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Mineral Dynamics and Animal Wellness: A Systems Biology Perspective

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***Abstract*—Mineral nutrition is a critical component of livestock health and productivity, influencing growth, reproduction, immune function, and overall metabolic efficiency. Traditional approaches to understanding mineral imbalances have primarily focused on individual nutrient deficiencies or toxicities. However, recent advances in systems biology provide a more holistic view, integrating genomics, transcriptomics, proteomics, metabolomics, and microbiomics to unravel the complex interactions between minerals, physiological systems, and the environment. This paper explores mineral metabolism in livestock from a systems biology perspective, highlighting the dynamic regulatory networks and homeostatic mechanisms that control mineral uptake, distribution, and utilization. It emphasizes how mineral imbalances—whether deficiencies, excesses, or antagonisms—can disrupt these networks, leading to subclinical disorders or overt disease. Furthermore, the paper discusses emerging diagnostic tools, predictive biomarkers, and precision feeding strategies that leverage systems-level data to optimize mineral nutrition and enhance animal health and productivity. Integrating systems biology into mineral nutrition research holds significant promise for sustainable livestock production in the face of changing environmental and nutritional challenges.**

***Index Terms*—Mineral nutrition, Livestock health, Systems biology, Macrominerals and Microminerals, Mineral imbalance and Sustainable livestock production.**

1. INTRODUCTION

Minerals are indispensable elements in animal nutrition and serve as the foundation for numerous physiological, biochemical, and structural processes in the body. These inorganic nutrients, though required in relatively small amounts compared to other dietary components, play a disproportionately large role in sustaining life and promoting optimal health, productivity, and reproductive efficiency in livestock. From the building of bones and teeth to the regulation of enzyme systems, nerve conduction, oxygen transport, and immune defence, minerals are intricately involved in almost every aspect of animal biology.

Scientific evidence reveals that out of the 90 naturally occurring elements, at least 78 can be detected in human and animal cells, suggesting a broad spectrum of biological interaction between trace elements and cellular metabolism. Even elements like gold have been found in red blood cells at trace levels, underscoring the extensive yet nuanced presence of minerals in biological systems (Bowen, 1968). At present, 28 of these elements are recognized as essential for life—these include both organic (C, H, O, N, S) and inorganic constituents, the latter of which are further classified into macro-minerals (e.g., calcium, phosphorus, magnesium, sodium, potassium, and chloride) and trace minerals (e.g., iron, zinc, copper, selenium, cobalt, iodine, manganese, molybdenum, and others).

The critical importance of mineral elements lies in their multifaceted roles within animal systems. Structurally, minerals such as calcium and phosphorus contribute to skeletal development and maintenance, while magnesium, silicon, and fluorine enhance mechanical stability and tissue integrity. Functionally, minerals serve as cofactors in enzyme activation, act as electrolytes for maintaining osmotic balance, and contribute to hormonal and immunological regulation. Iron, for example, is a vital component of hemoglobin and plays an essential role in oxygen transport and cellular respiration; cobalt is integral to vitamin B12 synthesis, and iodine is a key element in thyroid hormone production.

In addition to essential elements, various other minerals such as aluminum, cadmium, mercury, and lead, although not currently classified as essential, are found in biological tissues. These elements are typically acquired through environmental exposure and are often reflective of the ecological interactions between animals and their habitat. While traditionally considered contaminants, some of these elements may possess latent physiological roles that could emerge as analytical and biochemical techniques advance further.

A systems biology approach to mineral nutrition offers a holistic framework to understand these complex interdependencies between mineral elements, metabolic pathways, genetic regulation, and environmental influences. By integrating molecular biology, physiology, bioinformatics, and ecology, this perspective enables a deeper insight into how mineral imbalances—whether deficiencies, toxicities, or antagonisms—affect animal health and productivity at both individual and population levels.

2. CLASSIFICATION ON MINERALS

I. Macrominerals: These are required in larger quantities and typically expressed as a percentage of the ration dry matter (% DM).

Calcium (Ca) Phosphorus (P), Magnesium (Mg), Sodium (Na), Potassium (K), Chloride (Cl) and Sulfur (S).

