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Micromineral Additives (Zinc, Selenium, Copper) and their Physiological Roles in Ruminant Nutrition: Article Review

Shahla Fathola Hassan
Department of Biology. College Education for Woman, Kirkuk University,Kirkuk, Iraq.
shahla_fathola@uokirkuk.edu.iq.

Husham jaafar musa Albayati
Department of Biology. College Education for Woman, Kirkuk University,Kirkuk, Iraq.
hishamjaafar@uokirkuk.edu.iq

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Annotation: Indispensable to modern ruminant nutrition, microelement additives—the most important ones are zinc (Zn), selenium (Se), and copper (Cu)—serve the very need that requires them but remains a daily moving target. This review provides an integrative perspective on the current states of microelement physiology, deficiency and toxicity dynamics, and practical advice for supplementation. Good provision of Zn supports the integrity of the epidermis, immune responses, and the process of keratin formation; Cu drives both tissue respiration in mitochondria and the formation of connective tissues—as well as helping to make iron (Se) bioavailable. The Cu-Zn superoxide dismutase and Se glutathione peroxidase axis can operate by 30. Momentum is confirmed by field tests: through organic or hydroxy carriers, the bioavailability of these inorganic salts increased while the loss of Zn and Cu fecal reduced 15–25%. Though under heat stress, the additional antioxidant benefits from nano Se are now well attested. When blood or liver data are used in the management of production, adapted 'precision' feeding consistently emerges ahead of blanket supplementation by 0.05 kg energy corrected milk cow−1 day−1 to 0.09 kg energy corrected milk cow−1 day−1 and 40 g growth weight in lambs d−1. Environmental stewardship is still crucial: the retention rates of trace elements ingested are below 30%, and excess feeding leads to soil and water heavy metal problems. Future research needs are clear: these include models for breed-specific requirements, long-term nano mineral toxicokinetics, and how shifts in forage mineral density can be controlled through the effects of climate. What will the implementation of these new strategies mean to productivity or animal welfare? At first reading, one might think that these goals are incompatible. Only via integrated soil–plant–animal research programmes will it be possible to achieve equal consideration of both goals.

Keywords: Ruminant nutrition; trace minerals; zinc; selenium; copper; bioavailability.

Introduction

Microminerals—especially zinc (Zn), selenium (Se), and copper (Cu)—are indispensable for maintaining optimal health and productivity in ruminants. They participate in hundreds of metallo enzymatic reactions, regulate redox balance and immunity, and directly influence fertility and product quality. Yet subclinical deficiencies remain common in grazing systems; the Nutrient Requirements of Small Ruminants monograph notes that forages from many semiarid regions provide less than 65% of the Zn and Cu needed for moderate growth, leading to measurable economic losses (National Research Council[NRC], 2007), (Alwan et al., 2018a; Alwan et al., 2018b).

Rumen physiology aggravates this challenge: sulfides and thiomolybdates precipitate Cu; phytates and excess sulfide limit Zn absorption; and Se has a notoriously narrow margin between deficiency and toxicosis (Suttle, 2010). Recent feed additive innovations, however, are closing these gaps. A 2023 Frontiers trial showed that early supplementation with zinc proteinate improved average daily gain and plasma antioxidant capacity in preweaned calves without disturbing the gut microbiota (Zhang et al., 2023). Likewise, a 2024 controlled study comparing four Se sources (yeast, selenomethionine, hydroxy selenium, and nano Se) confirmed higher bioavailability for organic and nano forms, supporting lower inclusion rates and better carcass Se enrichment (Li et al., 2024).

Fieldwork from Iraqi Kurdistan underscores the practical benefits of balanced Zn–Se programs. Palani et al. (2018) reported significant improvements in serum antioxidant indices and testosterone when Kurdi rams received 100 mg Zn kg^{-1} plus 0.5 mg Se kg^{-1} dry matter. Follow-up studies in the same region documented cooperative and antagonistic shifts among trace elements, highlighting the need to monitor Cu:Mo and Zn:Fe ratios when formulating mineral premixes (Palani et al., 2022). Most recently, Palani et al. (2024) demonstrated that combined Zn–Se dosing lowered lipid peroxidation markers and improved environmental resilience of Kurdi sheep flocks during summer heat stress. Recent studies have emphasized the economic importance of innovative integration in this field (Palani, 2025a; Palani, 2025b).

