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PHYSIOLOGICAL IMPORTANCE OF MINERALS IN FARM ANIMALS - A REVIEW

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ABSTRACT

Minerals are essential modulators of the physiology of farm animals. Most important for the structure, maintenance of membrane potentials and fluid balance, for muscle contraction and transport of oxygen or for being part of enzymes, hormones and antioxidant systems. The effects are dependent on the amount of absorption and not just the concentration in the diet. Availability and response are modified by solubility, gastrointestinal factor, antagonist, endocrine control, tissue reserve, physiological stage and species. Macro-minerals calcium, phosphorus, magnesium, sodium, potassium, chloride and sulphur and trace minerals iron, zinc, copper, selenium, manganese, iodine, cobalt, chromium and molybdenum are summarized in a short review. A special focus is put on the interaction of minerals in ruminants, the low margin of safety for copper in sheep, electrolyte loss in horses, mineralization of skeleton in poultry and the restriction of serum diagnosis. There is evidence for a targeted approach where the whole diet and water is analyzed, species specific requirements applied and supplementation monitored by storage and functional biomarkers. It should be possible to avoid deficiency or excess with precision feeding and also to minimize losses from the environment of minerals.

Keywords: Ruminants, Skeleton, Biomarkers, Environment, Species

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Introduction

Although minerals are not a source of energy and cannot be produced by animals, almost every physiological system requires them. Calcium triggers contraction and secretion, sodium and potassium provide the excitability of the membranes, phosphorus is involved in transferring metabolic energy, iron carries oxygen, iodine enables the synthesis of thyroid hormone, zinc, copper, manganese and selenium are involved in many enzyme systems. Deficiency may manifest as poor growth, lowered fertility, weak immunity, abnormal behavior or a falling production, and may not be detected as a diagnostic sign initially (Goff, 2018; Suttle, 2022).

Requirement tables are key points which can only capture variation at intake, absorption, endogenous loss, production stage, climate, genotype and antagonistic elements. The physiological goal is to supply enough to make things safe, not to lead to over supplementing. This is particularly relevant since mineral overfeeding can lead to an increased risk of toxicity, and manure loading has no effect on performance (Duplessis & Royer, 2023; Weiss & Hansen, 2024).

The classification & Homeostatic Regulation

The microminerals are needed and held in relatively large concentrations, while the trace minerals are needed and held in relatively small concentrations. This is a quantitative, not functional, distinction. Bone

contains a high concentration of calcium, phosphorus and most of magnesium. Sodium, potassium and chloride are the main players in the regulation of fluid and electrolytes. There are two primary modes of action for trace elements: metalloproteins, transport proteins, hormones and redox enzymes (Goff, 2018; Suttle, 2022).

Absorption takes place by controlled transcellular absorption and paracellular absorption by concentration gradient. The rumen can facilitate the absorption of magnesium in ruminants, and the absorption of

microbial cobalt, however it can also form unavailable complexes. Ruminal magnesium absorption is lowered by high levels of potassium and sulphur and molybdenum forms thiomolybdates that decrease copper availability. Absorbed minerals are carried in free or protein-bound forms and stored in a selective manner particularly in bone and liver. The kidney regulates reabsorption/excretion of key minerals; parathyroid hormone, aldosterone, antidiuretic hormone and the thyroid axis regulate other mineral systems (Goff, 2018; Wilkens & Muscher-Banse, 2020).

Table 1. Shows the core physiological roles of macro-minerals

Mineral	Principal functions	Homeostatic feature	Key concern
Ca	Bone and teeth; contraction; secretion; coagulation	PTH-calcitriol-bone-kidney axis	Periparturient hypocalcemia; skeletal loss
P	Bone; ATP; nucleic acids; phospholipids; buffering	Renal control and salivary recycling in ruminants	Poor intake/growth; excess fecal loss
Mg	ATP-dependent enzymes; nerve and muscle stability	Continuous gut absorption; limited reserve	Hypomagnesemic tetany, worsened by high K
Na	Extracellular volume; action potentials; cotransport	Thirst, ADH, aldosterone, kidney	Deficiency with sweat loss; salt toxicity without water
K	Intracellular osmolality; membrane potential; muscle	Cellular distribution and renal excretion	Low intake losses; Mg and Ca interactions when excessive
Cl	Electroneutrality; gastric acid; acid-base balance	Renal handling linked with Na and K	Sweat/GI loss; acid-base disturbance
S	Sulfur amino acids, vitamins, glutathione, microbial protein	Dietary supply and ruminal transformation	Excess sulfide; Cu antagonism; neurologic toxicity

