

Area-Specific Mineral–Vitamin Nutrition in Indian Dairy Cattle and Buffaloes: Integrating Regional Deficiency Mapping, Trace-Mineral Bioavailability, Vitamins and Precision Supplementation

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ABSTRACT

Mineral and vitamin nutrition in Indian dairy cattle and buffaloes cannot be adequately described by a single national supplementation formula because nutrient supply is shaped by agro-climatic conditions, soil mineral status, water quality, crop choice, fodder species, preservation practices, animal genotype, physiological stage and the extent of concentrate feeding. Area-specific mineral mixture (ASMM) therefore provides a rational framework in which mineral supplementation is based on measured regional deficiencies and practical dietary supply rather than on indiscriminate addition of all nutrients at fixed levels. This review examines the scientific basis of area-specific mineral–vitamin nutrition, with particular emphasis on regional deficiency mapping, diagnostic approaches, trace-mineral bioavailability, mineral–mineral and vitamin–mineral interactions, organic mineral sources,

antioxidant micronutrients and precision supplementation. Indian evidence demonstrates substantial heterogeneity: studies in Jharkhand, Haryana, Uttarakhand, Andhra Pradesh, Punjab, Karnataka and Kashmir have identified different combinations of deficient or excessive minerals in feeds, fodders, soil and animal tissues. A recent study from the Pir Panjal region of Kashmir reported widespread deficiencies of Ca, Cu, Mn and Zn in plasma, whereas a 2025 field study in Chittoor, Andhra Pradesh documented improved plasma Ca, P, Cu and Zn and reproductive hormones after supplementation of a locally formulated ASMM. In 2025/2026, a controlled study in periparturient Murrah buffaloes further reported higher milk yield and better postpartum reproductive responses with ASMM than the unsupplemented control. The review argues that the next generation of ASMM should move from static regional recipes toward dynamic, biomarker-informed formulations that consider native dietary mineral supply, antagonists, source bioavailability, seasonal changes, heat stress, production stage and the risk of both deficiency and over-supplementation. Such an approach can improve animal health, fertility, milk production, resource efficiency and environmental sustainability in Indian dairy systems.

INTRODUCTION:

Minerals and vitamins represent a small fraction of the ration by mass, yet they participate in skeletal development, osmotic regulation, enzyme function, antioxidant defense, immune responses, endocrine signaling, rumen microbial activity, reproduction and milk synthesis. The classical approach to supplementation has been to provide a generalized mineral mixture intended to cover likely requirements. This remains useful for preventing deficiency, but it can be inefficient when native mineral supply varies markedly among regions or when some minerals are already present in excess. NASEM (2021) and ICAR (2013) emphasize that mineral requirements depend on physiological stage, production level and dietary conditions; more recent analysis has highlighted the uncertainty of absorption coefficients and the possibility that conventional safety margins can result in unnecessary over-supplementation (NASEM, 2021; ICAR, 2013; Weiss and Hansen, 2024).

The Indian dairy sector presents an unusually strong case for region-specific mineral

nutrition. Cattle and buffaloes are maintained under diverse agro-climatic environments ranging from Himalayan and temperate systems to humid coastal regions, arid and semi-arid areas, and intensive irrigated plains. Feed resources range from cereal straws, stovers and tree leaves to cultivated green forages, crop by-products, oilseed cakes and commercial concentrates. The mineral content of these resources is influenced by soil parent material, soil pH, rainfall, crop species, fertilizer use, irrigation, maturity and processing. Consequently, the same nominal dairy diet formulation can deliver different absorbed mineral supplies in different locations.

Area-specific mineral mixture technology was developed in India precisely to address this heterogeneity. ICAR-NIANP reports that its Karnataka programme evaluated soil, water, feed and fodder and animal mineral status across ten agro-climatic zones, formulated mixtures around the most limiting minerals, field-tested the approach and subsequently commercialized the technology. The institute

notes that balanced provision of the most limiting minerals can avoid unnecessary supplementation of minerals already present in

adequate or excessive amounts (ICAR-NIANP, 2021; ICAR-NIANP, n.d.).