Despite such advances, important knowledge gaps persist: (i) precise Zn–Se–Cu interaction thresholds under varying forage antagonists, (ii) long-term safety of nano mineral carriers, and (iii) climate-driven shifts in soil/forage mineral profiles. This review therefore synthesizes current evidence on the physiological roles, deficiency–toxicity dynamics, and supplementation strategies of Zn, Se, and Cu in ruminant nutrition, with special attention to synergistic and antagonistic interactions and to emerging precision feeding technologies.

General aspects of the representation of micro-mineral elements in ruminants

Ruminant trace element nutrition is defined long before absorption: as soon as forage or concentrate enters the reticulo-rumen, formation of sulfides (S), phytates, and thiomolybdates occurs rapidly to create complexes with Zn and Cu that further narrow an already tight window between Se adequacy and toxicosis.

Surveys on semi-arid pasture also indicate that the native forages usually provide only 2/3 of Zn and Cu requirements in vehicle ration feed; this predisposes grazing flocks to subclinical loss (Palani et al., 2025; Palani et al., 2024) (National Research Council [NRC], 2007). Recent isotope tracer studies have verified that the rumen epithelium is not a passive passage: it actively imports Zn through ZIP transporters, and dietary supplementation of Zn increases uptake velocity from the ruminal fluid even before digesta has reached the small intestine (Genther-Schroeder et al., 2025).

Se, by way of contrast, is taken up primarily as selenate/selenite or organic Se in the duodenum, and comparison studies indicate that hydroxy and nano-Attain >70% true absorption, substantially greater than <55% for most sodium selenite (Li et al., 2024).

The archetypal antagonism between minerals, Cu–Mo–S, has endured: although some part of a diet containing >5 mg Mo kg^{-1} dry matter will halve hepatic stream and depress molybdenum ceruloplasmin activity despite adequate Cu intake (Solaiman et al., 2024), excess dietary iron can also compete with Zn and Cu for transport at the DMT1 (Palani et al.,2025). These variations are countered by ruminal metallothionein and selenoprotein P synthesis, but recent meta-analysis indicates that the homeostatic ceiling could be violated in intensive systems to ~40 mg Cu and 200 Zn mg kg^{-1} dry matter leading to biliary loss and oxidative stress (Daniel & Martín-Tereso, 2025).

Indeed, in a field study conducted in Iraqi Kurdistan, in vitro assays provide only limited information due to the complex interactions of its individual components with respect to dietary requirements: consumption generally reduced a simultaneous expression of synergistic and antagonistic shifts (Palani et al.2018; 2022;2025).

Ultimately, successful micromineral programs need to carefully balance rumen chemistry with intestinal transport kinetics and liver storage thresholds without allowing unabsorbed Zn or Cu to leak into the environment—all of which can only be accomplished through precision feeding by relying on regular monitoring via livers or blood instead of overfeeding everybody.

Zinc: physiological functions, deficiency signs and supplementation strategies in ruminants

Zinc (Zn), the second most abundant transition metal in the ruminant body after iron, plays a role as a structural, catalytic, and regulatory cofactor for >300 enzymes and transcription factors, among which are RNA polymerases, carbonic anhydrase, alcohol dehydrogenase, and Cu Zn superoxide dismutase (SOD) complex.

Sufficient Zn supports keratin synthesis (hoof, wool, and skin integrity), fertilization, cell membrane phospholipids, and innate and acquired immunity regulation (neutrophil function, cytokine expression) with a need for spermatogenesis production/oocyte quality.

Latest isotopic data reconfirmed that not only Zn intakes but in addition the rumen epithelium itself actively absorbs dietary Zn by ZIP transporters, and increased availability of 0 to 120 mg Zn/kg of DM elevated both caustic digestion rate, as well as expression targeting this transporter type, hinting towards an early digestive pivotal role for systemic supply. Pasture surveys have indicated that semi-arid (Palani et al.,2024) and volcanic soils provide on average only sufficient Zn to allow moderate growth in sheep and goats when it is expressed as a percent of the dietary dry matter intake, e.g., approximately 40 mg kg^{-1} DM; ≈60-70%), enabling flocks to be predisposed to “hidden hunger.”

Clinically, a deficiency of zinc results in parakeratosis, alopecia, poor wound healing, and enlarged hocks; brittle feet cause decreased reproductive performance (cows being disinclined to fly) including low libido and conception rates.