Homeostasis is a protection of extracellular function but can mask depletion. In the case of calcium, for instance, the readily mobilized pool is the bones and in the case of magnesium there is no such reliable pool that can

Physiological Importance of Macro-minerals

Calcium, Phosphorus and Magnesium

99 percent of the body's calcium is bound to bone and teeth, but the free-ionized calcium is essential for muscle contraction, for release of neurotransmitters and hormones, for blood clotting, for stabilizing the cell membrane, and for generating signals inside cells. Demand increases quite quickly during growth, gestation, lactation and eggshell formation. Calcium export to colostrum may also be higher than the rate of absorption or mobilization of calcium from the bone, resulting in subclinical or clinical hypocalcemia in dairy cows. Responsive parathyroid signaling, activation of calcitriol, sufficient levels of magnesium, and proper dietary cation-anion balance are required for effective adaptation (Goff, 2018; NASEM, 2021).

A role for phosphorus in the formation of hydroxyapatite and the production of ATP, nucleic

easily be mobilized. Therefore, It is not advisable to automatically assume that a normal circulating value is an adequate long-term status.

acids, phospholipids, phosphorylated signaling proteins and buffers inside cells. In ruminants' phosphorus is recycled with saliva to keep the microbial fermentation going. Deficiency leads to reduced appetite, growth, fertility and skeletogenesis, and excess brings excessive phosphorus in the feces and environmental load. A large proportion of the phosphorus in the pig and poultry is bound to phytin and digestible-phosphorus systems and phytase can increase digestibility of phosphorus allowing a reduction of excretions of phosphorus. (Sampath et al., 2023).

Mg is capable of stabilizing ATP and nucleic acids, modulating ion channels, influencing enzyme activity and inhibiting the over-excitability of the neuromuscular system. Ruminants with rumen absorb daily nutrition. Magnesium uptake can be inhibited by lush, highly-fertilised forage, which is high in potassium and degradable nitrogen. When assessing forage magnesium, the following should be taken into

account: forage potassium, forage intake, weather conditions, and severe hypomagnesemia can cause hyperexcitability, tetany, convulsions and death. (Arthington & Ranches, 2021).

Sodium, potassium, chloride, and sulphur

Sodium ions are the most abundant in the ECF, potassium ions are most abundant in the ICF and chloride ions are most abundant in the ECF. Together with other mechanisms, they maintain normal osmolality, transport of water, acid base balance, membrane potentials, transport of nutrition, and the function of neuromuscular system. Kidney, thirst and endocrine functions are responsible for sodium and water retention as well as the regulation of potassium excretion. Often, plant feeds are deficient in sodium and forage has a high potassium level. There can be increased losses of weight when there is heat, diarrhoea, lactation, transport or exercise that compromises the animals and they may become weak, lethargic, in different to feed and suffer acid base disturbances. (Lindinger, 2022; Maier & Kienzle, 2025).

Methionine and Cysteine contain sulfur, Thiamine contains sulfur, Biotin contains sulfur, Co-Enzyme-A contains sulfur, Glutathione contains sulfur, and Structural molecules contain sulfur. Sulfur aids metabolism by the rumen microbes for the production of sulfur amino acids but a high level feeder, by-products or water can increase the sulfate, which can then be reduced to sulfide. However, total exposure of sulphur must include water, as well as feed, because of the risk of neurologic disease and that sulphur worsens copper antagonism (Suttle, 2022).