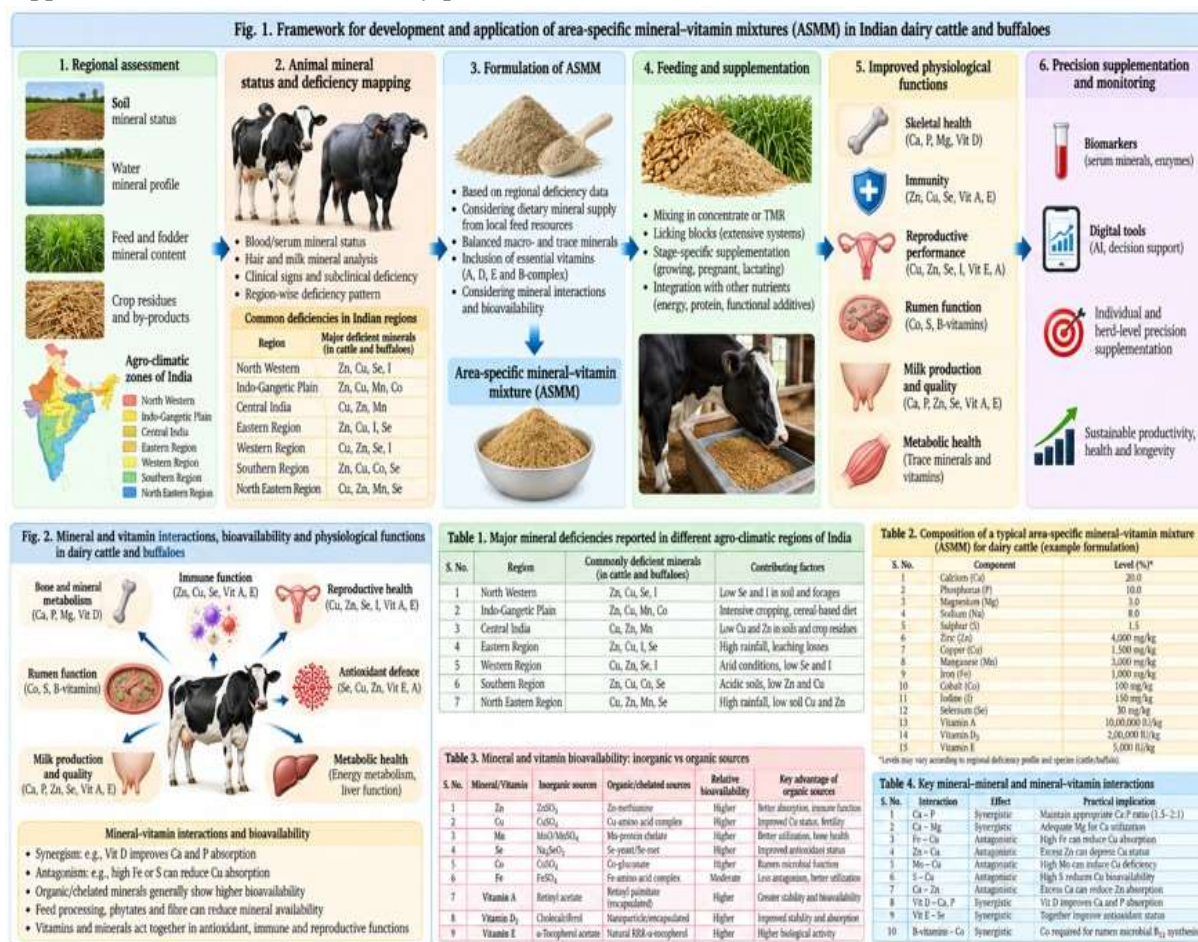


Figure 1. Conceptual framework for development and application of area-specific mineral-vitamin mixtures (ASMM) in Indian dairy cattle and buffaloes. Source/reference basis: ICAR-NIANP ASMM methodology; Bhandari *et al.* (2016); Weiss and Hansen (2024); NASEM (2021).

Figure 1 summarizes the central logic of the review: a regional assessment is followed by animal-status evaluation, formulation of a region- and stage-appropriate mixture, implementation under farm conditions, outcome monitoring and feedback to refine the formulation. This closed-loop view is important because an “area-specific” mixture should be treated as an evidence-based intervention rather than a permanently fixed recipe. The same district may contain different diets, production systems and seasonal feed supplies, and a mixture designed for one class of animals may not be optimal for another.

1. Why a Regional Approach Is Necessary in India

Regional variation begins before feed is offered to the animal. Soil mineral concentrations determine the pool from which plants acquire minerals, while water can contribute materially to some elements and affect total exposure. Plant uptake is further modified by pH, moisture regime, species, tissue type and maturity. The resulting mineral concentration in fodder can vary within short geographic distances. In addition, antagonists may reduce biological availability even when the laboratory concentration appears adequate.

Sulfur can interfere with copper and zinc utilization under some dietary conditions, high dietary iron can reduce copper availability, and high dietary molybdenum can precipitate with sulfur and copper to reduce copper status. These interactions make total concentration an imperfect proxy for absorbed supply (Suttle, 2010; Byrne and Murphy, 2022; Weiss and Hansen, 2024).

Indian field investigations demonstrate this heterogeneity. Bhanderi *et al.* (2016) reported that, in Jharkhand, feeds and forages were insufficient to support approximately 10 kg milk/day with respect to Ca, P, Mg, Cu, Zn

and Co; however, some resources were relatively rich in Fe and Mn, illustrating why a blanket mixture could supply unnecessary quantities of certain elements. A North-West Himalayan field study reported subclinical deficiencies of Cu, Zn, Fe and Mn in portions of the buffalo population and considerable variation in fodder mineral concentrations across locations and seasons. More recently, Akhter *et al.* (2026) reported low P, Mg, Cu and Zn in commonly offered fodders in parts of Kashmir and estimated plasma deficiencies of Ca, Cu, Mn and Zn in a large proportion of sampled dairy cattle.

Table 1. Indian evidence illustrating regional heterogeneity in mineral supply and animal status.

Source basis: ICAR-NIANP (n.d.); Bhanderi *et al.* (2016); Tiwari *et al.*; Burman *et al.* (2020); Devasena *et al.* (2025); Akhter *et al.* (2026); Faiz *et al.* (2026).

S. No.	Region/study	Animals/resources	Key finding	Implication for ASMM
1	Karnataka, ICAR-NIANP	Crossbred dairy animals; soil, water, feeds, blood	Most limiting minerals varied among agro-climatic zones; formulations were built around the most deficient minerals	Regional formulation can reduce unnecessary supplementation and antagonistic interactions
2	Jharkhand (Bhanderi <i>et al.</i> , 2016)	Dairy cows; feeds, forages, hair	Potential deficiencies of Ca, P, Mg, Cu, Zn and Co; high Fe in some resources	Formulation should use actual intake and mineral density of local feed resources
3	Nainital hills, Uttarakhand	Cattle and buffaloes	Ca, P, Zn, Mn and Cu were below critical levels in sampled soil/feeds/serum	Combined mineral mapping and field supplementation can target reproductive problems
4	Haryana, Palwal	Cows and buffaloes under farmer field conditions	Energy/protein supplies were also imbalanced; mineral mixture improved milk-related performance	Mineral correction should be integrated with whole-ration balancing
5	Chittoor, Andhra Pradesh (Devasena <i>et al.</i> , 2025)	Crossbred cattle with reproductive problems	ASMM containing Ca, P, Cu and Zn improved plasma minerals and reproductive hormones	Local deficiency diagnosis can guide reproductive nutrition
6	Pir Panjal, Kashmir (Akhter <i>et al.</i> , 2026)	201 dairy cattle; feedstuffs and plasma	Low P, Mg, Cu and Zn in fodders; high prevalence of plasma Ca, Cu, Mn and Zn deficiency	Area-specific mixtures remain relevant where feed supply is highly localized

S. No.	Region/study	Animals/resources	Key finding	Implication for ASMM
7	Meerut, Uttar Pradesh (Faiz <i>et al.</i> , 2026)	Periparturient buffaloes	Murrah ASMM at 50 g/day increased milk yield versus control and improved postpartum reproductive indicators	ASMM can be evaluated against standard mineral mixtures in controlled trials

Table 1 demonstrates that “mineral deficiency” is not a single national condition. Instead, the composition of the risk can shift from Ca/P-dominant deficiency in some cereal-residue-based systems to Zn/Cu/Mn problems in other regions. This argues for a diagnostic framework that combines feed intake, analytical mineral concentration and animal status before finalizing the mixture.

