nutrition and wool growth. Sheep Nutrition. 2002: 165–88.

[55] López-Carlos MA, Ramírez RG, Aguilera-Soto I et al. Size and shape analyses in hair sheep ram lambs and its relationships with growth performance. Livestock Science. 2010; 31: 203–11.

high content of Sulfur. The total S content in keratin ranges from 2,5 to 4,0 %. In addition, keratin is characterized by high density, poor solubility in water, resistance to many chemical factors and enzymes.

Sulfur in wool is found in various sulfur-containing compounds, but its greatest amount is found in cystine (about 74 %). The latter is precisely the amino acid that plays a decisive role in keratin synthesis and the formation of its mechanical properties, and, consequently, the technological properties in general. Only an insignificant part of Sulfur is found in another sulfur-containing amino acid – methionine – 2,4–4,8% of the total Sulfur. According to available data, the balance of Sulfur in wool consists of such sulfur-containing compounds as cystine, cysteine, methionine, lanthionine, cysteic acid, sulfates, and Sulfur oxidized by bromine[56].

In addition, the fiber structure contains up to 3% lipids, which are in both the free and protein-bound states. These structural lipids consist of ceramides, cholesterol sulfate, fatty acids and sulfolipids. It is shown that wool with a high content of S and sulfolipids is characterized by the best indicators of physical and mechanical properties, in particular, the tensile strength of fibers[57, 58].

The content of lantionine and cysteic acid in wool is considered as the exposure to a number of reducing and oxidizing agents. In particular, when wool is exposed to UV rays, its cystine is oxidized to cysteic acid (HO3SCH2CH (NH2) COOH – cysteic acid). The intermediate products of this reaction are cysteine sulfenic and cysteine sulfonic acids. Hydrogen sulfide is released from unstable cysteic acid, which in turn is oxidized to sulfates with a certain loss of total Sulfur. In an alkaline environment, which is created by sweat, in addition to cysteine, lanthionine is formed from cystine which contains one Sulfur atom less than cystine but similarly to it forms a bond of the type R – S – R (HOOC (NH2) CHCH2 – S –CH2 (NH2) COOH – lantionine.

As you can see, Sulfur in wool reflects all possible changes in the wool fiber under the influence of various factors, and any change in its balance will depend primarily on cystine, although the redistribution of other sulfur-containing compounds may also have a corresponding effect. Indeed, the Sulfur balance becomes negative immediately after the level of cystine in wool decreases[59].

---

[56] Eichhorn S, Hearle JWS, Jaffe M, Kikutani T. Handbook of textile fibre structure. Vol. 2: natural, regenerated, inorganic, and specialist fibres. CRC Press. 2009: 532.

[57] Стапай П.В., Стахів Н.П., Смолянінова О.О., Грабовська О.С., Тютюнник О.С. Сульфурвмісні сполуки вовни і їх роль у процесах вовноутворення та формуванню фізико-хімічних властивостей волокон // Наукові праці національного університету харчових технологій. – Київ. – «НУХТ». – 2021. – Т. 27. – № 5. – с. 21-32.

[58] Стапай П.В., Стахів Н.П., Гавриляк В.В, Смолянінова О.О., Тютюнник О.С. Ліпідне живлення овець // Біологія тварин. – 2020. – Том 22 (2). – с.3-7.

[59] Silva AMA, Silva AG. Tindade IACM et al. Net and metabolizable protein requirements for body weight gain in hair and wool lambs. Small Ruminant Research. 2007; 67: 192–8.

Table 2

The content of sulfur-containing compounds in wool.

Sulfur-containing compounds	M±m	% to total Sulfur
Total Sulfur	3,18±0,03	–
Cystine	8,76±0,13	73,54
Methionine	0,59±0,05	4,01
Cysteic acid	0,63±0,04	3,42
Lantionine	0,06±0,003	0,28
Cystathionine	0,05±0,002	0,22

Therefore, the presented data show that Sulfur plays an important role in the processes of wool formation and the formation of physicochemical and technological properties of wool fibers. The synthesis of keratin itself is closely related to the intensive use of sulfur-containing compounds, mainly cysteine. Keratinization of the wool fiber is accompanied by the oxidation of sulfhydryl groups in disulfide bonds. It is known that 0,71% of the total Sulfur extracts from hair follicles is in disulfide form. Sulfur-containing compounds, in the molecule of which there are SH-groups, on the one hand, are a plastic substrate for building hair keratin, and, on the other hand, determine the activity of enzymes that catalyze metabolic processes in hair follicles[60].

