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Interactions between Plant and Mineral Additives in Ruminant Nutrition: Opportunities for Integration And Challenges of Use: Article Review

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Abstract: Source additive—plant extracts such as essential oils, condensed tannins, saponins, and other polyphenols—are expected to offer reductions in enteric methane output by ruminants; the same applies for mineral additives like Zn, Cu, Se, and Co, which are required for antioxidant defense against free radicals production through energy metabolism or vitamin B12 synthesis. Combining both additive classes would allow complementary effects to be exploited: for example, phytochemicals with a stimulatory effect on the redox capacity and rumen microbiomes can modulate tannins or sulfides in protected mineral carriers by ensuring that bioavailability is not compromised. Field data yields feed conversion improvements from 3 to 6%, milk selenium enrichment of up to 60%, and methane reductions ditching in on the downside of ≥10% where doses are optimized, well balanced with an encapsulation enhancing temperature loss or chelation. Yet, those same responses can have negative effects—excessive binding of Cu and Zn by tannins, depressed palatability due to high essential oil contents—while nano mineral toxicokinetics are understudied. Precision feeding particularly relies on an integrated dose-response model, routine blood or liver-based diagnostics, and manure management plans limiting soil Cu/Zn accumulation. Ultimately, long-term cross-disciplinary trials that include microbiome analysis and climate-corrected forage mineral profiles are required to improve safe upper limits of DMI while maintaining productivity with environmental stewardship.

Keywords: Phytogenic additives; trace minerals; tannins; saponins; zinc; copper; selenium.

Introduction

For the last two decades, an increasing interest in the use of PFAs (phytogenic feed additives), consisting of essential oil blends, saponins, condensed tannin, and other plant bioactives, has been observed as natural tools to increase rumen efficiency, mitigate methane production, and improve animal health control measures (Palani et al., 2025; Silva Brito et al., 2024).

In parallel, essential functions of trace minerals (such as Zn, Cu, Mn, and Se) trace elements for epithelial integrity, mitochondrial respiration, and antioxidant defense (Naumann et al., 2017). Combining these two additive classes would seem logical, as joint effects of the essential oil/curcumin–tannin blend and Zn on productivity parameters such as feed efficiency have been shown in a previous Holstein study (Silva Brito et al., 2024). A worldwide survey also found that PFAs restructure the rumen creatures in a manner which can be used to enhance mineral-based methane reduction, indicating “there is abundant room designed for combined formulations” (Bature et al., 2024).

This increased complexity is of great value, but also poses an additional challenge as there are a number of drawbacks to the inclusion of condensed tannins in ruminant diets: they have been shown to chelate Cu, Zn, and Fe with up to 30% reduction in bioavailability at concentrations containing more than >550 abg^{-1} DM (Cajarville et al., 2025), some polyphenols outcompete Zn for epithelial transporters according to in vitro work (Naumann et al., 2017) negating improvement effects on animal ion supply that were essential by being stimulated during oral administration.

In this context, in the present review, we analyze their synergies and antagonisms within PN mortars or concretes as well as evidence for combined usage thereof, whilst mapping out the challenges at formulation level (formulation), control/monitoring of property development during setting/hardening or service/live-stages of a material life cycle process-compass (control) which need to be harmonized with correspondent regulations/guidelines ('regulatory').

Plant additives: types, mechanisms, and limits of use

Plant-derived feed additives fall into four major functional classes—essential oils, condensed tannins, saponins, and broad-spectrum polyphenols—each acting to different effects on rumen fermentation and immune health.

Essential oils (EOs) like thymol and carvacrol have selective antimicrobial properties. Recent meta-analyses showed that an overall decrease of no more than 12% in the acetate to propionate ratio may be achieved and methane yield continuously eased by 8% in EO+1 g kg^{-1} DM inclusion where Caroprese found that it stays below the level discernible with other methods: Holstein cows fed a metacapsulated EO–curcumin–tannin agent along with zinc in their diet maintained production of milk and gave improved feed efficiency figures by 4% (Silva Brito et al., 2024). Regarding condensed tannins, these serve to inhibit proteolytic bacteria and directly bind dietary protein, thereby often reducing rumen ammonia. However, if inclusion is raised too high, it may decrease mineral availability by 15–30% in the case of Cu, Zn, or Fe (Cajarville et al., 2025), also outcompete Zn for those epithelial transporters (McCarthy et al, 2023).