2. Regional Mineral Mapping: From Soil to Animal

A robust ASMM programme requires an explicit sampling chain. Soil should be characterized at representative production sites, drinking water should be included where relevant, and dominant feeds and fodders should be sampled in proportion to actual feeding practices rather than convenience. Animal assessment should use appropriate biomarkers and a clearly defined physiological population. For example, a dry pregnant cow and a high-yielding lactating cow may consume similar forages but have different requirements and different vulnerability to metabolic stress. Mineral mapping should therefore be stratified by agro-climatic zone, species or breed group, physiological stage

and feeding system wherever the sample size permits.

Laboratory analysis is another critical component. Macro-minerals are usually measured by validated wet-chemistry or spectrometric approaches, while trace-mineral assessment may require ICP-OES, ICP-MS or atomic absorption. Sampling and contamination control become particularly important at trace concentrations. A regional survey that measures total feed mineral concentration but ignores feed intake, source, stage of maturity and mineral antagonists may overestimate or underestimate actual supply. Byrne and Murphy (2022) emphasized that apparent relative bioavailability is affected by source and study design, while Weiss and Hansen (2024) noted that trace-mineral absorption coefficients are among the major uncertainties in current requirement systems.

Animal diagnostics should be interpreted as part of a matrix rather than as a single number. Plasma or serum concentrations can be useful for screening Ca, P, Mg, Cu and Zn, whereas liver stores may be more informative for certain elements such as Cu and Se.

Table 2. Suggested components of an Indian regional mineral-mapping and diagnostic programme. Source basis: Suttle (2010); NASEM (2021); Byrne and Murphy (2022); Weiss and Hansen (2024); Indian regional mineral surveys cited in Table 1.

S. No.	Region/study	Animals/resources	Key finding	Implication for ASMM
1	Karnataka, ICAR-NIANP	Crossbred dairy animals; soil, water, feeds, blood	Most limiting minerals varied among agro-climatic zones; formulations were built around the most deficient minerals	Regional formulation can reduce unnecessary supplementation and antagonistic interactions
2	Jharkhand	Dairy cows; feeds,	Potential deficiencies of	Formulation should use actual

	(Bhanderi <i>et al.</i> , 2016)	forages, hair	Ca, P, Mg, Cu, Zn and Co; high Fe in some resources	intake and mineral density of local feed resources
3	Nainital hills, Uttarakhand	Cattle and buffaloes	Ca, P, Zn, Mn and Cu were below critical levels in sampled soil/feeds/serum	Combined mineral mapping and field supplementation can target reproductive problems
4	Haryana, Palwal	Cows and buffaloes under farmer field conditions	Energy/protein supplies were also imbalanced; mineral mixture improved milk-related performance	Mineral correction should be integrated with whole-ration balancing
5	Chittoor, Andhra Pradesh (Devasena <i>et al.</i> , 2025)	Crossbred cattle with reproductive problems	ASMM containing Ca, P, Cu and Zn improved plasma minerals and reproductive hormones	Local deficiency diagnosis can guide reproductive nutrition
6	Pir Panjal, Kashmir (Akhter <i>et al.</i> , 2026)	201 dairy cattle; feedstuffs and plasma	Low P, Mg, Cu and Zn in fodders; high prevalence of plasma Ca, Cu, Mn and Zn deficiency	Area-specific mixtures remain relevant where feed supply is highly localized
7	Meerut, Uttar Pradesh (Faiz <i>et al.</i> , 2026)	Periparturient Murrah buffaloes	ASMM at 50 g/day increased milk yield versus control and improved postpartum reproductive indicators	ASMM can be evaluated against standard mineral mixtures in controlled trials

3. Macro-Minerals in Area-Specific Nutrition

Calcium and phosphorus are the most visible components of dairy mineral nutrition because of their central role in bone tissue, milk secretion and acid-base regulation. Their requirements are strongly influenced by milk yield, gestation and skeletal turnover. In Indian smallholder diets dominated by straw and limited concentrate, Ca and P deficits can occur simultaneously, but the balance between them is also important. The Ca:P ratio should be interpreted alongside dietary concentration, absorption and stage of production rather than used as an isolated formulation target. NASEM (2021) provides current dairy cattle requirement estimates, while ICAR (2013) remains an important Indian reference for cattle and buffalo feeding recommendations.

Magnesium is essential for neuromuscular function and carbohydrate metabolism and

becomes particularly important when high potassium forages, lush pasture or unusual feeding conditions reduce Mg absorption. Potassium and sodium have important roles in osmotic balance, acid-base regulation and feed intake. Under Indian heat-stress conditions, mineralized drinking water and electrolyte balance can become increasingly relevant, but blanket increases in sodium or potassium should be avoided where the basal diet *already* supplies large quantities. Sulfur is required for microbial protein synthesis and sulfur amino acid metabolism, yet excessive sulfur can disrupt trace-mineral utilization and can increase hydrogen sulfide production in the rumen under certain conditions. Thus, the macro-mineral component of an ASMM should be formulated as part of the whole ration rather than as a fixed premix.

Table 3. Major macro-minerals and practical indicators for Indian dairy cattle and buffaloes.

Source basis: NASEM (2021); ICAR (2013); Suttle (2010).