Physiological Importance of Trace Minerals

Trace minerals act as catalytic and regulatory proteins in the form of enzymes, transport proteins, transcription factors, and hormones. Iron is involved in binding to hemoglobin, myoglobin, and cytochromes. Zinc is also necessary for epithelium, keratin production, wound healing, reproduction and immunity, and is a stabilizer for enzymes and zinc-finger proteins. Copper is involved in Oxidative Phosphorylation, Antioxidant Defense, Collagen Cross-Linking, Pigmentation, Iron Mobilization, Nervous-System-Function. Selenium's linkage with antioxidant protection and thyroid-hormone metabolism is seen in the involvement of selenoenzymes such as glutathione peroxidases, thioredoxin reductases and deiodinases (Goff, 2018; Swecker, 2023).

Manganese also encourages cartilage development, helps mitochondria produce more superoxide dismutase and effects reproduction. Both thyroxine and triiodothyronine require iodine. In ruminants, physiologic roles of cobalt concern its ability to be microbially converted to vitamin B12, which is essential for metabolizing propionate and the metabolism of methylmalonyl-CoA for gluconeogenesis. Stress- and insulin-signaling pathways have been studied with regard to Chromium needs, but such a consistent requirement for essential role and reliable marker of status have not been fully determined in farm species. The role of molybdenum is as a part of a molybdoenzyme and it is clinically important only because its metabolism can result in mug mentation leading to secondary copper deficiency in the rumen.

Table 2. Outline the function of the trace mineral and any cautions that are of clinical relevance.

Mineral	Main physiological roles	Interpretive caution
Fe	Hemoglobin, myoglobin, cytochromes	Microcytic anemia if deficient; oxidative injury if excessive
Zn	Enzymes, epithelium, keratin, reproduction, immunity	Limited reserve; high Zn may impair Cu use
Cu	Energy metabolism, SOD, collagen, Fe mobilization	Sheep accumulate hepatic Cu and are toxicity-prone
Se	Antioxidant selenoproteins; thyroid deiodinases	Narrow safety margin; source affects tissue response
Mn	Mn-SOD, cartilage, bone, metabolism, fertility	Status is difficult to assess from serum
I	Thyroid-hormone synthesis	Deficiency or excess can impair thyroid function
Co	Microbial vitamin B12 synthesis in ruminants	Deficiency reduces propionate use and appetite
Cr	Proposed modulation of insulin/stress responses	No universal requirement or validated biomarker
Mo	Molybdoenzymes; Cu antagonism in rumen	High Mo plus S promotes secondary Cu deficiency

The margin of margin safety is particularly narrow between deficiency and toxicity for selenium and

copper. Sheep have a limited ability to excrete copper in the bile, allowing it to build up in the liver without

causing any symptoms, until a haemolytic crisis occurs. Hence mineral mixtures containing minerals for cattle or goats should not be used without checking the level of copper in these products and the amount of exposure this provides to sheep (Van Saun, 2023). (Van Saun, 2023).

Species and Physiological-Stage Differences

The demand for minerals is proportional to physiological output. Calcium, phosphorus, magnesium, iron, zinc, copper, manganese, selenium and iodine are needed for the growth of animals to deposit in the skeleton, synthesize tissue, synthesize red blood cells (erythropoiesis), protect intra-cells from oxidative damage, and mature the endocrine system. Mineral requirements are increased during pregnancy, lost during lactation, and essential during breeding for development of gamete quality, steroidogenesis, development of the uterus, and development of the placenta. Supplementation will likely have the greatest

effect on performance when basal levels are restricted, not when animals are sufficiently basal (Weiss & Hansen, 2024).

These priorities change for different species. Around calving dairy cows will have a high mineral export and need careful attention with the management of calcium, magnesium, phosphorus and dietary anions/cations. Selenium, copper, zinc, manganese, cobalt, iodine and antagonists should be evaluated in beef cattle since they are highly dependent on forage and variable free-choice intake in the region. Copper should be carefully controlled in sheep. Goats are selective feeders and cannot be considered as small cattle or sheep. Horses need to receive electrolytes based on weight loss and poultry need much narrower window on calcium and timing to ensure eggshell; also need phosphorus to ensure rapid skeletal development (Alagawany et al., 2021; Corbett, 2023; Van Saun, 2023).