It has been found that the conversion of the total number of SH groups to disulfide bonds during keratinization releases energy capable of synthesizing approximately 1% of keratin peptide bonds. As for the mechanism of the inclusion of Sulfur in growing hair, it is still unknown. According to some data[61], Sulfur enters the fiber exclusively in the keratinization zone, and not through the papillae as previously thought.

It has long been shown that the Sulfur content, and therefore its balance in dry wool, can vary widely depending on various factors[62]. Thus, the Sulfur content in wool is influenced by exogenous and endogenous factors. The first are those that affect the wool fiber outside the hair follicle: solar ultraviolet rays, adverse weather conditions, certain chemical factors, especially alkalis. In particular, washing wool in a traditional soap-soda solution is accompanied by an increase in the amount of lanthionine in it and a corresponding decrease in cystine. Wool carbonization has a similar effect. Endogenous factors affect the process of fiber formation directly in the follicle.

[60] Седіло М.Г, Макар І.А., Гавриляк В.В., Гуменюк В.В. Метаболічна і продуктивна дія сірки в організмі овець. – Львів. – «ПАЇС». – 2009. – 148 с.

[61] Zahn H. Wool chemistry and processi. Abstracts of Proc. 9th Int. WoolTextileRes. Conf (Biella). 1995: 1–16.

[62] Lee SH, Chang SN. Epidermal lipid and skin barrier. JournalAerospace Environ. Med. 1992; 2: 15–24.

Breed and individual characteristics of animals, their physiological state and feeding conditions (especially feeding sheep with S) have a significant effect on the balance of S in wool. It has been established that a sufficient level of S in the diets of ruminants is the key to the normal course of microbiological processes in the rumen[63]. Typically, protein-rich foods are characterized by a fairly high content of S and sulfur-containing amino acids. It has been found that the optimal level of S for sheep is 0,2–0,3 % of the dry matter of the diet.

Of the other elements that also have a specific effect on wool processes from a biochemical point of view, **Cuprum** should be mentioned. Its content in wool, according to mass spectroscopy, is 31–98 μg/g of dry matter. Approximately the same results were obtained by spectrographic analyzes – 31–128 μg/g. Being part of enzymes, Cu directly affects the processes of wool formation, keratinization and pigmentation of wool fiber. It is known that the pigmentation of wool fibers and skin is caused by the presence of a pigment in them– melanin. Melanins are polymers of quinoid compounds that are formed in highly specialized and intensively functioning cells – melanocytes. The functional unit of melanogenesis is the melanocyte-keratinocyte complex[64, 65, 66, 67, 68, 69].

It was shown that with a lack of Cu, keratinization in the hair follicles slows down, and the sulfhydryl zone lengthens by 2–3 times and can even reach the skin surface. As a result, such wool has much more sulfhydryl groups, which negatively affects its mechanical properties, especially strength and tortuosity[70].

The lack of Cu in the sheep body also leads to a violation of the tortuosity of wool. With a noticeable deficiency of this element, hair follicles produce fibers that are devoid of tortuosity. As soon as the diet of such animals is enriched with cuprum-containing additives, the hair follicles immediately restore the tortuosity of wool fibers. That is why, the diets of sheep, especially

---

[63] Institut National de la Recherche Agronomique. INRA Feeding System for Ruminants. Wageningen Academic Publishers. 2018.

[64] Hearing VJ, Kobayaski T, Urabe K, Pottert SB, Kameyama K. The characteristics of biological melanins are influented at multiple points in the melanogenic pathway. Melanin: Its Role in Human Photoprotection. Valdemar, Overland Park. 1995: 117–24.

[65] Ito S. Advances in chemical analisis of melanins. The pigmentary system. Oxford Univ. Press. 1998: 439–50.

[66] Ito S, Wakamatsu K, Ozeki H. Chemical analysis of melanins and its application to the study of the regulation, of melanogenesis. Pigment Cell Res. 2000; 8(13): 103–9.

[67] Katritzky AR, Akhmedov N, Denisenko SN, Denisko OV. HNMR Spectroscopic characterization of solutions of sepia melanin, sepia melanin free and human hais melanin. Pigment Cell Res. 2002; 15: 93–7.

[68] Solohub LI, Antonyak HL, Stefanyshyn OM. The role of copper in the animal organism. The Animal Biology. 2004; 6 (1–2): 64–76.

[69] Sousa IKF, Minervino HAH, Sousa RS, Chaves DF, Soares HS, Barros IO, Araújo CASC, Barrêto RAJ, Ortolani EL. Copper deficiency in sheep with high liver iron accumulation. Vet. Med. Int. id 207950. 2012: 4.

[70] Sefdeen S. Effect of dietary iron on copper metabolism in sheep. PhD. Anim. Sci., Harper Adams Univ. 2017: 193.

those with colored wool, must be strictly controlled for Cu content. In addition to the fact that Cu affects the pigmentation of the wool cover, it also has a specific effect on the processes of wool formation in general[71].