S. No.	Mineral	Principal functions	When deficiency risk increases	Practical assessment
1	Calcium	Bone, neuromuscular function, milk secretion	High milk yield, late gestation, low-Ca roughage diets	Dietary Ca; serum Ca interpreted with stage and clinical context
2	Phosphorus	Bone, ATP, cell membranes, reproductive and energy metabolism	Cereal-straw diets, low-P forages, inadequate concentrate/mineral sources	Dietary P; serum P; Ca:P ratio as a contextual indicator
3	Magnesium	Enzyme activation, neuromuscular and glucose metabolism	High-K diets, lush forage, low-Mg roughages	Dietary Mg; serum Mg when clinically relevant
4	Sodium	Extracellular osmotic balance, nerve and nutrient transport	Low-salt diets, heavy sweating/heat stress	Dietary Na; water intake and total electrolyte supply
5	Potassium	Intracellular osmotic balance and acid-base regulation	Low-K diets more uncommon; requirements rise with some heat-stress situations	Dietary K; water intake and diet balance
6	Sulfur	Microbial protein and sulfur amino acid synthesis	Low-protein/low-sulfur diets or highly unusual forage profiles	Dietary S plus consideration of S antagonism
7	Chloride	Acid-base and gastric HCl formation	Unbalanced electrolyte diets	Dietary Cl and dietary electrolyte balance

4. Trace Minerals: Beyond Total Dietary Concentration

Trace minerals are required in very small amounts but their functional reach is large. Zinc contributes to hundreds of zinc-dependent proteins, epidermal integrity, immunity and reproductive physiology. Copper is required for oxidative enzymes, connective tissue formation, iron metabolism and immune function. Manganese contributes to cartilage and bone formation, glycosyltransferase activity and reproductive processes. Selenium supports selenoproteins involved in antioxidant defense and thyroid hormone metabolism. Iodine is required for thyroid hormone production, cobalt is necessary for rumen microbial vitamin B12 synthesis, and iron participates in oxygen transport and numerous enzymatic reactions. Chromium is not usually treated as a conventional essential mineral requirement in the same way as Zn or Cu, but it has been

investigated for stress and metabolic effects in dairy cattle (NASEM, 2021; Suttle, 2010).

A key problem in trace-mineral nutrition is that total intake does not equal absorbed intake. Mineral source, solubility, rumen chemistry, intestinal transport, antagonists and the animal's current mineral status can all change the response. Byrne and Murphy (2022) reviewed evidence that organic and inorganic forms can differ in relative bioavailability, while Weiss and Hansen (2024) emphasized that uncertainties in absorption coefficients are large enough to affect requirement calculations. Therefore, an ASMM that correctly identifies a regional deficiency can still underperform if the selected chemical form is poorly absorbed under the specific diet.

4.1 Zinc

Zinc is closely associated with epithelial integrity, hoof health, immune competence,

antioxidant enzymes and reproductive function. Cereal straws and some mature roughages can supply relatively little bioavailable Zn. However, high dietary phytate, fiber and certain mineral interactions can reduce utilization. Organic Zn sources, including zinc amino-acid complexes and other organically bound forms, have therefore attracted interest when a basal diet contains multiple antagonists. Indian work in Sahiwal cows found that chelated mineral supplementation altered Ca utilization and antioxidant status, although the study did not demonstrate a milk-yield response, illustrating that biochemical improvement does not invariably translate into a production effect (Tyagi, 2021).

4.2 Copper

Copper is required for ceruloplasmin, lysyl oxidase and antioxidant enzymes and has recognized interactions with iron, sulfur and molybdenum. In some Indian feed systems, Cu deficiency is reported in specific fodders or animal groups, while Fe may be abundant. Because Cu absorption can be depressed by Fe, S and Mo, a diet containing an apparently adequate Cu concentration may still support marginal status. The practical implication is that ASMM formulation should consider antagonists, not simply the concentration of Cu in the feed. Excess Cu also deserves attention because cattle have a relatively narrow safety margin compared with some other species (Suttle, 2010; Weiss and Hansen, 2024).

4.3 Manganese, Selenium, Iodine, Cobalt and Iron

Manganese supports skeletal integrity and reproductive processes, but status markers are relatively weak compared with Cu or Se. Selenium is central to glutathione peroxidase and other selenoproteins and is particularly relevant during periods of oxidative challenge.

Iodine affects thyroid hormone synthesis and therefore basal metabolic rate, growth and reproductive physiology. Cobalt is important mainly through rumen microbial synthesis of vitamin B12, making cobalt supply a microbiome-linked nutrient. Iron is essential but often more abundant than other trace minerals in Indian feeds; indiscriminate iron addition can interfere with the utilization of Cu, Zn and other minerals. A well-designed ASMM therefore avoids the “more is better” assumption.

Table 4. Trace minerals in dairy cattle and buffaloes: functions, antagonists and diagnostic priorities. *Chromium is included here as a research-oriented trace element rather than a universally established dietary requirement for dairy cattle. Source basis: Suttle (2010); NASEM (2021); Byrne and Murphy (2022); Weiss and Hansen (2024).

S. No	Trace mineral	Key biological roles	Major antagonists / constraints	Useful diagnostic considerations
1	Zn	Enzyme function, skin /hoof integrity, immunity, reproduction	Phytate, high Fe/Ca interactions, fiber effects	Plasma/serum Zn with clinical and dietary context
2	Cu	Antioxidant enzymes, iron metabolism, connective tissue, immunity	S, Mo, Fe	Liver Cu where feasible; plasma Cu/ceruloplasmin
3	Mn	Bone/cartilage, enzyme activation, reproduction	High Fe and other dietary interactions may modify use	Diet + reproductive/orthopedic outcomes; status markers less sensitive
4	Se	Selenoproteins, glutathione peroxidase, redox and immune function	Excess Fe/S interactions can affect availability; narrow safety margin	Whole blood/serum Se and glutathione peroxidase activity
5	I	Thyroid hormones, metabolism, fetal development	Goitrogenic compounds and variable water/feed iodine	Dietary I and serum/thyroid-related indicators when indicated
6	Co	Rumen microbial vitamin B12 synthesis	Low supply of Co in some feeds; vitamin B12 synthesis depends on rumen function	Dietary Co; rumen vitamin B12-related indicators
7	Fe	Hemoglobin, oxygen transport, enzymes	High Fe can reduce Cu/Zn use	Serum Fe, ferritin and dietary Fe context

S. No	Trace mineral	Key biological roles	Major antagonists / constraints	Useful diagnostic considerations
8	Cr*	Investigated for glucose and stress-related responses	Response depends on physiological stress and source	Research/response variable rather than routine deficiency test

5. Vitamins in Indian Dairy Mineral–Vitamin Mixtures

Vitamins are distinct from minerals in chemical nature and dietary fate, but the practical feeding programme often combines them because their physiological functions overlap. Vitamin A supports epithelial integrity, immunity and reproduction; vitamin D is central to Ca and P homeostasis; and vitamin E is a major lipid-soluble antioxidant that works closely with selenium-dependent antioxidant systems. Beta-carotene status and B-group vitamins can also be relevant, particularly where high-quality green forage is limited or animals experience stress, though the interpretation depends on diet and production system.