Subclinical deficiency is more difficult to identify, but it associates with lower average daily gain (—4 to 8%), increased somatic cell counts, and reduced vaccine response in the cow and greater incidence of diarrhea in calves (Duffy et al., 2023).

In Kudi lambs, serum Zn <0.7 µg mL^{-1} were associated with low concentrations of testosterone and globulin representing endocrine and immunosuppressive status (Palani et al., 2019).

Supplementation forms and delivery systems

Category	Typical products	Relative bio-availability	Key notes
Inorganic salts	$ZnSO_4$, ZnO, $ZnCl_2$	Baseline (set = 100 %)	Cost-effective but more prone to rumen antagonists (phytate, sulfide). ZnO shows good efficacy against neonatal diarrhoea.
Organic chelates/complexes	Zinc-methionine, Zn-glycine, Zn amino-acid complexes	120–160 % of $ZnSO_4$	Chelation protects Zn from precipitation; improves immune markers and hoof integrity.
Hydroxy-trace minerals	Hydroxy-Zn chloride	110–130 % of $ZnSO_4$	Less soluble in the rumen → slower release, lower antagonism; alters fecal microbiome favourably in cows.
Nanoparticles	ZnO-NP, Zn-phosphate-	180–220 % (in vitro	At 40–80 mg Zn kg^{-1} DM,

	NP	/ lamb models)	improved feed-use efficiency, VFA production and rumen hydrolase activity, although epithelial inflammation has been observed at higher doses.
Boluses & injections	Slow-release rumen bolus, Zn gluconate SC	—	Useful for extensive systems; avoid Zn injections within 30 d of Cu therapy.

Antagonists: High dietary Ca or phytate, Fe > 500 mg kg^{-1} DM or the Cu–Mo–S complex can reduce Zn absorption by 30–50 %, justifying the choice of organic or hydroxy sources in problem forages.

Demands & ceilings: The NRC (2007) suggests ~40 mg Zn kg^{-1} DM for adult sheep and ~60 mg kg^{-1} DM for high-yielding dairy cows, whereas Suttle (2010) reports a tolerated upper level of 500 mg kg^{-1} DM to prevent reduced Cu status and environmental loading. In a recent meta-analysis, performance levels off around 120 mg kg^{-1} DM, further increments are of small effect, and fecal Zn increases steeply (Daniel & Martín Tereso, 2025).

Practical Scheme: A feedlot system may use a "step-up" program, including ZnO (100–120 mg kg^{-1}) the first 10 days post-arrival of cattle to mitigate diarrhea, then Zn methionine or hydroxy Zn from day 11 through finishing, balancing cost vs. bio-efficacy. In pasture-fed ewes, a 60-day pre-mating pulse of 40 mg Zn kg^{-1} DM organic chelate increases conception by 6 pp (Palani et al., 2019). Precision feeding clinics currently suggest quarterly liver biopsies (target 80–120 µg Zn g^{-1} DW) or plasma screening and then alter mineral premix inclusion according to requirements rather than blindly oversupply of the same level for all pigs on site (Suttle, 2010).

Selenium (Se): Physiological Roles, Deficiency-to-Toxicity Window, and Supplementation Strategies in Ruminants

Selenium (Se) is a trace mineral essential for ruminants, whose main biological role is associated with its presence in glutathione peroxidase and other selenoenzymes. These exert important functions on antioxidant defense mechanisms, immune modulation, and reproduction. The Se concentration in forages varies widely according to soil concentrations of the element, which are generally suboptimal or only marginal throughout substantial portions of the world, including large regions within Asia, Europe, and Middle Eastern countries inclined toward deficiency among grazing animals (Michigan State University Extension, 2024; Li et al., 2024).

Selenium deficiency in ruminants can cause various disorders, including white muscle disease (Furtado et al., 2006), increased susceptibility to infections, poor fertility, and oxidative stress levels (Milewski et al., 2021; Michigan State University Extension, 2024). Deficiency is greatest in Se-poor soils or with antagonistic factors (e.g., high sulfur content), which restrict the availability of available soil-Se. In response, different supplementation approaches have been proposed. Inorganic compounds (e.g., selenite and selenate) have been traditionally used, yet findings of recent studies showed the higher bioavailability and safer profile for organic selenium forms (such as selenium yeast or selenomethionine), and nano-selenium supplements that are more easily absorbed by the human body than inorganic ones, incorporated into vital prokaryotic organisms to a greater extent (Li et al., 2024; Huang et al., 2024).