II. Microminerals (Trace elements): Needed in minute amounts and expressed in parts per million (ppm).

Iron (Fe), Copper (Cu), Zinc (Zn), Manganese (Mn), Iodine (I), Selenium (Se), Cobalt (Co), Molybdenum (Mo)

(Others: Chromium, Fluorine—occasionally included)

a. Importance of Mineral Nutrition in Dairy Cows

Minerals are indispensable for:

- Bone and tissue development
- Milk production
- Reproductive efficiency
- Immune competence
- Enzymatic and hormonal functions

Correcting mineral imbalances can often resolve chronic health or fertility problems without significant additional cost. Strategic supplementation is vital in intensive dairy operations.

b Roles, Requirements, and Deficiency Symptoms

Macrominerals

Mineral	Key Functions	Deficiency Symptoms
Calcium (Ca)	Bone and teeth formation, blood clotting, muscle contraction	Rickets, poor bone growth, milk fever, reduced yield
Phosphorus (P)	Bone formation, energy metabolism (ATP), part of DNA/RNA	PICA, post-parturient haemoglobinuria, infertility
Magnesium (Mg)	Nerve/muscle function, enzyme activator	Grass tetany, lethargy, irritability
Potassium (K)	Electrolyte balance, nerve/muscle excitability	Reduced intake, dull coat, low blood K^+
Sodium (Na) & Chloride (Cl)	Osmotic balance, acid-base regulation, nerve impulse	Salt craving, weakness, incoordination
Sulfur (S)	Component of amino acids (methionine, cysteine), vitamins	Poor wool/hair/hoof growth

Microminerals

Mineral	Key Functions	Deficiency Symptoms
Iron (Fe)	Hemoglobin formation, oxygen transport	Anemia, weakness, pale mucosa
Copper (Cu)	Iron metabolism, pigmentation, CNS health	Anemia, infertility, depigmentation, steely wool
Zinc (Zn)	Enzyme activator, skin integrity, wound healing	Poor weight gain, skin lesions, low feed efficiency
Cobalt (Co)	Part of Vitamin B12, rumen function	Anemia, rough coat, low milk, diarrhea
Iodine (I)	Thyroid hormone (thyroxine) synthesis	Goiter, infertility, weak calves
Manganese (Mn)	Bone formation, estrus cycle	Poor conception, delayed estrus, deformities
Selenium (Se)	Antioxidant (with Vit E), immune function	White muscle disease, mastitis, retained placenta
Molybdenum (Mo)	Enzyme cofactor (xanthine oxidase)	Weight loss, diarrhea, emaciation

c. Mineral Supplementation Strategies

Minerals for Milk Production

Calcium and phosphorus are the most critical for lactation and should be supplemented in a 1.4:1 **ratio**, reflecting the content lost in milk (1.2g Ca and 0.9g P/kg of milk). Deficiency results in milk fever and lowered productivity.

LACTIVET by Alved: Supplies Ca and P in optimal ratio plus trace minerals (Cu, Zn, I, Co) and vitamins A, D, E to support mammary gland health and milk yield.

Microminerals for Reproduction

Low levels of cobalt, copper, iodine, manganese, phosphorus, and selenium, or high molybdenum, impair fertility. Effects are mostly indirect, influencing energy metabolism, hormonal cycles, and oxidative stress.

CYCLOMIN 7 by Alved: A slow-release bolus containing essential microminerals tailored to reproductive needs. Corrects subfertility, delayed estrus, poor conception, and embryonic mortality.

Micromineārl	Reproductive Role	Deficiency
Cobalt	Vitamin B12 synthesis, gluconeogenesis	Anestrus, energy deficiency
Copper	Antioxidant, energy metabolism	Infertility, embryonic loss
Iodine	Thyroid hormone for fetal development	Weak/dead calves, goiter
Manganese	Hormone production, ovulation	Delayed estrus, poor conception
Zinc/Selenium	Enzyme systems, antioxidant defense	Embryonic death, poor egg quality

3. IMPORTANCE OF MINERALS

Importance of Minerals in Animal Physiology: Role in enzymatic function, immune regulation, bone development, nerve transmission, and energy metabolism.