In India, vitamin inclusion should be considered in relation to the feed calendar. Fresh green forages can supply carotenoids and vitamin precursors, whereas prolonged storage, drought, heat exposure and low-quality roughage feeding can reduce effective vitamin supply. Vitamin D is influenced by sunlight exposure and animal housing, so a fixed supplement may have different marginal value in housed and grazing systems. Vitamin E requirements may increase when oxidative stress is elevated, particularly around calving or during heat stress. A meta-analysis of 36 papers comprising 53 trials found that vitamin E supplementation increased serum vitamin E around parturition and reduced days open and services per conception, while the milk-yield response was heterogeneous; the authors also noted interactions with selenium, parity and breed (Moghimi-Kandelousi *et al.*, 2020).

Indian evidence also supports integrated micronutrient approaches. Jyani *et al.* (2021) evaluated periodic supplementation of Zn, Cu, Co, Cr, Se, vitamins E and A, and niacin in peri-parturient Murrah buffaloes, focusing on reproductive responses. A 2025 Indian study in Jersey cows reported that combined prepartum vitamin E and selenium supplementation reduced the time to placental expulsion and the proportion of retained placenta, while not changing calf growth or milk yield significantly. These findings suggest that vitamin–mineral combinations may have their strongest effects on resilience and reproductive health rather than necessarily on immediate milk volume.

Table 5. Vitamins and vitamin–mineral interactions relevant to Indian dairy systems. Source basis: NASEM (2021); ICAR (2013); Jyani *et al.* (2021); Indian 2025 vitamin E–Se field study; Suttle (2010).

S. No	Vitamin/ component	Primary role	Important mineral interaction	Indian feeding relevance
1	Vitamin A / beta-carotene	Vision, epithelial integrity, immunity, reproduction	Works with Zn and other antioxidant systems; beta-carotene responds to forage quality	Fresh greens may supply precursors; drought/storage can lower supply
2	Vitamin D	Ca and P homeostasis, skeletal health	Strongly linked with Ca and P absorption and endocrine regulation	Sunlight exposure and housing affect marginal value of supplementation
3	Vitamin E	Lipid antioxidant, cell-membrane protection, immunity	Works closely with Se-dependent glutathione peroxidase system	Important around calving, disease challenge and heat stress
4	Niacin (B3)	Energy metabolism; studied in heat and transition management	Interacts indirectly with energy metabolism and redox balance	Used selectively; response depends on dose and physiological stress
5	Vitamin B12-related supply	Propionate metabolism and one-carbon pathways via rumen microbial synthesis	Dependent on adequate cobalt for rumen microbial synthesis	Cobalt supply and rumen function matter in low-quality diets
6	B-complex vitamins	Microbial synthesis	Specific dependencies	Supplementation should be targeted

S. No	Vitamin/component	Primary role	Important mineral interaction	Indian feeding relevance
		usually contributes substantially in adult ruminants	include cobalt-B12 and folate-related pathways	rather than assumed necessary in all diets

6. Bioavailability: The Missing Link in Mineral Mixture Formulation

Bioavailability refers to the fraction of a supplied nutrient that becomes available for physiological use. In practical mineral nutrition, bioavailability is shaped by source chemistry, solubility, interactions in the gastrointestinal tract, microbial transformations, absorptive pathways and the animal's mineral status. Consequently, two mineral mixtures with the same declared percentage of Zn, Cu or Se may not deliver identical biological outcomes. This is one of the strongest arguments for moving from concentration-based to supply-and-response-based ASMM formulation.

Inorganic sulfates, oxides and chlorides are common because of cost and manufacturing practicality. Organic or organically complexed minerals include amino-acid complexes, proteinates, chelates and yeast-associated forms. Byrne and Murphy (2022) concluded that relative bioavailability varies among mineral forms and that interpretation should consider study design and response criteria. In Indian field studies, chelated mineral mixtures have produced mixed but informative results: Kantwa *et al.* reported increased milk yield and favorable reproductive responses in lactating buffaloes, whereas Tyagi (2021) found improved Ca/protein utilization and antioxidant-related changes in Sahiwal cows without a milk-yield effect. These differences reinforce the point that source effects cannot be separated from basal diet, animal status, dose, stage of lactation and experimental design.

Table 6. Practical comparison of common mineral-source categories for ASMM design.
Source basis: Byrne and Murphy (2022); NASEM (2021); Kantwa *et al.* (2021); Tyagi (2021).

S. No	Source category	Examples	Potential advantages	Limitations/considerations
1	Inorganic salts	Sulfates, carbonates, chlorides	Cost-effective, predictable mineral concentration, easy premix manufacture	Bioavailability can vary; greater exposure to dietary antagonists
2	Oxides	ZnO, CuO, MgO	Widely available and sometimes useful where high concentration is desired	Some forms may be poorly soluble or less bioavailable than salts/organic sources
3	Amino-acid complexes / chelates	Zn-amino acid, Cu-amino acid, etc.	Potential protection from antagonists and improved absorption	Higher cost; product-specific evidence is needed
4	Proteinates / yeast-associated forms	Mineral bound to peptides or yeast fractions	May provide alternative absorption pathways	Composition and relative bioavailability can vary among products
5	Hydroxy specialty sources	Hydroxy trace minerals and other structured forms	Potential stability and targeted release characteristics	Response depends on diet and product; independent validation required
6	Organic selenium	Selenomethionine / selenized yeast	Can support tissue and milk Se deposition	Total Se dose must be controlled because Se has a narrow safety margin

7. Mineral–Mineral and Vitamin–Mineral Interactions

The central practical challenge in mineral supplementation is that the nutrients do not act independently. Ca and P have linked absorption and skeletal functions; sulfur, molybdenum and copper form a well-known antagonistic network in ruminants; iron can interfere with copper utilization; and high levels of some dietary components can reduce Zn availability. Vitamin D supports Ca and P absorption, while vitamin E and selenium operate through complementary antioxidant systems. These relationships explain why a complete mineral–vitamin mixture must be

balanced, not simply assembled by adding individual nutrients to a carrier.