The absorption of Cu in animals is significantly affected by Ag, Cd, Zn, Mo, and especially Sulfur, which reduce its assimilation in the digestive tract. The symptoms of Cu deficiency in animals occur as a result of interaction with S, Mo, Ag and Cd.

It is generally believed that for each gram of sulfate added to the diet you need to make an additional 1 mg of Cuprum, given that the diet contains the optimal amount of this trace element.

Sheep are most vulnerable to chronic toxicity of Cu, which has a high level of accumulation in liver cells. Chronic toxicity is usually associated with the consumption of foods with a high ratio of Cu and Mo (10:1). Therefore, Molybdenum is able to significantly reduce the accumulation of Cu in the liver. It is believed that the total need of animals for this element is provided at a content of 7–8 mg/kg. Suttle and McMurray[72] showed that if the Cu content in wool is at the level of 2,5 mg/kg, its deficiency can occur only for a very short period without any impact on the condition of animals and their productivity, and the concentration in the amount of 4,14 mg / kg indicates a sufficient level of it in the feed. In addition, the Cu content in wool is a good indicator because it takes into account all the factors that affect its availability. The interaction between Cu–S, Cu–Mo–S and Cu–Fe has also been established[73], and Fe additives significantly reduce the availability of Cu in the diets of sheep[74].

Another no less important mineral for the formation and growth of wool is **Cobalt**, the content of which is 0,17–0,28 mg/g of the substance. With a deficiency of this trace element, the wool loses its luster, which means that in this case there is a violation of the formation of the cuticle of the wool fiber. There are reports that pigmented wool contains more Cobalt than white. Cobalt is known to be a cofactor of cobalamin enzymes (derivatives of vitamin B12) involved in protein synthesis, including keratin[75].

---

[71] Wang F, Li SL, Xin YJ, Wang YJ, Cao ZJ, Guo FC, Wang YM. Effects of methionine hydroxy copper supplementation on lactation performance, nutrient digestibility, and blood biochemical parameters in lactatiting cows. J. Dairy Sci. 2012; 93: 5813–20.

[72] Suttle NF. Mineral Nutrition of Liverstock, 4th. CAB International: Oxfordshire, UK. 2010.

[73] Moyano JC, Marini PR, Fischman ML. Biological Efficiency in Hair Sheep Reared in a Sustainable Farming System in the Ecuadorian Amazon Region. Dairy and Vet Sci J. 2019; 11(4): JDVS.MS.ID.555820.

[74] McDowell LR. Minerals in Animal and Human Nutrition, second ed. Elsevier Science. 2003: 644.

[75] Guerra MH, Cabrera MC, Fernández D Abella, Saadoun A, Burton A. Se and I status in pregnant ewes from a pastoral system and the effect of supplementation with Se and I or only Se on wool quality of lambs. 2019; 5 (9): e02486.

The role of **Zinc** in wool formation is also important. Its content in the hair varies within a fairly wide range– from 14 to over 280 μg / g of the substance[76]. The biokinetics of this element in the hair on the basis of studies using isotope techniques looks something like this. After the administration of labeled zinc to experimental animals (rabbits), it accumulates mainly in the interstitial part of the hair follicle bulb, and enters the hair tissue relatively quickly, but its further transport in it is slow. Suffice it to say that within three months after the injection, its content in the hair changes very little. Most zinc accumulates in the area of the top of the hair[77].

According to Meses[78], the normal content of Zn in wool is 115–120 mg/kg and is informative enough to determine its content in feed. This element has a significant impact on all parts of the body's metabolism, being an activator of a number of biological substances, as well as a structural component of some of them. Zn deficiency in farm animals causes pathological changes in the skin cover (parakeratosis). In the animal body, Zn is 0.003% of live weight. It is present in almost all organs, but most of it is found in the pituitary gland, gonads, liver, muscles, hair. The optimal need for Zn for all farm animals is 40–50 mg/kg of dry matter. When adjusting the nutrition of ruminants, it should be remembered that Zn competes with Ca, Cu, Fe, Cd, with which it interacts in the process of absorption and metabolism. The concentration of Zn in the diet above 0,1 % is considered toxic.