Structural functions: The structural function of minerals encompasses far more than skeletal health. From the bone matrix to cellular membranes, proteins, and hormones, minerals are the cornerstone of structural integrity in livestock. Deficiencies or imbalances in these minerals can compromise growth, reproduction, and general health, often resulting in deformities, reduced productivity, or metabolic disorders. Understanding these roles within systems biology framework helps elucidate how mineral status affects not just anatomy, but the entirety of animal physiology and performance.

Large number of elements has a structural role in building the frame work of the body (skeleton) and synthesis of structural proteins. Calcium and phosphorous provide strength and rigidity to skeleton system and mechanical stability is provided by magnesium, silicon and fluorine. Likewise certain minerals are the constituent part of organic compounds in the tissues like phosphorous and sulphur in muscle proteins, iron is a constituent of haem and play an important role in respiration, cobalt is a component of vitamin B_{12}, sulphur in methionine and cystine and iodine in thyroxine and calcitonin etc.

a. Structural Functions of Minerals in Livestock

Minerals perform a multitude of physiological roles in animal systems, one of the most fundamental being their structural function. These structural roles are essential for the physical development, mechanical integrity, and maintenance of the body framework, particularly the skeletal system, connective tissues, and cellular architecture. Unlike energy-yielding nutrients, structural minerals are primarily non-caloric yet vital to life. Their presence in bone, cartilage, teeth, proteins, and even hormones underlines their indispensable role in maintaining the physical structure and function of animals.

Bone and Skeletal Development

The skeleton is the primary structural component of the body and is largely mineralized. It serves not only as a framework for muscle attachment and mobility but also as a major reservoir for essential minerals.

- Calcium (Ca) and Phosphorus (P) are the principal structural minerals of the skeleton, accounting for about 99% and 80%, respectively, of their total body content. They are deposited in the form of hydroxyapatite crystals ($Ca_{10}(PO_4)_6(OH)_2$), which provide rigidity and mechanical strength to bones and teeth.
- The Ca:P ratio, particularly in growing animals, is critical. An imbalance (commonly deficiency in Ca or excess P) may lead to conditions such as rickets in young animals and osteomalacia or osteoporosis in adults.

Supportive Role of Other Minerals in Skeletal Stability

- Magnesium (Mg): While ~60% of the body's magnesium is located in bones, it is not merely a filler mineral. Magnesium contributes to bone density and works synergistically with Ca and P in maintaining bone metabolism. Its role also extends to regulating calcium transport.
- Fluorine (F): Incorporated in small amounts as fluorapatite in bones and teeth, fluorine enhances resistance to demineralization and protects against dental caries. However, excess intake may lead to fluorosis.
- Silicon (Si): Although not officially classified as essential, silicon is associated with the formation of connective tissues and is believed to play a key role in the initiation of bone mineralization, particularly during early growth stages.

Mineral Role in Structural Proteins and Tissues

Beyond skeletal tissues, several minerals are embedded within proteins, enzymes, and hormones that form or stabilize body structures.

- Sulphur (S): Found in essential amino acids like methionine and cystine, sulphur contributes to the structural integrity of keratin, collagen, and elastin. It plays a key role in forming disulfide bonds, which are critical for the three-dimensional structure of proteins, especially in hair, wool, skin, and cartilage.
- Phosphorus: Besides its skeletal role, phosphorus is also a part of phospholipids (structural components of cell membranes), nucleotides, and ATP, which are critical for cellular structure and energy transfer.
- Iron (Fe): While primarily known for its functional role in oxygen transport (as part of hemoglobin and myoglobin), iron also contributes structurally to cytochromes and other metalloproteins that are embedded in membranes, participating in redox reactions critical for cellular metabolism.
- Cobalt (Co): Cobalt is a structural component of vitamin B_{12} (cobalamin), which is essential for nucleic acid metabolism and cell growth. Its presence influences erythropoiesis and nervous system development.
- Iodine (I): Iodine is an integral part of thyroid hormones (thyroxine - T_4 and triiodothyronine - T_3), which regulate the basal metabolic rate and influence tissue growth and development, especially during fetal and neonatal stages.