Interaction also creates the risk of secondary deficiency caused by inappropriate supplementation. If a producer increases one mineral because a laboratory report identified a deficiency but fails to account for its antagonists, the expected response may not occur. Conversely, adding all minerals at high levels “for safety” can increase feed cost and mineral excretion. Weiss and Hansen (2024) specifically identified mineral antagonism and uncertainty in absorption as reasons why many practical diets are formulated above calculated requirements. For Indian ASMM, the formulation objective should therefore be to minimize total mineral imbalance, not simply to maximize the concentration of named deficient nutrients.

Table 7. Important mineral–mineral and vitamin–mineral interactions to consider during ASMM formulation. Source basis: Suttle (2010); NASEM (2021); Weiss and Hansen (2024); Ding et al. (2025).

S. No.	Interaction	Type	Biological consequence	Formulation implication
1	Ca–P	Synergistic but balance-dependent	Bone mineralization, milk secretion and endocrine regulation	Formulate as a balanced pair rather than maximizing one nutrient
2	Cu–Mo–S	Antagonistic network	Reduced Cu absorption and status	Consider dietary Mo and S before increasing Cu dose
3	Fe–Cu	Often antagonistic	High Fe can depress Cu utilization	Avoid unnecessary Fe supplementation when basal Fe is high
4	Fe–Zn	Potential competition	May alter trace-mineral absorption	Evaluate whole-diet trace-mineral profile
5	S–Se/Zn/Mn	Diet-dependent antagonism	High S may alter trace-mineral use	Include sulfur concentration in high-by-product diets
6	Vitamin D–Ca/P	Synergistic	Facilitates mineral homeostasis	Coordinate vitamin D with Ca/P supply and

S. No.	Interaction	Type	Biological consequence	Formulation implication
			and absorption	sunlight exposure
7	Vitamin E–Se	Complementary antioxidant	Membrane protection and glutathione-peroxidase activity	Consider joint adequacy during transition and heat stress
8	Vitamin A/Zn	Functional interaction	Epithelial integrity, immunity and reproduction	Avoid isolated supplementation when the diet has multiple deficiencies

8. Area-Specific Mineral–Vitamin Mixtures: Formulation Principles

An ASMM should begin with the “dietary gap”, defined as the difference between the animal’s estimated mineral and vitamin requirement and the amount supplied in the actual ration at the relevant stage of production. The formulation should then incorporate bioavailability, antagonists, safety margins, physical form, palatability, stability, mixing uniformity and expected intake. In smallholder systems, the final product also needs a realistic delivery route: top-dressing concentrate, incorporation into total mixed ration, mineral lick, loose mineral mixture or a carrier feed. Dose and adherence matter because a theoretically perfect formula has little value if animals consume it inconsistently.

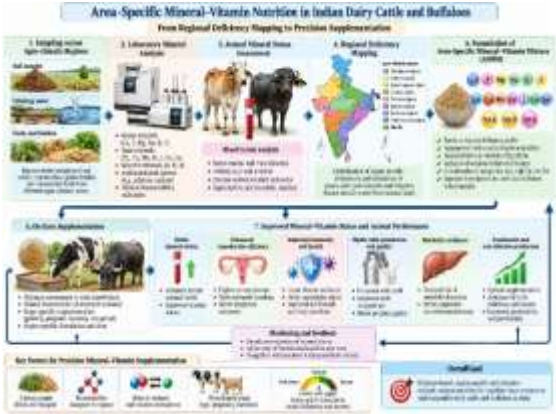


Figure 2. Area-specific mineral–vitamin nutrition as a precision-feeding cycle: regional diagnosis, formulation, on-farm delivery, monitoring and feedback. Source/reference basis: ICAR-NIANP ASMM technology; Bhandari et al. (2016); Devasena et al. (2025); Akhter et al. (2026); Faiz et al. (2026); Weiss and Hansen (2024).

Figure 2 emphasizes the move from a “mineral mixture as a product” to a “mineral–vitamin programme as a decision system.” The programme should use regional feed data, animal biomarkers, physiological stage and farm records, then return to monitoring after supplementation. This allows the recipe to be revised when fodder sources change, a new concentrate is introduced, or production stage moves from late gestation to early lactation.

ICAR-NIANP’s Karnataka technology demonstrates the feasibility of this approach. The institute reports that mixtures were formulated around the most limiting minerals identified in ten agro-climatic zones, while reducing or excluding minerals already present in adequate or excessive quantities. Older field experience from Karnataka suggested substantial reproductive improvement and modest milk-yield improvement, and the technology was commercialized through multiple partners. More recently, Faiz *et al.* (2026) provided controlled evidence in Murrah buffaloes that an ASMM at 50 g/day increased average milk yield from 6.14 to 7.20 kg/day relative to the unsupplemented group and was associated with faster postpartum reproductive recovery, although the small sample size means the findings should be interpreted as supportive rather than universal.

Table 8. A stepwise formulation pathway for an Indian area-specific mineral–vitamin mixture.

Source basis: ICAR-NIANP (n.d.); NASEM (2021); Weiss and Hansen (2024); Indian ASMM field studies.

S. No.	Decision	Information required	Expected output
1	Define target animal	Species/breed, body weight, parity, milk yield, pregnancy/lactation stage	Stage-specific target group
2	Quantify dietary supply	Actual feed intake and mineral/vitamin composition	Baseline nutrient supply
3	Identify	Compare supply	Deficiency

S. No.	Decision	Information required	Expected output
	limiting nutrients	with requirements and functional markers	or marginality profile
4	Assess antagonists and source	S, Mo, Fe, phytate, oxalate, high K and mineral form	Adjusted estimate of usable supply
5	Select mineral/vitamin sources	Inorganic vs organic; stability and compatibility	Source-specific ingredient list
6	Set inclusion rate	Requirement gap + appropriate safety margin	Daily dose and formulation concentration
7	Choose delivery route	TMR, concentrate, lick or carrier feed	Practical farm delivery plan
8	Monitor response	Serum/whole-blood status, milk, fertility, disease and intake	Evidence of efficacy or need for adjustment
9	Reformulate	Use seasonal and herd-level feedback	Dynamic ASMM programme

9. ASMM, Reproductive Health and Production

Mineral and vitamin deficiencies can impair reproductive performance through effects on ovarian function, steroidogenesis, antioxidant defense, uterine involution, embryo survival and immune competence. In field conditions, however, reproductive disorders are multifactorial and must not automatically be attributed to mineral deficiency. This distinction is important when interpreting ASMM trials. The strongest evidence comes when a regional deficiency is demonstrated, the mixture specifically addresses it and improvement is accompanied by changes in animal mineral status or functional biomarkers.