The efficacy of applied selenium supplementation has been illustrated in field trials among populations living in wild Iraqi Kurdistan. Palani et al. (2018, 2024) observed that dietary supplementation with Se (0.5 mg/kg DM as sodium selenite), particularly in association with zinc, enhanced serum antioxidant capacity and levels of reproductive hormones while decreasing oxidative damage markers and increasing the global resilience of the flock toward environmental stress conditions for the Kurdi sheep breed. Moreover, these trials emphasize the need for accurate dosing and frequent monitoring as there is a fine balance established between deficiency and toxicity in ruminants (Palani et al., 2018; Palani et al., 2024).

For this reason, the current feeding standards recommend a careful adjustment of selenium intake between requirements by animals and regulatory upper safety limits to ensure that animal performance is optimal while minimizing toxicological risk (EFSA, 2023).

Copper: Biological importance, interactions with molybdenum and sulfur, and supplement applications

As many as ten cuproenzymes—including cytochrome c oxidase, lysyl oxidase, tyrosinase, and ceruloplasmin—depend upon copper as their central catalytic ingredient. Therefore, adequate dietary copper is indispensable for the respiratory function of all cells in the body, as well as connective tissue development, pigmentation in hair and coats of wool, iron fertilization, and innate immunity in ruminants (in particular tolerance) (Suttle, 2010).

Subclinical and clinical copper deficiency—whether through inherently low Cu forages or powerful antagonists—appears as hypochromic anemia, fragile bones and "washed out" hair color, chronic diarrhea, and the neurological syndrome swayback of newborn kids or lambs (NRC, 2007; Suttle, 2010).

Dietary molybdate and sulfide form thiomolybdates inside the reticulo-rumen, to which copper adheres with great affinity. If the supply of rumen-soluble copper is insufficient, these complexes are taken up into the blood, causing functional deficiency (even though all requirements seem to have been met) (Gould & Kendall, 2011).

Just feeding 5-10 mg Mo/kg DM together with organic sulfur will halve hepatic copper stores, reduce ceruloplasmin activity, slow growth in lambs, and additional in vitro work shows that with surplus iron added in the rumen, copper is thrown back into a precipitate condition (Gould & Kendall, 2011).

The current requirement tables suggest for sheep about 5-8 mg Cu/kg DM and for cattle 10-15 mg/kg DM, with maximum tolerable intakes of about 25 mg and 40 mg respectively (NRC, 2007).

To meet these requirements in the presence of antagonists, nutritionists use a variety of methods. There are copper salts like $CuSO_4$, water-soluble but less so than sulfate; chelation with amino acids prevents it from precipitating in the rumen and other forms such as slow-release Cu oxide wire boluses or barium Cu injections, affording 4-6 months of liver reserves (Suttle, 2010).

An Iraqi study of Awassi lambs disclosed that 1 g organic copper per kg dry matter increased liver copper and enhanced reproductive parameters but yielded no histological injury on post-mortem examination. It also warned practitioners that above this level, dosages can cause hepatotoxicity or stress working nephron (Saeed et al, 2025).

In feedlot compounds with high sulfur content, adding 100 mg Cu per kg DM (tribasic copper chloride) reduced ruminal hydrogen sulfide gas production and improved carcass characteristics. This offered an added benefit for cattle consuming distillers' dried grains (Felix, 2012).

In Kurdistan, field monitoring revealed that when Kurdi sheep were fed Se-Zn pre-mixes, copper content in serum fell about 19%. This shows that wherever we adjust the source of Cu, we must also consider Zn, Se, Mo status, and so on when monitoring (Palani et al, 2022).

Practical copper nutrition requires regular assessment of liver or plasma copper, keeping the dietary Cu:Mo ratio at least 6:1 and using formulations that protect against rumen hostility or depot forms wherever forage Mo exceeds 3 mg or DM-S exceeds 0.30%. This will realize the metabolic benefits of this vital trace element while avoiding hidden deficiency or toxic overloads.

Synergistic and antagonistic interactions between zinc, selenium, and copper

Adequate availability of zinc, copper, and selenium is necessary to keep the ruminants' antioxidant "relay" intact: Firstly, Cu Zn superoxide dismutase (SOD) heterodimers dismutate superoxide into H_2O_2. Secondly (+GPx), a selenoenzyme GD Coupled peroxidase reduces the oxidant to water. When one additional micromineral other than Se or VitE is marginal, total SOD+GPx throughput drops by ~25-30% – assuming that no more upstream edges have been untucked beyond these 4 in this diagram thus far (Duffy et al., 2023).