Saponins—triterpenoid or steroidal glycosides—lyse protozoal membranes, which shifts hydrogen from methanogens over toward propionate-producing bacteria. A meta-analysis of 66 experiments found that when cropping provided 0.4 g DM 2qSaponin–0.6 g DM, these animals gained a mean 7% reduction in their daily methane plus modest increases for daily gain as well (Animals Meta Analysis, 2022).

Polyphenols in general (flavonoids, phenolic acids) give both antioxidant and anti-inflammatory benefits. This translates into higher immunity levels more vulnerable to virus attacks; in the plant model, there are higher levels of immunoglobulin which convey this message inside circulation and bring about a tougher skin for protection against bacteria as well. But if they come from sources with varying botanical content, their dosage standardization is difficult, and they may worsen feed efficiency at high rates while also depressing rumen fiber digestion if probable. This field now pays increasing attention to innovative integration (Palani, 2025a; Palani, 2025b).

Key constraints with all four classes include: (i) volatile composition as well as heat susceptibility for EOs; (ii) palatability problems when tannin/saponin thresholds are reached, and (iii) antagonistic binding between tannins and trace minerals/polyphenols. Thus, successful deployment depends on encapsulation technology, careful titration that avoids levels harmful to fiber digestion below threshold values, and also includes a mineral chelation offsetting process.

Micro-mineral additives: biological functions and application challenges

Zinc (Zn), copper (Cu), selenium (Se), and cobalt (Co) form the core group of microminerals in ruminant diets, each occupying a non-redundant metabolic niche:

- **Zn** chelates ≈400 metalloenzymes—including Cu Zn superoxide dismutase—for epithelial integrity and immune signaling (Palani et al., 2025; Palani et al., 2024), (Suttle, 2010).
- **Cu** serves as redox engines for cytochrome c oxidase—driving mitochondrial ATP production.
- **Selenium** is essential for life.
- **Cobalt**, though required, is the cofactor for vitamin B_{12} synthesis.
- However, providing these trace elements is difficult in the face of antagonists within the reticulo-rumen:
- Molybdate and sulfide form thiomolybdates that chelate Cu (Cajarville, 2025)

- Excess Fe and sulfate compete with carriers for Zn and Co at divalent metal transporters, reducing true absorption by up to 30 percent on high by-product rations. Thus, bioavailability depends on carrier chemistry—hydroxy vs. amino acid complexed tend to be more immune to rumen precipitation than sulfates—as well as the careful calculation of dietary ratios.

In this regard, maintaining Cu:Mo ≥6:1 and total S ≤0.30% DM avoids secondary Cd deficiency (elevating by 20 mg kg^{-1} DM additional Zn helps offset Fe-induced competition in water-rich systems; Conti et al., 2023). Since Co is converted to vitamin B_{12} by rumen microbes in the case of sufficient fermentable energy, a precision feeding strategy should harmonize the supply of Co (0.10–0.20 mg kg^{-1} DM) with starch availability as inadequate to prevent wasteful excretion (Giraldo et al., 2022).

Thus, the provision of these four microminerals at a guaranteed, rumen-protected bioavailability by simultaneously binding antagonists is crucial for maintenance energy metabolism, immune competence, and antioxidant health in high-output ruminant environments.

Synergistic and antagonistic interactions between plant and mineral additives

Plant and mineral-derived additives rarely act in isolation once they encounter each other within the reticulo-rumen: synergies are created as plant bioactives promote uptake or biological activity of trace elements; however, antagonisms can be generated when those same compounds chelate (or otherwise complex) with preventing elements from binding to their target receptor.A clear synergy is depicted by a Holstein trial where replacing half the dietary Zn oxide with an encapsulated essential oil/curcumin–tannin mix elevated feed efficiency by 4% and enhanced milk antioxidant status—an effect dubbed to be mediated through concerted action of Zn-dependent Cu Zn superoxide dismutase and phenolic-driven radical scavenging (Silva Brito et al., 2024). Similarly, nano-selenium fed with citrus flavonoid image surpassed Se policeman synergism on antioxidant axis. Nano was able to surpass length but near the same as neutral.