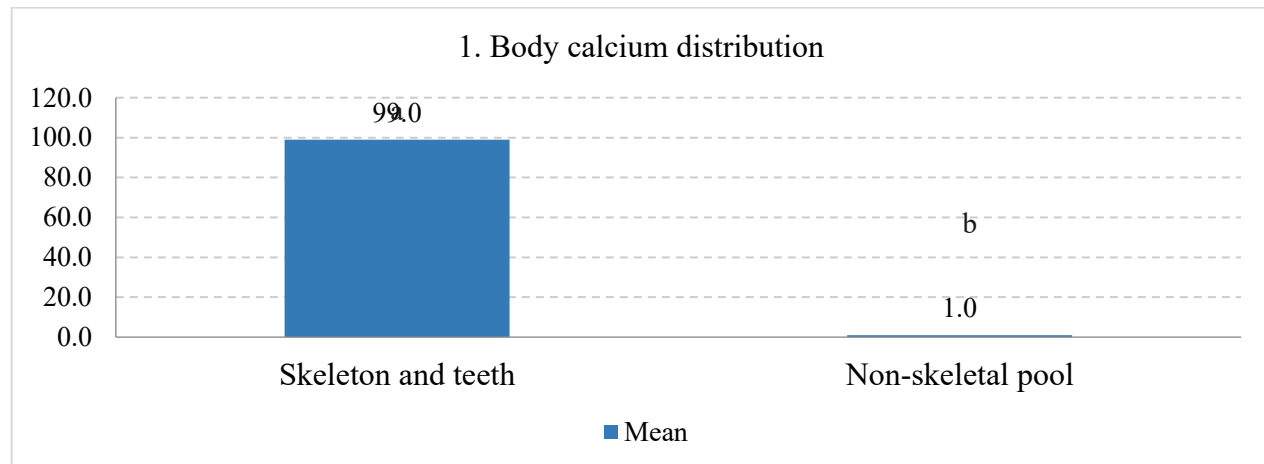


Figure 1. A brief description of the distribution of calcium and mineral classes. The body distribution of calcium.

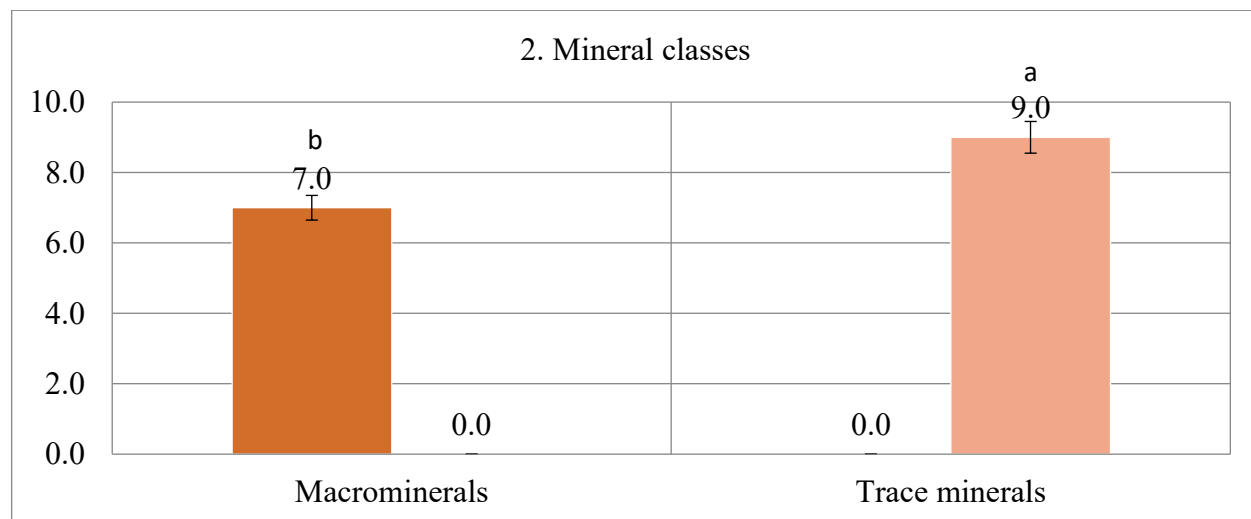


Figure 2. Includes the nine macrominerals and nine trace minerals discussed in this figure.