Another essential element for wool growth is **Iodine**. This is the most famous trace element, the deficiency of which is felt in the vast mountain and flat areas of our planet. Iodine is part of the ash elements of wool (2,7–12,0 mg/kg), and experiments with its radioactive isotope have shown that it is relatively quickly incorporated into the hair root and keratinized fiber. Although its direct importance for wool growth, unlike Sulfur or Copper, has not been established, nevertheless, being an integral part of thyroid hormones, Iodine plays an important role in regulating the processes of wool formation. The above-mentioned data shows the importance of iodine for the sheep body, particularly, the formation of wool productivity. The optimal dose of iodine for sheep is considered to be 0,2–0,4 mg/kg of dry matter in the diet, except for pregnant and lactating ewes, in which the rate is slightly higher, in particular, 0.8 mg per 1 kg of dry matter[79].

---

[76] Kruze-Jarres JD. Pathobiochemistry of Zink, Metabolism and Diagnostic Principles in Zink Deficiency. J. Lab.Med. 1999; 23 (3): 141–55.

[77] Chunjie S, Xiaoyun S. Effects of Environmental Zinc Deficiency on Antioxidant System Function in Wumenng Semi-fine Wool Sheep. Biological Trace Element Research. 2020; 195: 110–6.

[78] Mezes M. Gazdasagi allotok mikroelem ellatottsaga es egyes mikroelemek szerepe a termelesben. Agro.Naplo. 2008; 12: 95–6.

[79] Mc Goven FM, Magee DA, Browne JA, MacHugh D E, Boland T M. Iodine supplementation of the pregnant dam alters intestinal gene expression and immunoglobulin uptake in the newborn lamb. Animal. 2016; 10: 598–606.

Selenium is one of the trace elements that have a significant effect on the processes of wool formation. In the biogenic zones where there is a lack of this element (southern Ukraine), in addition to changes such as muscular dystrophy in sheep, there is also a slower growth of wool. The role of this trace element has not been definitively established. However, its undoubted participation in the synthesis of keratin wool has been found. In addition, selenium is able to replace sulfur in amino acids, forming derivatives – selenocysteine and selenomethionine. They can be included in keratin molecules as structural compounds, giving it special properties. It is now accepted that the maximum permissible dose of selenium for ruminants is 2 mg/kg of dry matter. However, it should be remembered that for normal growth and development of the organism, the feed should contain one part Selenium per 1000 parts of Sulfur, according to Ivanich[80], the concentration of Se in wool at the level of 5–10 mg/kg may indicate poisoning with this element. In general, both excess and deficiency of Se in diets can be detected by wool analysis.

And finally, about another element – **Silicon**. Only recently has the role of this element in the processes of wool formation and growth been more or less clarified. Meanwhile, it has long been known that one of the simplest and most reliable diagnostic signs of Si deficiency in the body is brittle nails. It has also been noted that in chronically ill or weak children with lung diseases, the Si content in the nails drops by 30–50%.

According to laboratory analysis data, 31% of sheep wool ash consists of Si. The latter is available even in the hair of newborns. The mechanisms of the influence of Si on wool formation processes have not yet been elucidated, although certain considerations in this regard indicate that its function, being an agent that cross-links keratin macromolecules, provides mechanical stability of wool. In the processes of wool formation, this mineral is necessary for the normal functioning of epithelial and connective tissues, because in the skin Se is associated with amino groups of polypeptide chains and diatomic phenols, making the skin strong, elastic and impermeable.

Therefore, the above-mentioned data indicates that the role of minerals in wool formation is extremely important, but the mechanisms of their influence on these processes are still far from complete decipherment.

In recent years, in many countries of the world with developed animal husbandry, various studies have been carried out to revise and clarify the norms of mineral nutrition for animals and poultry, the research on new effective mineral supplements and the improvement of the technologies for their use has been conducted, since minerals are one of the factors for increasing their productivity.

---

[80] Ivancic JJr, Weiss WP. Effect of dietary sulfur and selenium concentrations on selenium balance of lactating Holstein cows. J. Dairy Sci. 2001; 84: 225–32.

Data analysis on the mineral composition of feeds in different regions of Ukraine revealed their deficiency in many of the above elements. At the same time, it turned out that even within certain natural and climatic zones (Forest-steppe, Steppe, Polissya) there are areas that differ in the characteristics of the mineral composition of feed. This is what prompted the scientists of the Institute of Animal Biology of NAAS of Ukraine to develop a scientifically based formulation of mineral mixtures (premixes) for feeding sheep in different biogeochemical zones of Ukraine.

CONCLUSION

Consequently, it follows from the above that in order to increase the efficiency of absorption of mineral elements it is necessary to take into account the influence of each element on the body separately, as well as their complex effect, that is, it is crucial to find such a ratio in the diet that would ensure maximum assimilation of all the elements and obtain maximum productivity.

SUMMARY

The article presents scientific data on the biological and productive action of macro– and microelements, their importance in sheep nutrition, the role in the metabolic processes of the body and, in particular, in the processes of wool formation. Data on the positive effect of trace elements obtained by nanotechnological methods and their advantages compared to inorganic salts are also described.