Indian field studies offer several examples. Tiwari *et al.* reported that Ca, P, Zn, Mn and Cu were low in soil, feeds and blood in parts

of the Nainital hills and that ASMM supplementation reduced anoestrus and repeat-breeding problems. Devasena *et al.* (2025) studied 40 crossbred cattle with reproductive disorders in Chittoor and used an ASMM containing Ca, P, Cu and Zn. Plasma Ca, P, Cu and Zn improved in relevant groups, estrogen and progesterone increased, and approximately 62.5% of animals were considered responders. These results support the chain of evidence from deficiency diagnosis to supplementation to physiological response.

Production responses can also occur, but they are not always large or consistent. Burman *et al.* (2020) found that mineral supplementation in Haryana field conditions improved milk yield and fat/protein responses in early-lactation cattle and buffaloes, after first correcting broader ration imbalances. In Bihar, field mineral feeding was associated with increases in average milk yield and milk fat/SNF and higher net returns. Conversely, Tyagi (2021) observed no milk-yield response to inorganic or chelated mixtures in Sahiwal cows despite some changes in Ca utilization and antioxidant status. The lesson is that ASMM is most likely to generate a visible production response when a genuine limiting deficiency exists and the rest of the ration is reasonably adequate.

Table 9. Indian intervention evidence relevant to area-specific mineral–vitamin supplementation. Source basis: Indian Journal of Animal Sciences/Indian Journal of Animal Nutrition reports cited above; individual references listed below.

S. No.	Study	Species/system	Intervention	Major reported response
1	Tiwari <i>et al.</i>	Cattle and buffaloes, Nainital hills	ASMM correcting Ca, P, Zn, Mn and Cu deficiencies	Lower anoestrus/repeat breeding; improved mineral status
2	Burman <i>et al.</i> (2020)	Field cattle and buffaloes,	Mineral mixture after ration	Milk yield and milk-fat/protein responses

S. No.	Study	Species/system	Intervention	Major reported response
		Haryana	reappropriation	improved; broad nutrient imbalances were also corrected
3	Tyagi (2021)	Lactating Sahiwal cows	Inorganic vs chelated mineral mixture	Similar DMI/BW; higher CP digestibility; Ca and total antioxidant status changed; milk yield unchanged
4	Jyani <i>et al.</i> (2021)	Peri-parturient Murrah buffaloes	Zn, Cu, Co, Cr, Se, vitamins E/A and niacin	Reproductive outcomes and follicular dynamics evaluated under periodic micronutrient supplementation
5	Jadoun <i>et al.</i> (2024)	Buffaloes under Farmer FIRST	Mineral mixture under field conditions	Productive and reproductive responses assessed in an Indian farmer-participatory programme
6	Devasena <i>et al.</i> (2025)	Crossbred cattle with reproductive disorders, Chittoor	ASMM with Ca, P, Cu and Zn at 40 g/day	Improved plasma minerals and reproductive hormone profile; ~62.5% responders
7	Faiz <i>et al.</i> (2026)	Periparturient Murrah buffaloes	ASMM 50 g/day vs control and BIS mixture	Higher milk yield vs control and earlier postpartum reproductive recovery

10. Mineral–Vitamin Nutrition for Immunity and Oxidative Stress

The immune system is highly dependent on adequate micronutrient supply because immune cells have high rates of proliferation, membrane remodeling, redox signaling and enzyme activity during challenge. Zinc and copper support antioxidant enzymes and cellular signaling; selenium is incorporated into selenoproteins; vitamin E protects membrane lipids; vitamin A contributes to epithelial and immune function. Around calving, oxidative stress and inflammation rise

while dry matter intake can fall, making micronutrient status particularly important. However, the response to supplementation is often non-linear and depends on baseline status.

The vitamin E–selenium combination illustrates this complexity. A 2025 study in transition dairy cows reported improved antioxidant biomarkers, lower inflammatory markers and lower incidence of several diseases with combined vitamin E and selenium supplementation, although the intervention used relatively high experimental doses and the study was outside India. Indian work in buffaloes has also shown responses of udder health, reproductive performance and antioxidant status to strategic antioxidant micronutrient supplementation. These results support the use of antioxidant status as an outcome in future ASMM studies rather than relying only on milk yield.

The concept is important for Indian smallholder systems because health losses during the transition period can be economically larger than modest changes in daily milk volume. An ASMM programme could therefore be evaluated against a broader set of endpoints: retained placenta, metritis, subclinical mastitis indicators, BCS recovery, time to first estrus, services per conception, and biomarkers such as glutathione peroxidase and total antioxidant capacity. Such endpoints may detect benefits that a short production trial would miss.

11. Mineral Nutrition under Heat Stress and Environmental Variability

Heat stress changes feed intake, water consumption, sweating, respiration, blood flow distribution and endocrine status. Lower dry matter intake can reduce mineral and vitamin intake even when dietary concentration remains unchanged. Oxidative stress may also increase, altering the functional demand for

antioxidant nutrients. Heat stress therefore provides a strong rationale for stage- and season-sensitive mineral–vitamin supplementation. Yet the intervention should be based on the whole diet and water supply because electrolytes may already be abundant in some diets.

Indian dairy systems often face seasonal heat load together with variable forage availability. The resulting interaction can be viewed as a “double constraint”: the animal requires nutrient-dense feed precisely when forage intake and quality may deteriorate. A precision ASMM approach can address this by increasing the emphasis on limiting minerals and antioxidant vitamins only where a deficiency or elevated risk is demonstrated. The 2024 Weiss and Hansen review also identified stress-state responses as an area requiring better mineral requirement research, indicating that the standard maintenance/production framework may not fully capture the biology of heat-stressed cattle.