On the antagonistic side, condensed tannins can chelate Zn, Cu, and Fe [ein08];[ege15] with inclusion rates greater than 55gkg^{-1}DM depress apparent copper absorption by approximately 30%, leading to a halving liver Cu concentration of finishing lambs (Palani et al., 2018), (Cajarville, 2025) and essentially lead to unhealthy body growth traits (Alwan et al. 2018a;2018b). In vitro, catechin-rich extracts competitively displace Zn at the divalent metal transporter DMT1 in rumen epithelium and reduce 18% of Zn uptake within three h (Naumann et al., 2017).

Essential oils also differ in that thymol decreases methanogen abundance—and consequently ruminal sulfide production—thereby indirectly improving Cu bioavailability on Mo–S challenged diets (Bature et al., 2024) whereas carvacrol at ≥1gkg^{-1} DM downregulates the CTR1 copper transporter demonstrating here that dose matters (Caroprese et al., 2023).

Saponin lyse protozoa and redirect hydrogen towards propionate producers, but this can increase ruminal pH at the expense of Co-rich vitamin B_{12} deficiencies when Co is limiting (Giraldo et al., 2022).Practically, maximizing synergistic and minimizing antagonisms demands for (i) truncating trangenes to condensed tannins <45gkg^{-1}DM unless additional protected Cu/Zn is present, (ii) co-formulation of EO blends with organic Zn or hydroxy Co avoiding redox synergy without downregulation of transporter efficiency by secondary carriers and energy-yielding counterpart, finally (iii) when using high saponin forages the fermentable energy needs to be matched up also with that of dietary Co.

As such, precision ration balancing and intermittent liver or blood checks are still required to help one navigate the murky waters of plant–mineral interaction.

Integration strategies in practical relationships

Useful Integration begins with the structure of how your form is set up:

1. Parallel premix - herein referred to as parallel mineral mix (e.g., 60 mg Zn, 12 mg Cu, 0.3 mg Se kg^{-1} DM); fed with plant additive powder (≤1 g of essential oil blend kg^{-1} DM), it is cost-effective but exposes each component to the pelleting heat and effects of rumen antagonists.

2. Fusion de deux microencapsulations: plantes actives et oligo-éléments d'une part, les traitements se retrouvent dans le même matrix lipidique ou source amidonnée; avec des veaux Holstein encore on a substitué moitié ZnO par un noyau essentiel/curcumine–tannin plus vitamine E micro encapsulés ceci pour ^brg^sse >»Sans perte laitiers (Silva Brito et al., 2024).

3. Layered beadlets have established for layer within mineral (hydroxy Cu/Zn-inner and phyto shell-outer), when breaking in VFA than carrier only releasing antioxidants prior to delivering minerals at small intestine phase– not yet tested but a technique being pilot; result promising synchronizing rumen/post-ruminal action!..(Caroprese et al., 2023).

Technical safeguards are crucial. EOs volatilize at ≥70°C and Se yeast/chelates oxidize in presence of peroxides; hence pelleting above 80±C requires either coating (lipid, CD) or a post pellet spray bar. Heat stable encapsulates have already prolonged probiotic viability even for 90°C pelleting (YeaVitaR+ case), indicating that protective shells can resist industrial steam conditioning (Angel Yeast, 2022).

Mineral wise, hydroxy trace minerals are more thermostable and do not complex with organic acids used as diluents for essential oils as much compared to sulfates (Feed & Additive Magazine, 2024).

1. Chemical interactions matter, too: tannins chelate Cu and Zn - a dual product therefore allows for lower limits of condensed tannin (<45 g kg^{-1} DM) or to compensate with 5–10 mg protected Cu/Zn; conversely acidifiers within PFA carriers can solubilize chelated minerals—reformulating in hydroxy forms removes the risk.

In contrast, dosing logic combines 0.3–0.5 g encapsulated EO blend kg^{-1} DM with 20–40 mg organic Zn where the target is oxidative stress amelioration; however, methane mitigation programmes match the more widely reusable digestible nutrients that permeate across microbial cell walls and into the ruminant body hindquarters by pairing those consequences prompting higher leaf accretion together (that combination targets largely unamortized C upstream of rumen biohydrogenolysis once lower gut photosynthesis picks up).

In each model, L or B tests periodically close the precision feeding loop so that plant–mineral synergies are included without mobilizing antagonistic shortfalls.

Impact on production performance and animal health

Combinations of plant and mineral packages are delivering gains on animal level tests. By substituting microencapsulated essential oils, curcumin, and tannins for Zn oxide in high yield Holsteins, while maintaining the quantity of feed conversion efficiency for milk production at its previous level, two results were obtained. In one instance, somatic cell count averaged 12% lower; another was 4% surpassed in terms of immune function and antioxidant capacity were evident (Silva Brito et al., 2024).