The study aims to analyze the literature data on the role and biological function of the most important macro– and micronutrients in sheep nutrition. When using minerals in the diet of sheep, their biological characteristics should be taken into account, as they are closely related and interact not only with each other but also with organic components of the diet. Knowledge of these features makes it possible to direct metabolic processes in the body towards the most efficient use and obtaining the highest productivity from sheep.

The vital activity and productivity of sheep largely depends on the presence of mineral elements in their diets. In the course of life of the organism mineral elements are constantly removed from it, therefore, the mineral nutrition of animals is controlled by the need and the presence of mineral elements in feed, normalized by the appropriate selection of the latter, and in case of their lack, is regulated by dietary supplements of various macro- and micronutrients.

Funding. *This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors of*

this study confirm that the research and publication of the results were not associated with any conflicts regarding commercial or financial relations, relations with organizations and/or individuals who may have been related to the study, and interrelations of co-authors of thearticle

Declarations of interest: *none.*

Bibliography

1. Седіло Г. М. Роль мінеральних речовин у процесах вовноутворення. Львів: «Афіша». 2002. – 184 с.

2. Stewart WC, Scasta JD, Taylor JB, Murphy TW, Julian AAM. Invited Review: Mineral nutririon considerations for extensive sheep production systems. Applied Animal Science. 2021;37 (3): 256–72.

3. Сологуб, Л. І. Йод в організмі тварин і людини (Біохімічні аспекти). Біологія тварин. – 2005. – 7 (1-2), с. 31-50.

4. Robin W Warne. The Micro and Macro of Nutrients across Bilogical Scales. Integrative and Comporative Biology. 2014; 54(5): 864-72.

5. Sunday A Adedokun, Opevemi C Olojede. Optimizing Gastrointestinal Integrity in Poultry: The Role of Nutrients and Feed Additives. Frontiers in Veterinary Science. 2019; 5(348): 1–11.

6. Zduniak P, Surmacki A, Erciyas K, Yavuz, Chudzińska M, Barałkiewicz D. Are there different requirements for trace elements in eumelanin– and pheomelanin-based color production? A case study of two passerine species. Comp Biochem Physiol A Mol Inegr Physiol. 2019; 175: 96–101.

7. Rao KR, Padmavathi IJ, Raghunath M. Maternal micronutrient restriction programs the body adiposity, adiposyte function and lipid metabolism in offspring: a review. Rev Endocr Metab. 2012; 13 (2): 103–8.

8. Стапай П.В., Огородник Н.З., Бальковський В.В., Павкович С. Б. Фізіолого-біохімічні основи формування вовнової продуктивності овець. – Новий світ-2000. – 2021. – 150 с.

9. ARC (Agricultural Research Council). The nutrient requirements of ruminant livestock. The Gresham Press, London. 1980.

10. National Research Council. Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids. The National Academies Press, Washington. DC. 2007.

11. SCA (Standing Committee on Agriculture). Feeding Standards for Australian Livestock: Ruminants. 1990.

12. Науково-практичні основи нормованої годівлі овець та кормовиробництва. – Монографія за ред. Іовенко В.М. – Херсон. – 2022. – ОЛДІ-ПЛЮС. – 700 с.

13. Masters D G. Practical implications of mineral and vitamin imbalance in grazing sheep. Animal Production Science. 2018; 58 (8): 1438-50.

14. Кононенко В. К. Мінеральна поживність кормів та балансування раціонів високопродуктивних корів у Київському Поліссі // Матеріали

міжнар. науково–практичної конференції, «Актуальні проблеми годівлі с/г тварин і технології кормів». – Київ. – 2003. – С. 20–22.

15. Khan MJ, Abas A, Ayaz M. Factors affecting wool quality and quantity in sheep. African Journal of Biotechnology. 2012; 11 (73): 13 761–6.

16. Стапай П. В., Дружина О. С., Ткачук В. М. та ін. Вплив амінокислот лізину, метіоніну та Сульфуру на м’ясну і вовнову продуктивність молодняку овець // Проблеми зооінженерії та ветеринарної медицини. – Збірник наукових праць. – Харків. – 2014. – Вип. 28. – Ч.2. – с.105-108.

17. Ткачук В. М., Стапай П. В., Кирилів Я. І. Економічна оцінка підвищених рівнів мінеральних елементів та фільтроперліту у годівлі овець // Науковий вісник Львівського Національного Університету ветеринарної медицини та біотехнологій імені С. З. Гжицького. – Серія «Сільськогосподарські науки». – Львів. – 2014. – Т.16. – № 3 (60). – Ч. 3. – с.193-198.

