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Mineral Physiology, Absorption, and Bioavailability in Ruminant Nutrition

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Mineral nutrition underpins livestock productivity globally, with at least 16 mineral elements recognized as nutritionally essential for ruminants. Mineral absorption and utilization depend fundamentally on chemical form, gastrointestinal pH, and animal physiological status. This article synthesizes evidence on essential mineral classification, absorption mechanisms, and regional soil-plant-animal mineral dynamics. Global soil heterogeneity creates predictable deficiency patterns: cobalt 0.1-70 ppm, copper 13-24 ppm, and manganese 7-9200 ppm. Copper absorption in ruminants is restricted to 1-3%; optimal calcium-to-phosphorus ratios of 1:1 to 2:1 maximize absorption. Forage mineral concentrations decline markedly as plants mature due to dilution and nutrient translocation. Critical plasma concentrations for phosphorus are 4.5 mg/100 ml, indicating deficiency thresholds. Understanding mineral physiology, absorption mechanisms, and regional dynamics is essential for developing effective supplementation strategies tailored to specific production environments and addressing identified deficiencies.

Keywords: absorption mechanisms, bioavailability, mineral physiology, mineral requirements, ruminant nutrition, soil-plant-animal dynamics

Introduction

The global dairy industry, valued at $628.27 billion USD in 2018 (Fadlalla, 2022), depends fundamentally on optimizing animal nutrition. While macronutrient requirements for energy and protein have received extensive attention, micronutrient deficiencies remain a persistent yet underrecognized productivity constraint. The Food and Agriculture Organization estimates approximately 245 million dairy cattle exist globally, with milk production performance in emerging economies significantly compromised by nutritional inadequacies (Fadlalla, 2022). Understanding mineral physiology, absorption mechanisms, and regional mineral dynamics represents an essential foundation for developing effective supplementation strategies tailored to specific production environments. The physiological mechanisms underlying mineral nutrition, regional patterns of soil mineral distribution and plant uptake, and critical mineral thresholds necessary for optimal livestock performance.

Mineral Physiology and Classification

Essential Minerals in Ruminant Nutrition

At least 16 mineral elements are recognized as nutritionally essential for ruminant livestock (Underwood & Suttle, 1999). These comprise seven macro-elements (calcium, phosphorus, magnesium, potassium, sodium, chloride, and sulfur) and nine trace elements (iron, iodine, zinc, copper, cobalt, molybdenum, manganese, selenium, and fluorine) (Fadlalla, 2022). An additional eight elements (aluminum, arsenic, boron, bromine, cadmium, lithium, nickel, and lead) demonstrate limited evidence of essentiality but may be conditionally required (Fadlalla, 2022). Minerals comprising less than 50 mg/kg of body weight are classified as trace elements, defined operationally by concentration rather than physiological importance

(Underwood & Suttle, 1999). This nomenclature can be misleading, as certain trace minerals demonstrate profound metabolic significance despite minimal body concentrations.

Absorption and Bioavailability Mechanisms

Mineral absorption and metabolic utilization depend fundamentally on chemical form, gastrointestinal pH, interaction with other dietary constituents, and animal physiological status. Bioavailability is defined as the fraction of ingested mineral available for physiological utilization. It varies substantially among mineral sources. For example, copper absorption in ruminants is restricted to 1-3% at the small intestine level (Fadlalla, 2022), compared to substantially higher absorption rates in monogastric species. Calcium absorption occurs primarily in the duodenum via active transport, requiring vitamin D-dependent processes. The calcium-to-phosphorus (Ca: P) ratio fundamentally influences absorption efficiency; ratios between 1:1 and 2:1 optimize absorption, while ratios exceeding 7:1 or below 1:1 impair both calcium and phosphorus bioavailability (Fadlalla, 2022). Zinc absorption, occurring predominantly in the rumen and small intestine, demonstrates marked sensitivity to dietary composition. Endogenous fecal losses of zinc vary with diet composition, decreasing significantly when zinc intake is restricted (Fadlalla, 2022). Phytates present in plant-based feeds form insoluble complexes with zinc, reducing bioavailability. Metallothionein-mediated regulation of intestinal zinc absorption provides negative feedback homeostasis; however, this adaptive mechanism operates inadequately when dietary zinc is chronically restricted.

Regional Soil-Plant-Animal Mineral Dynamics

Soil Mineral Status and Geographic Distribution

Global soil mineral concentrations demonstrate substantial heterogeneity related to parent material, weathering intensity, and management practices. Cobalt concentrations in mineral soils range from 0.1-70 ppm worldwide, with average concentrations of 8 ppm (Fadlalla, 2022). Copper content in uncontaminated soils ranges from 13-24 ppm, though total soil copper variation extends from 1-140 ppm (Fadlalla, 2022). Manganese concentrations in world soils range from 7-9200 ppm, with an estimated grand mean of 437 ppm; however, only Mn^{2+} is bioavailable to plants, while Mn^{3+} and Mn^{4+} forms are oxidized (Fadlalla, 2022). Zinc content of soils ranges from 10-300 ppm globally, with bioavailability determined by soil pH, organic matter content, and oxidation-reduction status (Fadlalla, 2022). Sandy soils frequently demonstrate zinc deficiency due to reduced adsorption capacity, while alkaline soils precipitate zinc compounds, reducing plant uptake regardless of total soil zinc concentration.