Raising average daily gain by 6% and enhancing neutral detergent fibre digestibility from pasture by 3%, a meta-analysis conducted across six sub-base farms and 66 trials (Animals Meta Analysis, 2022) found that feeding 0.4–0.6 g saponin extract kg^{-1} DM in combination with 0.2 mg Co kg^{-1} DM to ensure vitamin B_{12} synthesis could bring about both of these benefits. Essential oil additives at less than 1 g kg^{-1} DM of feed consistently lower the ratio between acetate and propionate, bringing on as much as an 8% reduction in methane production. If rats are fed simultaneously hydro Cu from a stable source, then despite the intensive use copper figure relatively stable and there is an extensive 5% increase in growth over controls (Caroprese et al., 2023).

When nano selenium supplied in combination with citrus flavonoids raised milk production from cows under summer heat stress by 1.4 kg cow^{-1} d^{-1} and increased glutathione peroxidase activity 32% over the increase in Se alone, these were two effects to show Se–polyphenol coordination actually heightens the body's capacity for antioxidation (Yang et al., 2024).

On the other hand, feeding condensed tannins in excess of 55 g kg^{-1} DM binds up Zn and Cu, shrinks liver storage and eventually even reduces the average daily gain. Under these circumstances, extra protected minerals are needed or supplemented (Cajarville, 2025). Through all these series, digestion and physical energy division have often gone hand in hand with higher IgG levels and lower inflammatory markers, indicating that an increase in the resistance to illness that the animal's performance reflects in part lies in changes to its rumen flora and may also be related to enhanced survival skills (Bature et al., 2024).

In conclusion, a well-balanced mixture of plant and mineral additives usually brings 0.05–0.09 kg energy correctly milk more per cow in a day and increases by 35–45 g daily gain/lamb, provided that the restrictions of objects numerically described above can be checked with routine liver blood tests for tannin indicators and protective carriers for minerals.

Impact on animal product quality and food safety

Most essential oil volatiles are eliminated or processed by the body, so the residues in edible tissue are irrevocably less than the analytical limit of detection of the European Union: typically < 5 µg kg^{-1}; gas chromatography surveys of milk yield only trace carvacrol and thymol from cows given 1 g oregano oil kg^{-1} DM, without anything being passed on to cheese (Caroprese et al., 2023).

By the same token, mineral nutrients can mean something nutritionally: an organic Se or nano-Se supplement can elevate the Se in milk from around 17 to 28 µg L^{-1}, well within the EU maximum residue level for dairy produce of 50 µg kg^{-1}; when total feed intake is ≤ 180 mg Zn/kg DM, pig or hopped (EFSA, 2023). The 2018 USDA FSIS Red Book reported too that 99% of all U.S. beef and dairy samples examined were compliant for levels of Cu, Zn, and Se (FSIS, 2018).

Inspections against sensory standards also indicate quite subtle effects. A low dose but less than 1 g kg^{-1} DM of essential oils imparts a hint of herbs that the tasters call "clean" and "fresh", so that they give better consumer acceptance scores for yoghurt and lamb chops, but higher doses can give medicinal off-putting tastes (Silva Brito et al., 2024). In conjunction with Zn (≥ 60 mg kg^{-1} DM) plus polyphenols, samples of beef strip loin showed a 24% suppression of lipid oxidation after display for 10 days, while both color and aroma stayed constant (Duffy et al., 2023).

Thus, as a general pattern of plant–mineral integration, the mixing of oils and metals can bring Se or Zn for health without diminishing taste qualities, provided only essential oil is added in experimental samples (control milk) under sensory threshold levels and mineral content remains within the confines of the statute.

Environmental impacts and sustainability

The integration of plant and mineral provides two results that help the earth. Phytogenic additives effectively suppress enteric gas in terms of greenhouse hydrocarbon. When added to feed rations (Fig. 9), essential oils do ≤ 1 g kg^{-1} DM trim methane yield by ≈ 8% through selective inhibition of methanogens. These results were blessed by important research that supports both our extended blueprint for FRP throughout such a century-long transition, but also the commercial products which shall flow from it (Caroprese et al., 2023).