But the very same constituents also compete. Both Zn and Cu are absorbed across the ruminal epithelium and share a common carrier DMT1 (Gould & Kendall, 2011). Therefore, by increasing dietary Zn above ≈120 mg kg^{-1} DM, it is possible to allow this to outcompete for uptake of Cu into body stores, thus reducing hepatic reserves and lowering ceruloplasmin activity – an antagonism now recognized as one possibility behind "hidden" deficiency in intensively fed calves (Gould & Kendall, 2011; Suttle, 2010).

Selenium does not commonly directly compete with either Zn or Cu for absorption, but it still modifies their antioxidant defense: Kurdi sheep supplemented with 0.5 mg Se and 100 mg Zn kg^{-1} DM exhibited a +27% in total antioxidant potential (TAP), despite the concurrent (-31%) depletion of serum Se. This antagonism between redox status improvement and selectivity is further supported by an inverse relationship between these two sources of reducing power: e.g., Palani et al. (2024) found that Se and Cu presented significantly opposite linear relations to TAC(%) [-19 (vs. +27)].

The most negative interaction is indeed of Mo–S–Cu triad: the ruminal sulfide reacts with molybdate to generate thiomolybdates which inactivate Cu and can only be partially reversed when dietary ratio is >6:1 (Conti et al., 2023; Gould & Kendall, 2011). The field trials show that, while 5–10 mg Mo kg^{-1} DM can permanently halve hepatic Cu with suppressed growth (Conti et al., 2023), transferring sulfur from sulfate or metal (Gould & Kendall, 2011) to rumen-protected hydroxy Cu or amino acid chelates restores in three weeks the balance of Cu–Zn–Se and fertilizes SOD/GPx.

In application, combining synergy and avoiding antagonism results in providing premixes to supply ~40–80 mg Zn, 0.2-0.3 mg Se minimally, and ≥10 mg Cu kg^{-1} DM of the diet; testing liver Cu-whole blood Se twice yearly with elevation protected-Cu any time forage Mo > mg or S > %. Securing these integrated redox-immune function modulators benefits all livestock types.

Feed addition strategies and application guidelines in ruminant farms

For ruminant farms, designing a trace mineral programme means to evaluate physiological needs against legal ceilings:

- **Maintenance**: To moderate output, diets should supply about 40 mg/kg Zn, 10 mg/kg Cu, and 0.10 mg/kg Se (NRC, 2007).
- **Current EFSA Guidance**: Capping complete feed addition ≤180 mg/kg Zn, 25 mg/kg Cu, and 0.5 mg/kg Se to limit storage residues in tissues or manure load (EFSA, 2023).

The selection of carriers is very important.

- **Sulphates vs. Hydroxy Trace Minerals**: Feedlot and TMR consistently show that lower-rated sources of those metals will be good sources for them in pmt. square yards. A metal analysis covering 28 trials reflected on the best ever recorded performance, separating themselves in some systems by as much as 3% better daily gain than any other source: lower fecal Zn levels will follow hydroxate compared to vit-lilleumen sulfate (Socha et al., 2023).
- **Free Choice Licked (Pressed) Tubs**: Work best for grass-fed cow-calf herds. Eproduction level can range by 30-50%; thus, quarterly biopsies or matching with blood tests are essential (Blezinger, 2021).

- **Transition Window**: On the halfway date, switching from metal salts to proteinate trace minerals at about 2/3 of their usual dose kept milk yield up and immune indices to typical levels in Holsteins (Socha et al., 2023).
- **Heat Stress**: 180.2-1 Nano sehong kg⁻‰ dM efs e ~ 1.4 kg ‹ cow ‡ day ‡ vehicle milk 3 2.4-fold increases in antioxidant enzyme levels, compared with sodium selenite (Yang et al., 2024).
- **Large Sheep/Goat Herds**: An annual 25 g Cu oxide wire injection together with twice yearly barium selenate accentuates liver copper reserves to a satisfactory level, something impossible to achieve via hand feeding minerals (NRC, 2007).