Cellular and Molecular Architecture

Certain minerals contribute to cellular structure at the molecular level:

- Zinc (Zn): Stabilizes DNA and RNA structure and is a component of numerous enzymes and zinc-finger proteins, playing a crucial role in gene expression and cell replication.
- Copper (Cu): Integral to lysyl oxidase, an enzyme involved in cross-linking collagen and elastin, thereby contributing to vascular and connective tissue strength.

- Manganese (Mn): Acts as a cofactor for enzymes that synthesize proteoglycans and mucopolysaccharides, which are structural components of cartilage and bones.

b. Catalytic functions of Mineral nutrients: Several minerals are the constituents of many enzymes and other biologically active organic compounds which may be physical, chemical or biological in nature. An indication of the wide range and functional importance of the metalloenzymes is given below

Metal	Enzyme	Function
Iron	Succinate dehydrogenase	Aerobic oxidation of carbohydrates.
	Cytochromes a, b and c	Electron transfer
	Catalase	Protection against H_2O_2
Copper	Cytochrome oxidase	Terminal oxidase
	Lysyl oxidase	Lysine oxidation
	Ceruloplsmin	Iron utilization: copper transport.
	Superoxide dismutase	Dismutation of superoxide radical O_2
Zinc	Carbonic anhydrase	CO_2 formation
	Alcohol dehydrogenase	Alcohol metabolism
	Carboxypeptidase A	Protein digestion
	Alkaline phosphatase	Hydrolysis of phosphate esters
	Nuclear poly(A) polymerase	polymerase Cell replication
	Collagenase	Wound healing
Manganese	Pyruvate metabolism	Pyruvate carboxylase
	Superoxide dismutase	Antioxidan by removing O^-_2
	Glycosyl aminotransferases	Proteoglycan synthesis
Molybdenum	Xanthine dehydrogenase	Purine metabolism
	Sulphite oxidase	Sulphite oxidation
	Aldehyde oxidase	Purine metabolism
Selenium	Glutathione peroxidase	Removal of H_2O_2 and Hydroperoxidases
Type I and III	deiodenases	Conversion of thyroxine to active form.

(Underwood and Suttle, 1999)

c. Electrochemical functions: Greater percentage of sodium, potassium and chlorine and small fraction of calcium, magnesium and phosphorous are the important electrolytes in the body fluids and soft tissues. The electrolytes in the blood and cerebrospinal fluids are responsible for maintaining acid-base balance and osmotic pressure, regulation of membrane permeability and produce normal biochemical effects on the excitability of the muscle and nerve fibres. The salts and ions present in the saliva, gastro-intestinal secretions and rumen fluid (in ruminants) provide suitable medium for the function of enzymes.

d. Regulatory: In recent years, minerals have been found to regulate cell replication and differentiation; calcium for example, influences signal transduction and zinc influences transcription, adding to long-established regulatory roles, such as that of the element iodine as a constituent of thyroxine.

4. SOURCES OF MINERALS

Sources of minerals: The common sources of minerals for the farm animals are:

- Minerals in the feedstuff.
- Minerals in drinking water.

- Minerals in soil.
- Mineral supplements in ration.

The farm animals derive a large proportion of their mineral nutrients from the feeds and forages that they consume. The concentration of all minerals in crops and forage plants depends on five basic independent factors:

Genus, species or strain (variety): Leguminous species are generally substantially richer in Ca, Mg, K, Zn, Fe, Co, Cu & S than grasses and non-leguminous fodders growing in comparable conditions. Substantial differences in the content of many minerals also exist among species of legumes and grasses. These characteristic differences also exist in the seeds e.g., maize contains remarkably low level of Mn than other grains.

Few plant species accumulate several time higher amounts of the element than its level in the soil. Rice straw can accumulate 10 times more Se than its level in soil.

Type of soil on which the plant grows: Mineral uptake by the plants and their mineral composition are greatly influenced by pH of soil, particularly in legumes. The absorption of nickel, cobalt, zinc, iron and manganese by the plants is favoured by acid conditions (Mitchell, 1957) and molybdenum and selenium by alkaline soils.

Another important factor is the interaction between minerals in growing plants as is the case within the animal body. A classical example is the fertilization of soil with potassium that increases K content of plants; also tend to reduce the content of sodium and magnesium in the plants.