The same dietary concentration may therefore have different effects on the different species, production systems and on different ages. The reference values as well as the limit of supplementation should be on species, breed, stage, climate and analytical method. For buffaloes and indigenous tropical breeds less is known than for intensively managed dairy cattle, and it is especially important for these.

Mineral Interactions, Deficiency and Toxicity.

Interactions that alter bioavailability

It is important to remember that minerals will interact before absorption, at transport proteins, in the cells and when they are excreted. The sulfur and molybdenum combine to form thiomolybdates in ruminants that combine with copper and lead to reduced usage of copper by enzymes, and in certain cases high iron can cause reduced usage as well. If potassium is added to the diet excess increases the electrical gradient for the uptake of magnesium in the rumen. Too much zinc will reduce the absorption of copper, and dietary calcium and phosphorus need to be fed in combination relating to bone accretion and endocrine adaptation. Phytate also chelates a number of cations in pigs and poultry. Thus, chemical analysis of a mineral does not give a true indication of its biological availability unless its diet or water chemistry is known (Arthington & Ranches, 2021; Byrne & Murphy, 2022).

The source of minerals also is important. The difference in sulfates, oxides, carbonates and organic complexes in terms of solubility, reactivity, stability and validated bioavailability. However, an increased solubility will not necessarily be a better solubility, since the decreased solubility will make the antagonistic binding in the feed or rumen contents more intense if partial dissociation occurs early. Not chemical category alone, but rather, evaluation of the source's absorptivity, tissue disposition, activity, and safety, are the most controlled factors to consider in judging source (Spears, 2023).

Physiological expression of deficiency

Often, biochemical reserve and enzyme activity deficiency is the first sign of deficiency and is followed by apparent disease. In the short-term, there are decreased appetites, growth rates, immune systems, upon reproduction, changes to the coat/wool and decreased production. Advanced deficiency results in

rickets or osteomalacia (calcium/phosphorus), tetany (magnesium), anemia (iron or copper), nutritional myodegeneration (selenium), goiter and weak neonates (iodine), or wasting that occurs with cobalt-vitamin B12 deficiency in ruminants. Mineral deficiencies have been shown to impact serum biochemistry and organ function, and targeted supplementation to reverse some of the changes, in controlled work on grazing sheep (Jin et al., 2023).

Toxicity & environmental excess

When water intake is limited, salt toxicity is easy to approach; when water levels are high, selenium excess may result in alopecia, hoof lesions and systemic injury, while it is important to watch how the calcium/phosphorus ratio is balanced to avoid skeletal or urinary damage in sheep, a high accumulation of copper can occur gradually and ultimately cause hemolysis in sheep. Risk level depends on the forage, concentrate, mineral premix, water, contamination of soil and medication. Constant overstocking also leads to the loss of faeces or urine which contributes copper, zinc, phosphorus and other elements to manure and soil (Duplessis & Royer, 2023). The rule of thumb here is: when an apparent deficiency persists despite supplementation, find out what other product it may be counterbalanced by and investigate total exposure when several supplements are given at once. Don't forget more supplement is not more of the solution, it is the definite solution.

Assessment and Evidence-Based Supplementation

Body status, functional response, clinical findings, and analytical quality should be considered along with exposure when performing mineral diagnosis. Both serum and plasma levels can be valuable for evaluating long-term reserves of trace minerals but are more valuable for evaluating acute electrolyte disturbances. The material influence on interpretation can be caused by the sample tube, laboratory method, albumin, inflammation, feeding time and hemolysis. Liver is the recommended storage tissue for copper, and can be used to assess levels of selenium and iron, while a functional test may be glutathione-peroxidase activity, hematology, thyroid hormones, vitamin B12, methylmalonic acid, and/or ceruloplasmin (Ensley, 2020; Swecker, 2023).