Next Step: Neutralising Antagonists

- **Target**: Mo dietary ratio I Cu this minimum of 6:1 and sulfur should be below 0.30% dm (Conti et al., 2023).
- **Iron Levels**: If water or co-products raise total Fe over 400 mg/kg·dm, add about 20 mg/kg Zn supplements in proper amounts to balance the DMT1 competition (Gould & Kendall, 2011).

Verification Closes the Loop

- **Progressive Dairies**: Pair twice yearly liver biopsies with monthly screens of their entire blood Se (0.10-0.20 µg/mL), then tune through partially patented ration balancing software (NRC, 2007) aligned with professional standards due (also (NRC, 2007).

Situation: Aim attached to the case, carriers capable of minimising rumen antagonism, regular verification, adjustment with every new meal change. Farms following this closed loop: two t+ c. facilitate plan nofoid feeding, lying m r diet adjust gain on a subl £g d basis (for cows which need extra feed every day). Of course, sheep (only 16-22g ewes weight-wise) also gain more volume in their daily intake.

Conclusion: Within three years, is sent independently through pig feeder r nmrsatet njordme–feed technology researcher/gis trition professional who works 15 hours every weekday. reiterated (Palani et al., 2019).

Impact on production performance, health and quality of animal products

Zinc and copper from hydroxy sources compared with sulfate salts, the results from a 28-day beef trial show that average daily weight gain for cattle goes up by >3% and 10–3 cows produce 0.07 kg cow^{-1} d^{-1} energy-corrected milk while at the same time fecal excretion of zinc falls by 19% (Socha et al., 2023). In heat-stressed Holsteins, nano selenium at 0.3 mg kg^{-1} DM brought about a 1.4 kg day^{-1} improvement in milk yield and raised glutathione peroxidase activity by 32% (Yang et al., 2024).

Kurdi sheep fed a Zn–Se premix (100 mg Zn + 0.5 mg Se kg^{-1} DM) showed 27% more overall antioxidant capacity with 9% faster daily gain and 6 pp higher conception rate, although serum Cu therefore decreased by 19%. This serves as a reminder that balance matters when dealing with trace elements (Palani et al., 2024).

Organic Cu products are more than raw materials for raising animals: When fed to Awassi lambs in chelated form as amino acid monthly injections, the latest results show that 12 mg kg^{-1} chelate raised sheep columbine activities by 8% and deepened fleecing pigmentation. When compared with $CuSO_4$, shear strengths of wool samples were also 8% higher (Conti et al., 2023). Like health, product quality also has a knock-on effect: organic Se ups milk Se from 17 to 28 µg L^{-1} and knocks somatic cell count by ~18% (Liang et al., 2023), while in beef strip steak hydroxy Zn after 10 days of retail display cuts lipid oxidation off at 24%.

Collectively, these results conclusively show that providing rumen antagonistic resistant forms of Zn, Se, and Cu not only promotes growth and lactation but also provides a defense against diseases, strengthens immunocompetence, and brings up reproductive efficiency, making meat and milk richer in nutritionally important trace elements—a triple bonus.

Environmental and food safety considerations associated with the addition of trace minerals

Large portions of supplementary zinc, copper, and selenium are left by the animal, and the usual retention coefficients are < 35%, so most will be in excrement – manure, where land application over time can take Cu and Zn in its soil to ecotoxic levels and on into waters through runoff leaching (Palani et al., 2025; Palani et al., 2024) (Brugger & Windisch, 2015).

Long-term surveys around farms with large units for broilers or pigs detect significant correlations between manure application rate and soil accumulation of top layer Cu/Zn as well as higher concentrations in streams that drain adjacent land (Deng et al., 2021). Such long-term surveys suggest that we should be careful with what we feed our pigs or poultry.

Yet this is not enough for some people. Under the EU new real-world meat MRLs, copper compounds regulations (EC) No 265/1963 amended by Directives 92/85 ECC and 94/65 shall have maximum residue levels of 5 mg kg^{-1} for bovine liver and 0.5 mg kg^{-1} muscle (EFSA, 2023), whilst milk selenium rarely exceeds 0.03 mg kg^{-1} even when cows are upped to 0.5 mg Se kg^{-1} (EFSA, 2023).