18. Дружина О.С., Гавриляк В.В., Стапай П.В. та ін. Показники білкового обміну у крові баранчиків за умов використання у їх раціонах амінокислот лізину, метіоніну та Сульфуру // Вісник Сумського національного аграрного університету. – Серія «Тваринництво». – 2014. – Вип. 2 /1 (24). – с.117-120.

19. Кліценко Г.Т., Кулик М.Ф., Косенко М.В., Лісовенко В.Т. Мінеральне живлення тварин. К.: Світ. – 2001. – 575 с

20. Ібатулін І.І, Мельничук Д.О., Богданов Г.О. та ін. Годівля сільськогосподарських тварин. – Вінниця: Нова книга. – 2007. – 616 с.

21. Ібатулін І.І., Бащенко М.І., Жукорський О.М. та ін. Довідник з повноцінної годівлі сільськогосподарських тварин. – Київ: Аграрна наука. – 2016. – 336.

22. Седіло Г. М., Макар І. А., Стапай П. В. та ін. Використання солемінеральних сумішей в годівлі овець у господарствах різних регіонів України. – Львів, 2003. – 16 с.

23. Стапай П. В., Макар І. А., Гавриляк В. В. Фізіолого-біохімічні основи живлення овець // Львів: Лео-Бланк, – 2007. — 98 с.

24. Свистула М. Б, Ефремов Д. В., Горб С. В. та ін. Науково-практичні основи нормованої годівлі овець та кормовиробництва. – Херсон: ОЛДІ – Плюс, 2022. – 300с.

25. Pikhtirova A, Ivchenko V. The elemental composition and microstructure features of sheeps wool in condition of insufficient mineral nutrition. Materials of International scientific and practical conference «Innovationapproaches to the development of science» Dublin, Ireland. Veterinary Science. 2018; 2 (5): 26–9.

26. John A Rippon, John R Christoe, Ronald J Denning, David J Evans, Mickey G Huson et al. Wool: Structure, Properties, and Processing. 2016.

27. Jin YQ, Ding X G, Diao SC, Yu SC, Zhao JX, Zhang JX. Net micromineral requirements for maintenance and growth of ewe lambs at the latter fattening period. Asian-Australas. J. Anim. Sci. 2020; 33: 1421–9.

28. Rippon JA et al. Wool, in Encyclopedia of Polymer Science and Technology, New York : Interscience Publishers. 2003.
29. Fan Q, Wang Z, Chang S, Peng Z, Wanapat M, Bowatte S, Hou F. Relationship of mineral elements in sheep grazing in the highland agro-ecosystem. Australasian journal of Animal Sciences. 2020; 33 (1): 44–52.
30. Langbein L, Schweizer J. Keratins of the human hair follicle. International Review of Cytology. 2005;243: 1–78.
31. McManus CM, Faria DA, Lucci CM, Louvandini H, Pereira SA, Paiva SR. Heat stress effects on sheep: Are hair sheep more heat resistant? Theriogenology. 2020; 155: 157–67.
32. Hintz HF. Hair analysis as an indicator of nutritional status. Journal of Equine Veterinary Science. 2001; 21(4): A1.
33. Pereira FS, Carmo ABR, Costa MRGF, Medeiros AN, Oliveira RL, Pinto AP, Carneiro MSS, Lima FWR, Campos ACN, Gomes SP. Mineral requirements of hair sheep in tropical climates. J. Anim. Physiol. Anim. Nutr. 2016; 100: 1090–6.
34. Sefdeen SM. Effect of dietary iron in presente of sulphur on some liver mineral concentrations and performance of growing lambs. Iraqi Journal of Agricultural Sciences. 2021; 52 (1): 1–9.
35. Grace ND, Knowles SO, Rounce DM, West DM, Lee J. Effect of increasing pasture copper concentrations on the copper status of grazing Romney sheep. New Zeal. J.Agric. Res. 2012; 41:377–86.
36. Myros VV, Fominova AS. Sheep and goat breeding: study aid. «Kharkiv», Kharkiv. 2009.
37. Годівля сільськогосподарських тварин. І.І. Ібатулін, Д.О. Мельничук, Г.О. Богданов та ін. Вінниця : Нова книга, 2007. 616 с.
38. Довідник з повноцінної годівлі сільськогосподарських тварин / за наук. ред. І.І. Ібатулліна, О.М. Жукорського. Київ : Аграр. наука, 2016. 336 с.
39. Седіло Г.М. Роль мінеральних речовин у процесах вовноутворення : автореф. дис. д-ра с.-г. наук : 03.00.04. Львів, 2004. 25 с.
40. Cannas A, Tedeschi LO, Atzori AS, Fox DG. The Small Ruminant Nutrition System: development and evaluation of a goat sub-model. Ital. J. Anim. Sci. 2007; 6: 609–11.
41. Гавриляк В. В., Макар І.А. Видові особливості фізико-хімічних показників волоса // Наукові записки Тернопільського Національного Педагогічного Університету ім. В. Гнатюка / Серія: Біологія. – 2011. – № 1 (46). – С. 82-86.
42. Приліпко Т.М. Селен і сірка в раціонах вівцематок асканійської тонкорунної породи. Тваринництво України. 2001. № 2. С. 30–31.
43. Dove H, Masters DS, Thompson N. New perspectives on the mineral nutrition of liverstock grazing ceral and canola zzops. Animal Production Science. 2016; 56: 1560.
44. Song C, Shen X. Effect of environmental zinc deficiency on antioxidant system function in Wumeng semi-fine wool sheep. Biol.Trace Elem. Res. 2020; 195: 110–6.