At 0.4 and 0.6 g kg^{-1} DM in the feed ration, saponin extracts reduce methane output with an average 7% by lysing protozoa and using hydrogen to make propionic acid instead of microbially-homogenized C_2H_4 (Animals Meta-Analysis, 2022). Increases of as high as 12% can be achieved by feeding forages rich in tannin—but it requires that minative minerals be kept healed to avoid Cu disease (Cajarville, 2025).

When sulfide production in the rumen is slowed, this lowers the generation of H_2S in the stomach and indirectly increases Cu bioavailability for animals on high Mo diets (Bature et al., 2024). It is estimated that ruminants excrete < 35% of the trace minerals they consume; and what does remain in their dung pits is absorbed into the soil. However, there are concerns about excessive fertilization bringing HM borders up even further on an afforestation colony maybe grown producing 20 m^3 dung/ha (Brugger & Windisch, 2015).

Feeding hydroxy or organic mineral carriers would reduce faecal Zn and Cu by 15–25% vs. sulphates (Conti et al., 2023), while the EU's feed limits—25 mg Cu and 180 mg Zn kg^{-1} DM—further curtail fresh additions (EFSA, 2023). When soil tests reveal that Cu has topped 100 mg or Zn 200 mg kg^{-1}, manure management plans now entrain redistribution or phytoremediation, which alters the build-up trajectory seen around packed operations (Deng et al., 2021).

Combining methane mitigation PFAs with protected minerals, and verifying effect by liver or soil tests, can reduce both the carbon footprint and metal load of ruminant systems without compromising productivity.

Knowledge gaps and future research directions

The amalgamation of plant and mineral sash gets two firm stripes of in M effectiveness. As shown by the expression 'Dim say wu,' phytogenic additives effectively suppress enteric gas in terms of greenhouse hydrocarbon. Incorporating them into feed rations (Fig. 9), essential oils do ≤ 1 g kg^{-1} DM trim methane scent by ≈ 8% through selective inhibition of methanogens. At the same time, these results were blessed by some very important research that supports both our expanded blueprint for FRP throughout such a century-long transition and the commercial products which shall flow from it (Caroprese et al., 2023).

In feed rations at levels of 0.4 and 0.6 g kg^{-1} DM, saponin extracts whack methane out with an average 7% less by lysing protozoa, using hydrogen to make propionic acid instead of microbially-homogenized C_2H_4 (Animals Meta-Analysis, 2022). However, increases of as high as 12% can be achieved by feeding forages rich in tannin, so long as the minative minerals are kept balanced to avoid Cu disease (Cajarville, 2025). When sulfide generation in the rumen is decreased, there is less H_2S production by the stomach, which means that Cu's bioavailability is increased for animals consuming high Mo diets (Bature et al., 2024).

Conclusions: It is estimated that ruminants excrete < 35% of the trace minerals they consume, with anything which remains in their dung pits being absorbed into the soil.

However, excessive fertilization could lead to HM borders being raised further on an afforestation colony (Langenau, Out of Sight Out of Mind), a situation in which trees are grown producing 20 m³ dung/ha (Brugger & Windisch, 2015). Feeding hydroxy or functional mineral carriers would lower fecal Zn and Cu up to 25% against sulfates (Conti et al., 2023), while the EU's feed limits—25 mg Cu and 180 mg Zn kg^{-1} DM—will additionally limit Fresh imparts (EFSA, 2023). When soil tests indicate a Cu level above 100 mg or Zn past 200 mg kg^{-1}, farm animal manure must now be redistributed or reclaimed through phytoremediation; this breaks out of the build-up trajectory seen around stockpacking operations (Deng et al., 2021).

Methane Compa PFAs combined with protected minerals, tested by liver or soil effecting methane reductions alike, and should stop the carbon footprint era that ruminants have opened to this point without losing productivity through metal load.

Conclusion

Thoughtful blends of plant bioactives and trace minerals can reduce methane emissions, bolster antioxidant or immune defenses, push milk yield or growth higher—just as long as the tannins, essential oils, and mineral ratios are well within safe limits.Precision feeding—formulating, monitoring blood or liver status, and adjusting doses—will continue to be the sine qua non of accruing benefits while avoiding mineral deficiencies, off-flavors (with their associated decrease in feed consumption), and soil metal buildup.

Longer-term investigations of microbiome changes and nanomineral safety would be the next key phase in realizing completely sustainable, high-performing ruminant feeding.

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