Climate or seasonal conditions during growth: Climate and season influence the maturity of plants, which can be modified by irrigation and management practices. The tendency for forage concentration of copper to increase and selenium to decrease with increasing altitude (Jumba *et al.,* 1996) is probably a reflection of the influence of rainfall. Heavy rainfall, resulting in water logging increases the uptake of Co and Mo in plants from soil.

Stage of maturity of the plants: The extent to which these factors influence the concentration of mineral element in plants depends on particular element, use of fertilizers and water availability. The phosphorous and potassium contents of crops and forage plants decline markedly with advancing maturity but seasonal fluctuations in phosphorous concentrations are usually less in legumes than in grasses (Coates *et al.*, 1990). The concentration of magnesium, zinc, copper, manganese, cobalt, nickel, molybdenum, and iron also fall, but rarely to same extent as P and K, whereas the concentration of silicon usually increases as the plant matures. Bedi (1997) observed that iodine content in berseem fodder varies from 0.196 in first cut to 0.368 micro g/g of DM in the forth cut in December to April.

Part of plant: The mineral content of different parts of the same plant often vary appreciably. The grains or seeds generally have a characteristically different mineral content from the vegetative or forage portion e.g., grains contain more of P and lesser amount of Ca than forages.

Ingestion of soil as contaminant of herbage can at times provide a further significant source of minerals to grazing animals. Soil intake can rise to 163g/day in sheep in arid conditions (Vaithiyanathan and Singh, 1994) and can constitute 10-25% of total DM intake. Elements like Co, F, I and Se occur in soils in concentrations much higher than those of the plants growing on them, thus soil ingestion can be beneficial to the animal (Grace *et al.,* 1996). Soil ingestion can also provide an important route for toxic elements, such as lead and cadmium to accumulate in the tissues of grazing livestock.

5. MINERAL IMBALANCE

Minerals are essential inorganic nutrients required in precise concentrations for optimal growth, health, reproduction, and productivity in livestock. Any deviation—whether excess or deficiency—from the ideal mineral levels in the diet can disrupt homeostasis and impair physiological functions. These disruptions, collectively termed mineral imbalances, have become a widespread concern in both intensive and extensive livestock production systems.

The concentration of essential elements must be maintained within quite narrow limits if the growth, health and productivity of the animal are to be maintained. Continued ingestion of diets that are deficient, imbalanced or excessively high in the mineral induces changes in the form or concentration of that mineral in the body tissues and fluids, so that it falls below or rises above the tolerable limits. Large number of livestock in many parts of the world consume diets that do not meet these requirements (McDowell *et al.,* 1993). In consequence, nutritional disorders arise, which range from acute or severe mineral deficiency or toxicity diseases, characterized by well-marked clinical signs, pathological changes and high mortality, to mild and transient conditions, difficult to diagnose with certainty and expressed merely as unthriftiness or unsatisfactory growth, production and fertility. Practically, mineral imbalances occur in three forms: clinical, subclinical and a clinical. Due to difficulty in diagnosing subclinical deficiency is more important causing huge economic losses because frank clinical signs are few or absent but productivity and fertility is depressed in 20-50 per cent of the group. The levels of the element in blood and/or feed are also low. Such situations are confused with the effects of semi starvation due to underfeeding, protein deficiency and various type of parasitic infestation. A clinical deficiency does not affect health of animal despite of low concentrations of mineral in blood and feed. Health records indicate that 80 per cent of the reported diseases in livestock are nutritional, of which mineral deficiencies and toxicities account for more than 50 per cent of the confirmed diseases (Radostitis *et al.*, 1999).

Mineral imbalances are broadly classified into three categories:

I. Clinical Deficiencies or Toxicities**:** These are characterized by overt clinical signs, pathological changes, and in some cases, high mortality. They are easier to diagnose and manage but are often only recognized after significant damage has occurred.
II. Subclinical Imbalances: These occur without obvious clinical symptoms but result in reduced productivity, poor fertility, suppressed immunity**,** and generalized unthriftiness. Subclinical deficiencies are the most economically damaging due to their insidious nature and difficulty in diagnosis. Blood and feed analyses often reveal low concentrations of the deficient element.
III. Aclinical Imbalances: In this form, mineral concentrations in the feed or blood may be below recommended levels, yet the animals do not show any discernible clinical signs or reductions in performance**.** These cases often go unnoticed but may pose long-term health risks, especially under stress or additional nutritional burden.