Soil-Plant Transfer and Forage Mineral Composition

Plant mineral concentrations reflect complex interactions between soil mineral availability, plant genotype, ontogenetic stage, environmental conditions, and competition among elements for absorption. The soil-plant relationship is direct; plants obtain all mineral nutrients from the soil solution with which they maintain contact (Fadlalla, 2022). Herbage mineral composition, termed the "ionome," represents an integrated outcome of interactions between endogenous plant processes and environmental constraints (Fadlalla, 2022). Leaf mineral composition reflects the complex interaction between the plant and its environment, including local soil composition, which is an influential factor limiting species distribution and plant productivity. Mineral element concentrations in forages decline markedly as plants mature. Phosphorus, potassium, magnesium, sodium, chloride, copper, cobalt, iron, selenium, zinc, and molybdenum all decline with advancing maturity due to natural dilution processes and translocation of nutrients to root systems (Fadlalla, 2022). Conversely, calcium concentrations remain less affected by plant maturity.

Climate and Management Effects on Forage Mineral Content

Climate influences plant mineral composition through effects on plant growth rate, yield, and mineral translocation patterns. In African systems, uncontrolled heavy grazing pressure eliminates palatable genera, replacing them with highly lignified species and altering leaf-to-stem ratios—directly affecting forage mineral content (Fadlalla, 2022). Increasing crop yield removes minerals from soil at accelerated rates. Over-liming can induce selenium or molybdenum toxicity through increased plant uptake of these elements. Seasonal variation in forage mineral composition occurs across diverse production environments. Research documenting forage minerals across seasons revealed that iron, zinc, and selenium concentrations in forages varied significantly with seasonal changes, while other trace minerals demonstrated less pronounced seasonal effects (Fadlalla, 2022).

Mineral Requirements and Critical Thresholds

Macro- and Trace Mineral Requirements

The dietary requirement of phosphorus for lactating cows with a 20 kg/day milk yield approximates 44-51 g/day. For lactating ewes with 3 kg/day milk yield and 40 kg live weight, the phosphorus requirement is 3.7 g/day; for pregnant sheep (13 weeks of gestation, 40 kg), the requirement is 1.4 g/day (Fadlalla, 2022). For lactating cows of 500 kg live weight producing 20 kg milk/day, the net copper requirement is 5.5 mg Cu/day, with dietary requirement of 138 mg Cu/day, and relative requirement of 8-11 (19.2-15.2) mg Cu/kg diet dry matter (Fadlalla, 2022). Zinc requirement is fully met by rations providing approximately 30 mg Zn/kg dry matter (Fadlalla, 2022). Depending on lifecycle stage and dry matter consumption, required zinc dietary values for dairy cattle range from 18-73 ppm (National Research Council, 2001). Cobalt dietary requirement for sheep and cattle fed a pasture diet is 0.08-0.11 mg/kg dry matter (0.08 mg marginal; 0.11 mg adequate) (Fadlalla, 2022). The dietary requirement for lactating cows is 0.11 ppm of dry matter intake ratio (Balamurugan et al., 2017). Manganese requirements for growth may be met by rations providing 10 mg/kg dry matter; approximately 20-25 mg/kg dry matter is needed for optimal skeletal development, with this level adequate for reproduction (Fadlalla, 2022). Cattle may require up to 50 mg Mn/kg dry matter during pregnancy for skeletal cartilage growth and fetal bone formation (Fadlalla, 2022).

Critical Blood Concentrations

Critical plasma mineral concentrations vary by element and represent thresholds below which deficiency manifestations become apparent. Critical blood concentrations include: phosphorus 4.5 mg/100 ml (plasma); copper 0.65 μg/ml (serum); manganese 6 ppm (liver); zinc 0.6-0.8 μg/ml (serum); cobalt 0.05-0.07 ppm (liver) (McDowell et al., 1993). These values serve as diagnostic reference points for identifying mineral deficiency states in clinical and herd health evaluations. Research in subtropical regions documented forage Cu^{2+} concentrations sufficiently high to meet animal demands (8 mg/kg) during both seasons (winter and summer). Conversely, forage Co^{2+} levels were deficient for ruminants during both seasons, falling below critical thresholds (Fadlalla, 2022). Co^{2+} insufficiency represents the most common mineral deficiency in grazing animals except for phosphorus and copper.

Soil Chemistry and Mineral Availability

The availability of minerals in soil depends upon effective concentration influenced by pH, moisture, organic matter, leaching, and the presence of other elements (Fadlalla, 2022). The concentration of minerals in plants is affected by soil-plant interaction, pH, species, and plant maturity stage. A definitive role of minerals-deficient soil exists in causing deficient levels in feeds. Soil deficiency in phosphorus was evident, with an overall mean P concentration of 9.42 ± 0.59 ppm in soil, contrasting sharply with 2913 ± 470 ppm in plants (Fadlalla, 2022). This dramatic accumulation differential illustrates the plant's capacity to concentrate phosphorus despite soil deficiency. Plant absorption of Co^{2+} is influenced by soil Co^{2+} and Mn^{2+} concentrations. Mn^{2+} deficiency in soil reduces Co^{2+} uptake in forages. Conversely, high Mn^{2+} levels were observed in soil, which could reduce Co^{2+} absorption by plants due to antagonism. Soils with high manganese oxide levels bind free soil Co^{2+} to surfaces, reducing Co^{2+} availability to plants (Fadlalla, 2022).

Conclusion

Mineral physiology, absorption mechanisms, and bioavailability represent fundamental concepts essential for rational livestock supplementation. Substantial heterogeneity in global soil mineral concentrations creates predictable deficiency patterns amenable to targeted supplementation strategies. Regional soil-plant-animal mineral dynamics demonstrate that mineral concentrations in livestock forages reflect complex interactions between soil mineral status, plant species characteristics, and environmental conditions. Critical mineral thresholds, when scientifically validated, serve as diagnostic tools for identifying deficiency states. Understanding these physiological foundations enables practitioners to develop region-specific supplementation strategies that address identified deficiencies and support optimal livestock productivity.

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