12. Precision Supplementation: From Static ASMM to Dynamic Micronutrient Management

Precision nutrition does not require expensive automation in every dairy farm. At its simplest, precision supplementation means using better information to avoid both under- and over-supplementation. A practical Indian workflow could integrate feed analysis, ration balancing, animal stage, milk yield, season and a small set of biomarkers. Digital records can then identify animals or herds that are persistently below target status and can trigger re-evaluation of the mineral mixture or feeding method.

More advanced systems can combine portable mineral analysis, GIS-based mapping, NIR screening of feed composition, electronic milk recording and machine learning. The goal would be to estimate the probability of

deficiency or excess for each mineral rather than simply producing a single “mineral mixture” number. Such models could update recommendations when a farm changes from wheat straw to paddy straw, introduces a new commercial concentrate, enters the transition period, or experiences prolonged heat stress.

The key conceptual change is shown in Figure 2: formulation becomes iterative. Mineral status is measured before intervention, the mixture is delivered, responses are monitored and the formulation is adjusted. This is consistent with the 2024 call by Weiss and Hansen for better response models, more accurate absorption estimates and lower reliance on broad safety factors. For India, the same approach can be adapted to low-cost farmer conditions by using village-level feed sampling, pooled herd testing and seasonal reformulation rather than individual laboratory testing of every animal.

13. Risks of Excess Supplementation and Environmental Considerations

The principal argument for ASMM is not only to correct deficiency but also to avoid feeding minerals that are unnecessary. Zinc, copper, selenium, iodine and certain other trace minerals can cause toxicity when supplied excessively. More commonly, routine over-supplementation raises cost, increases manure mineral excretion and may create antagonistic interactions that reduce the utilization of other nutrients. Weiss and Hansen (2024) emphasized that broad safety factors can produce diets that substantially exceed established requirements, especially when absorption uncertainty is high.

Environmental stewardship strengthens the case for precision. Mineral elements are not degraded like organic nutrients; excess Zn, Cu and P are excreted and can accumulate in soils or enter water systems when manure is repeatedly applied. Thus, the environmental

objective of ASMM should be “adequate but not excessive”. This principle is particularly relevant to intensive dairy clusters where manure loading is spatially concentrated. Future Indian programmes should therefore evaluate nutrient-use efficiency and mineral excretion alongside productivity.

14. Research Gaps and Future Directions in India

Despite extensive Indian experience with mineral mixtures, several important gaps remain. First, national mineral maps are incomplete and often based on studies from different decades using different sampling designs and laboratory methods. Second, there are relatively few large, multi-state datasets that simultaneously capture soil, water, feed, animal status, diet intake and outcomes. Third, vitamin status is less consistently mapped than mineral status. Fourth, source-specific bioavailability data for Indian cattle and buffaloes are limited, particularly under typical crop-residue-based diets. Fifth, many intervention trials are small and short, making it difficult to separate true treatment effects from herd-level variation.

The next generation of research should use harmonized protocols and response-surface designs. Studies should compare not only “control vs mineral mixture” but also different mineral doses, source forms, antagonistic diet backgrounds and physiological stages. Larger herds should be followed longitudinally through the transition period and across seasons. Biomarker panels should be standardized for practical use. Multi-omics approaches, especially metabolomics and mineralomic profiling, could help identify early metabolic signatures of marginal deficiency before clinical signs develop.

For India, another research priority is to build regional decision-support systems. A digital ASMM platform could combine GIS layers of

soil and fodder mineral data with district-level feed calendars and laboratory-verified animal status. Machine-learning models could then predict the most likely limiting nutrients and suggest a candidate formulation, which is subsequently validated through a small field intervention. This would transform ASMM from a one-time regional product into a continuously updated nutritional technology.

Table 10. Priority research questions for next-generation area-specific mineral-vitamin nutrition in India. Source basis: Weiss and Hansen (2024); NASEM (2021); ICAR-NIANTP (n.d.); Indian ASMM studies summarized in this review.

S. No.	Research question	Suggested approach	Expected value
1	How stable are regional mineral-deficiency patterns across seasons?	Repeat soil/feed/animal surveys with standardized protocols	More reliable or annual or seasonal formulations
2	What is the true bioavailability of common mineral sources in Indian diets?	Controlled dose-response and absorption studies	More accurate formulation and lower safety margins
3	Which biomarkers best predict functional deficiency?	Compare serum, whole blood, liver, enzyme and performance markers	Earlier and more precise diagnosis
4	How do antagonists alter ASMM response?	Factorial studies with S, Mo, Fe, phytate and fiber levels	Diet-specific correction of apparent non-response
5	How should vitamins be integrated with ASMM?	Regional vitamin-status surveys and factorial interventions	Avoid unnecessary vitamin inclusion while protecting high-risk groups
6	Does precision ASMM improve farm economics?	Cluster-randomized farmer field trials with cost-benefit analysis	Evidence for scalable adoption
7	How much	Mineral balance	Environmental

S. No.	Research question	Suggested approach	Expected value
	mineral excretion can be reduced?	and manure analysis before/after precision feeding	and resource-efficiency gains
8	Can digital tools support reformulation?	GIS + feed databases + animal biomarkers + ML	Dynamic region- and animal-specific recommendations

CONCLUSIONS

Area-specific mineral-vitamin nutrition is particularly relevant to Indian dairy cattle and buffaloes because mineral supply is heterogeneous across agro-climatic regions and feed systems. The scientific basis is strongest when regional deficiency mapping is linked to actual dietary intake, animal status, physiological stage, antagonists and validated biological outcomes. Indian evidence from Karnataka, Jharkhand, Uttarakhand, Haryana, Andhra Pradesh, Punjab and Kashmir demonstrates that deficiencies can be highly localized and that targeted supplementation can improve reproductive, biochemical or productive responses when the underlying limitation is genuine.

The next stage of development should be a transition from fixed mineral mixtures to precision micronutrient programmes. Such programmes should distinguish deficiency from adequacy and excess, incorporate trace-mineral bioavailability, use vitamins strategically, recognize mineral-mineral interactions and monitor animal response. With increasing availability of laboratory diagnostics, digital farm records, GIS mapping and machine-learning tools, India has an opportunity to build dynamic ASMM systems that are region-specific, stage-specific and evidence-based. The ultimate objective is not simply to feed more minerals, but to deliver the right mineral and vitamin supply, in the

right source and amount, to the right animals at the right time.

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