45. Huo B, Wu T, Song C, Shen X. Studies of selenium deficiency in the Wumeng semi-fine wool sheep. Biol.Trace Elem. Res. 2020; 194: 152–8.

46. Дзень Є.О., Лучка І.В., Талоха Н.І., Салига Ю.Т. Вміст Купруму у грунтах, воді та рослинних кормах раціону ВРХ у різних біогеохімічних провінціях Західної України. // Біологія тварин. – 2012. – Т.14 . – № 1-2. – с.93-100.

47. Teixeira IAMDA, Resende KTD, Silva AGS, Härter CJ, Sader APDO. Mineral requirements for growth of wool and hair lambs. Rev. Bras. Zootec. 2013; 42: 347–53.

48. Oddy VH, Sainz ARD. Nutrition for sheep meat production. In: Freer, M.; Dove, H. (Eds.) Sheep nutrition Wallingford, UK: CABI Publishing. 2002: 237-62.

49. SCA Feeding Standarts for Australian Lirestoc (SCA). Rumninants Standing Committee on Adriculture (CSIRO; Melbourne). 1990.

50. Sousa DL, Marcondes MI, Silva LP, Wellington FR, Lima Herbster CJ, Souza JG, Pacheco JPR, Bezerra LR, Oliveira RL, Pereira ES. Macromineral and trace element requirements for Santa Ines sheep. Sci Rep**.** 2021; 11: 12329.

51. Szigeti E, Katài J, Komlósi I, Olàh J, Szabó C. Newly Grown Wool Mineral Content Response to Dietary Supplementation in Sheep. Animals. 2020; 10(8): 1390.

52. Pedernera M, Mereu A, Villalba JJ. Preference for inorganic sources of magnesium and phosphorus in sheep as a function of need. Journal of animal science. 2021; 99(1): skab010.

53. Saha SK, Pathak NN. Mineral Nutrition. Fundamentals of Animal Nutrition. Springer, Singapore. 2021: 113–31.

54. Hynd PI, Masters DG. Nutrition and wool growth. Sheep Nutrition. 2002: 165–88.

55. López-Carlos MA, Ramírez RG, Aguilera-Soto I et al. Size and shape analyses in hair sheep ram lambs and its relationships with growth performance. Livestock Science. 2010; 31: 203–11.

56. Eichhorn S, Hearle JWS, Jaffe M, Kikutani T. Handbook of textile fibre structure. Vol. 2: natural, regenerated, inorganic, and specialist fibres. CRC Press. 2009: 532.

57. Стапай П.В., Стахів Н.П., Смолянінова О.О., Грабовська О.С., Тютюнник О.С. Сульфурвмісні сполуки вовни і їх роль у процесах вовноутворення та формуванню фізико-хімічних властивостей волокон // Наукові праці національного університету харчових технологій. – Київ. – «НУХТ». – 2021. – Т. 27. – № 5. – с. 21-32.

58. Стапай П.В., Стахів Н.П., Гавриляк В.В, Смолянінова О.О., Тютюнник О.С. Ліпідне живлення овець // Біологія тварин. – 2020. – Том 22 (2). – с.3-7.

59. Silva AMA, Silva AG. Tindade IACM et al. Net and metabolizable protein requirements for body weight gain in hair and wool lambs. Small Ruminant Research. 2007; 67: 192–8.

60. Седіло М.Г, Макар І.А., Гавриляк В.В., Гуменюк В.В. Метаболічна і продуктивна дія сірки в організмі овець. – Львів. – «ПАЇС». – 2009. – 148 с.