a. Causes of Mineral Imbalances

- Soil and Forage Mineral Deficiency/Excess
- Antagonistic Interactions (e.g., Mo-S-Cu triangle, Ca-P balance)
- Seasonal Variations and Pasture Composition
- Water Quality and Its Mineral Content
- Improper Supplementation and Feed Formulation Errors
- Breed, Age, and Physiological Status of the Animal

b. Common Mineral Deficiency Disorders

- Calcium (Ca) Rickets, milk fever Cattle, goats Hypocalcemia
- Phosphorus (P) Poor growth, pica Sheep, cattle Postparturient hemoglobinuria
- Magnesium (Mg) Muscle tremors Cattle Grass tetany
- Copper (Cu) Coat discoloration, anemia Cattle, sheep Enzootic ataxia
- Zinc (Zn) Skin lesions, poor hoof growth Pigs, cattle Parakeratosis
- Selenium (Se) Muscular dystrophy Lambs, calves White muscle disease
- Iodine (I) Goiter, infertility Goats, sheep Iodine deficiency goiter

c. Mineral Toxicities

- Copper Toxicity in Sheep: Hepatic necrosis and hemolysis
- Selenium Toxicity: Hair loss, hoof sloughing, "blind staggers"
- Nitrate/Nitrite Toxicity (interaction with molybdenum)
- Salt Poisoning: Neurological symptoms due to hypernatremia
- Fluorosis: Chronic fluoride toxicity in bovines

Prevalence and Impact

A significant proportion of the global livestock population subsists on diets that fail to meet their mineral requirements. According to McDowell *et al.* (1993), mineral inadequacies are common in many regions due to factors such as poor-quality forages, soil deficiencies, seasonal variations, and lack of supplementation strategies.

Health data indicates that approximately 80% of livestock health issues are linked to nutritional factors, with mineral imbalances accounting for more than 50% of the confirmed cases (Radostitis *et al.*, 1999). The widespread occurrence of subclinical deficiencies contributes to substantial economic losses due to reduced growth rates, lower milk and meat yields, reproductive failures, and increased susceptibility to infections.

d. Diagnosis Challenges

Diagnosing mineral imbalances particularly subclinical and clinical forms is complex due to:

- Lack of distinct clinical markers
- Interactions with other deficiencies (e.g., protein, energy)
- Confounding effects from parasitic infestations or chronic infections
- Inconsistent or region-specific reference ranges for mineral levels in blood and feed

Routine laboratory analyses, feed mineral profiling, and herd performance monitoring are essential tools for early detection and effective intervention

e. Prevention and Management Strategies

- Balanced Mineral Supplementation: Oral (salt licks, premixes), injectable forms
- Customized Mineral Programs Based on Region and Species
- Soil and Forage Testing
- Use of Chelated Minerals or Organic Forms
- Monitoring and Evaluation in Herd Health Programs

f. Future Prospects and Research Needs

- Precision Nutrition and Smart Supplementation Technologies
- Development of Region-Specific Mineral Mixes
- Role of Genomics in Trace Mineral Requirements
- Integration of Mineral Mapping in Sustainable Livestock Management

6. CONCLUSION

Mineral nutrition plays a central role in maintaining the health, productivity, and welfare of livestock. The complexity of mineral metabolism—shaped by genetic, dietary, environmental, and physiological factors—necessitates a comprehensive, integrative approach. Systems biology offers powerful tools to decipher the multifaceted regulatory networks governing mineral homeostasis and to understand how imbalances lead to disease. By combining high-throughput omics technologies with computational modelling and systems-level analyses, researchers and nutritionists can move beyond reductionist paradigms to develop precision feeding strategies tailored to individual animals or herds. These approaches promise not only to improve mineral efficiency and animal performance but also to enhance environmental sustainability and economic viability in livestock systems. Future research must continue to bridge the gap between molecular insights and practical applications, enabling evidence-based interventions that support resilient and healthy animal populations.

7. CONFLICT OF INTEREST

Both authors declared that there is no conflict of interest regarding the said paper.

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