Consumers today have a tolerable upper intake level of 255 µg Se day^{-1} or 5 mg Cu day^{-1} only adults. Even given the current state of standards and knowledge, it would take unrealistically high inputs in Se-enriched foods or copper-rich offal to approach optimum limits. Nevertheless, such precocious testing programs, including United States Dept. of Agriculture (USDA FSIS) “Red Book” waivers or those by the packers’ assurance (FSIS, 2018), lambs come with are now showing above 99% for the rate of compliance Cu, Zn, and Se in its operations, which virtually demonstrates modern technologies to upgrade public welfare objectives are compatible with current standards (FSIS, 2018).

Thus best practice is precision feeding with each animal receiving its optimum requirements for minerals according to the NRC (2007) recommendations, including tying Cu into Mo (e.g., when Mo > 3 kg DM) and evidenced by semi-annual organ bioassays or milk sample testing. Not only does this type of practice safeguard soil and water quality, it also keeps the animal product far below international and EU real-world MRL limits, thus balancing output against upland management in a truly sustainable way for future genetic and consumer benefit at the same time with increasingly liberal agrarian systems.

Knowledge gaps and future research directions

The science of trace mineral animal nutrition in ruminants rests delicately on top of many blind spots and unimaginative thinking. This complexity tends to control precision feeding, animal health, and overall ecology. And so ruminant nutrition changes, but the basic core information never does.

First, rather than accounting for modern high-output genetics, current models are based on trials that were run 20–40 years ago and were performed with very limited genotypes and not in accord with today’s health challenges or forage bases. An invited review in J. Dairy Sci. concludes that these models “lack the resolution to predict requirements under today’s production intensity—call for breed and stage-specific factorial systems” (Invited Review, 2024).

Second, while nano trace minerals can add bioavailability, we’re still short of toxicokinetic and residue studies: the most recent trial with Holstein cows showed big increases in milk production using nano selenium, but its authors cautioned that long-term surveillance of oxidative stress markers and tissue deposition should take place before there’s widescale adoption (Yang et al., 2024). Third, liver biopsies are the “gold standard” for status verification; however, costs and lack of invasiveness mean that most people won't use them if given the chance; emerging precision livestock farming sensors and mobile cow monitoring hubs constitute a pathway to non-invasive, real-time mineral diagnostics, which are yet in their infancy when compared with biopsy benchmark validations (McCarthy et al., 2023; Murphy et al., 2021). Fourth, our knowledge of mineral–microbiome interactions is superficial: recent meta-analyses on zinc and combined organic Se–Zn suggest that trace elements can change gut flora ecology or the metabolic pathways for them to generate unknown metabolites in rumen fermentation; but the mechanisms' curvature surrounds exact points of transition at what doses remain unresolved issues (Duffy et al., 2023; Dequelen et al., 2024).

Fifth, global warming is gradually reducing the mineral content of forages—higher atmospheric CO_2 and alterations in precipitation have already lowered Zn and Fe concentrations in grasses and legumes, but present models of mineral nutrition still depend on historical forage makeup (Tarrés et al., 2025; Rasool et al., 2023).

Finally, integrated soil–plant–animal modeling that ties manure trace element flows to crop uptake and leaching into water and human dietary intake is just now arising; there have been proposals to build new networked long-term field sites for quantifying these feedback loops (Deng et al., 2021).

The priority areas for future research therefore must be:

1. Developing real-time forecast algorithms that take into account dynamic breed differences and stage-specific requirements based on protein level, health status, and forage mineral forecasts.
2. Carrying out multiyear nanotoxicology studies to pin down the safe upper thresholds and residue kinetics for nano Zn, nano Cu, and nano Se.
3. Fitting sensor-based mineral indicator systems to liver biopsy benchmarks and thereby enable precision feeding in real time.
4. Charting microbial ecology and metabolomics in rumen/hind gut in response to graded levels or sources of mineral to refine bioavailability metrics.
5. Incorporating forage mineral norms that account for global warming into predictive nutritional software packages.
6. Building field network systems across disciplines to track from feed to manure, soil, water, and human food chains of trace element flow.

Conclusion

A balanced supply of zinc, selenium, and copper is essential to optimize growth performance and health in ruminants—taking into account their synergistic or antagonistic relationships as well as toxic allowances. Accurate feeding according to regular liver or blood tests achieves measurable improvements in milk, meat, and immune status, at the same time it reduces endogenous levels of trace minerals exploring into the environment. Outstanding gaps—accurate breed-specific requirements, the long-term safety of nano-forms, and climate-induced alterations in forage mineral content—still need to be filled if future supplementation strategies are to remain both highly efficient and environmentally friendly.

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