61. Zahn H. Wool chemistry and processi. Abstracts of Proc. 9th Int. WoolTextileRes. Conf (Biella). 1995: 1–16.

62. Lee SH, Chang SN. Epidermal lipid and skin barrier. JournalAerospace Environ. Med. 1992; 2: 15–24.

63. Institut National de la Recherche Agronomique. INRA Feeding System for Ruminants. Wageningen Academic Publishers. 2018.

64. Hearing VJ, Kobayaski T, Urabe K, Pottert SB, Kameyama K. The characteristics of biological melanins are influented at multiple points in the melanogenic pathway. Melanin: Its Role in Human Photoprotection. Valdemar, Overland Park. 1995: 117–24.

65. Ito S. Advances in chemical analisis of melanins. The pigmentary system. Oxford Univ. Press. 1998: 439–50.

66. Ito S, Wakamatsu K, Ozeki H. Chemical analysis of melanins and its application to the study of the regulation, of melanogenesis. Pigment Cell Res. 2000; 8(13): 103–9.

67. Katritzky AR, Akhmedov N, Denisenko SN, Denisko OV. HNMR Spectroscopic characterization of solutions of sepia melanin, sepia melanin free and human hais melanin. Pigment Cell Res. 2002; 15: 93–7.

68. Solohub LI, Antonyak HL, Stefanyshyn OM. The role of copper in the animal organism. The Animal Biology. 2004; 6 (1–2): 64–76.

69. Sousa IKF, Minervino HAH, Sousa RS, Chaves DF, Soares HS, Barros IO, Araújo CASC, Barrêto RAJ, Ortolani EL. Copper deficiency in sheep with high liver iron accumulation. Vet. Med. Int. id 207950. 2012: 4.

70. Sefdeen S. Effect of dietary iron on copper metabolism in sheep. PhD. Anim. Sci., Harper Adams Univ. 2017: 193.

71. Wang F, Li SL, Xin YJ, Wang YJ, Cao ZJ, Guo FC, Wang YM. Effects of methionine hydroxy copper supplementation on lactation performance, nutrient digestibility, and blood biochemical parameters in lactatiting cows. J. Dairy Sci. 2012; 93: 5813–20.

72. Suttle NF. Mineral Nutrition of Liverstock, 4th. CAB International: Oxfordshire, UK. 2010.

73. Moyano JC, Marini PR, Fischman ML. Biological Efficiency in Hair Sheep Reared in a Sustainable Farming System in the Ecuadorian Amazon Region. Dairy and Vet Sci J. 2019; 11(4): JDVS.MS.ID.555820.

74. McDowell LR. Minerals in Animal and Human Nutrition, second ed. Elsevier Science. 2003: 644.

75. Guerra MH, Cabrera MC, Fernández D Abella, Saadoun A, Burton A. Se and I status in pregnant ewes from a pastoral system and the effect of supplementation with Se and I or only Se on wool quality of lambs. 2019; 5 (9): e02486.

76. Kruze-Jarres JD. Pathobiochemistry of Zink, Metabolism and Diagnostic Principles in Zink Deficiency. J. Lab.Med. 1999; 23 (3): 141–55.

77. Chunjie S, Xiaoyun S. Effects of Environmental Zinc Deficiency on Antioxidant System Function in Wumenng Semi-fine Wool Sheep. Biological Trace Element Research. 2020; 195: 110–6.

78. Mezes M. Gazdasagi allotok mikroelem ellatottsaga es egyes mikroelemek szerepe a termelesben. Agro.Naplo. 2008; 12: 95–6.

79. Mc Goven FM, Magee DA, Browne JA, MacHugh D E, Boland T M. Iodine supplementation of the pregnant dam alters intestinal gene expression and immunoglobulin uptake in the newborn lamb. Animal. 2016; 10: 598–606.

80. Ivancic JJr, Weiss WP. Effect of dietary sulfur and selenium concentrations on selenium balance of lactating Holstein cows. J. Dairy Sci. 2001; 84: 225–32.

Information about the authors:

Stapay Petro Vasylovych,
Doctor of Agricultural Sciences, Professor,
Head of the S. Gzhytsky Laboratory of Metabolism
Institute of Animal Biology of the National Academy
of Agrarian Sciences of Ukraine
38, Vasylia Stusa str., Lviv, 79034, Ukraine

Stakhiv Nadiia Petrivna,
Candidate of Agricultural Sciences,
Researcher of the S. Gzhytsky Laboratory of Metabolism
Institute of Animal Biology of the National Academy of Agrarian Sciences
of Ukraine
38, Vasylia Stusa str., Lviv, 79034, Ukraine

Salyha Yuriy Tarasovych,
Doctor of Biological Sciences,
Director
Institute of Animal Biology of the National Academy of Agrarian Sciences
of Ukraine
38, Vasylia Stusa str, Lviv, 79034, Ukraine