Table 3. Practical matrix for assessment of mineral status

Mineral	Preferred assessment	Strength	Limitation
Ca	Ionized Ca; total Ca with albumin/pH	Direct extracellular function	Total Ca may misclassify protein or pH changes
Na/K/Cl/Mg/P	Serum/plasma plus hydration, diet, kidney	Current clinically important disturbance	May not quantify total-body depletion
Cu	Liver; serum and ceruloplasmin as adjuncts	Detects depletion and accumulation	Biopsy invasive; inflammation affects proteins

Se	Whole blood, serum, liver, GPx	Combines exposure, storage, function	Source and erythrocyte turnover alter response
Fe	CBC plus ferritin/transferrin and inflammation	Links status with erythropoiesis	Inflammation can mimic deficiency
Co/B12	Vitamin B12 and methylmalonic acid	Assesses the ruminant functional pathway	Serum cobalt alone is weak

A supplementation program should start with representative feed and water analyses, proper intake estimates for each species, agonism-antagonism identification and species-specific requirements. Complete feed inclusion is the most effective feed intake control, whereas free-choice mineral appears to be effective on pasture yet individual consumption is dependent on salt appetite, environmental conditions, palatability, feeder location, and social status. Boluses/drenches/injectables can be effective when baseline is adequate, but can be toxic when baseline is adequate (Sager & Van Saun, 2023).

There must be a correspondence between monitoring and response time. The levels of electrolytes can change in a matter of hours, enzyme levels in several days or weeks, liver reserves more slowly, and reproductive effects can even take months. The appropriate end-point is the return of physiological function, with no build-up of unsafe tissues, and non-avoidable excretion. While they are still the starting point, the absorption coefficient is always under question, as is the individual variation (NASEM, 2021; Weiss & Hansen, 2024).

Emerging Directions and Research Priorities

Research in modern minerals is moving from named levels of concentrations to levels absorbed, endogenous loss, chemical species, tissue response and functional outcomes of minerals. Bioavailability estimates can be improved with the use of stable-isotope methods and transporters studies. If the deficiencies and antagonism is combined with toxicity then multi-element analysis will help. Individual level mineral intake, water use, feeder visits, activity, body temperature and production data may be considered precision livestock tools to help identify individual animals with a mineral intake that differs from the group mean (Weiss & Hansen, 2024; Byrne & Murphy, 2022).

There are huge uncertainties that need to be addressed for buffaloes, goats, indigenous breeds and tropical grazing systems. The requirements need to be validated under the local conditions of forage, soil, water, heat and diseases. In addition to the mineral content of feed their retention and apparent digestibility are influenced by exercise intensity and sweat losses (Maier & Kienzle, 2024, 2025). Poultry and pig systems are in the maturation process, where the addition of phosgene oxime sources and trace minerals to the feed needs to be further optimized to promote performance while reducing environmental emission (Alagawany et al.,

2021; Sampath et al., 2023). Future studies should report Basal, water, antagonist diet, actual intake, physiological stage, analytical method, and benefit/tx endpoints should be reported in future research. The functional biomarkers must be validated in relation to clinically relevant parameters like disease resilience, reproduction, and longevity and lifetime productivity. Precision feeding and monitoring will only prove useful if they can identify sub-optimal and excessive feeding and be proven in commercial herds and flocks.

Conclusion

Minerals provide the structure, electrical activity, metabolism, endocrine function, hematological, reproductive, and antioxidant systems of farm-animal physiology. But it is not only the concentration of the feed, which determines their biological value; their absorption, interaction, storage, homeostatic regulation, losses, species, and stage of production all play a role. Macrominerals primarily function in skeleton, fluid and acid-base balance, and neuromuscular function, and trace minerals facilitate oxygen transport, enzyme function, thyroid activity, connective tissue synthesis, antioxidant function, and rumen synthesis of B12. To manage minerals, complete diet and water analysis, species specific needs, valid biomarkers and follow up at a physiologically meaningful time are necessary. A level just below and above both are equally bad. A program specifically designed and based on evidence is less harmful, more cost effective and more eco-friendly than a general over-supplementation program.

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