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Alternative Sources of Livestock Nutrition for Indian Conditions: Availability, Safe Inclusion Levels, Anti-Nutritional Hazards, and Production Efficacy

Dr. Kirti Dadaram Fanase[1], Dr. Pranav Sunil Jadhav[2] Dr. Rajwardhan Chandrakant Nimbalkar[3*] Dr. Rajwardhan Chandrakant Nimbalkar[3]
[1]MVSc Veterinary Pathology, College of Veterinary Science & Animal Husbandry, Sardarkrushinagar.
[2]MVSc Animal Nutrition, Indian Veterinary Research Instituten Bareilly
[3]MVSc, Poultry Science, ICAR- Central Avian Research Institute, Izatnagar, Bareilly
Dr. Rajwardhan Chandrakant Nimbalkar e-mail: rajnimbalkar700@gmail.com
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Abstract

India supports the world's largest livestock population and ranks first globally in total milk production; however, per-animal productivity remains substantially below global averages due to chronic, nationwide deficits in green fodder, dry roughages, and concentrate feedstuffs. With cultivated fodder area stagnating at roughly 4% to 5% of total arable land due to intense food-feed competition, rapid urbanization, shrinking common property grazing lands, and escalating climate variability, transitioning toward alternative and unconventional feed resources (UFRs) has become an economic and ecological imperative (Amad and Zentek, 2023; Leitanthem et al., 2022; Pexas et al., 2023). Across India's diverse agro-ecological zones, a vast reservoir of underutilized nutritional resources is available, including aquatic pteridophytes (*Azolla pinnata*), multipurpose tree foliages (*Moringa oleifera*, *Azadirachta indica*, *Leucaena leucocephala*, and *Prosopis cineraria*), CAM-pathway drought-resilient succulents (spineless cactus, *Opuntia ficus-indica*), hydroponically sprouted grains, fruit and vegetable processing pomaces, distilleries grains (DDGS), and non-edible oilseed meals such as karanj (*Pongamia pinnata*), neem, and mahua (*Madhuca longifolia*) cakes (Chen et al., 2024; El-Zaiat et al., 2022; Hassanein et al., 2023; Ikusika et al., 2024; Pastorelli et al., 2022). While these alternative feedstuffs supply economical crude protein, bypass amino acids, fermentable energy, and bioactive phytonutrients that enhance antioxidant status and mitigate enteric methane (CH_4) emissions by 10% to 35% (Leitanthem et al., 2022; Soldado et al., 2021; Vastolo et al., 2025), their unregulated incorporation carries toxicological hazards arising from endogenous anti-nutritional factors (ANFs)—such as hydrolyzable and condensed tannins, saponins, mimosine, oxalates, azadirachtin, karanjin, and non-starch polysaccharides—as well as heavy metal bioaccumulation and mycotoxins (Gaviria-Uribe et al., 2022; Ikusika et al., 2024; Sundararaman et al., 2021). Processing interventions including solid-state fermentation (SSF), exogenous enzymatic-probiotic synergy, water washing, alkali/urea treatment, and ensiling effectively neutralize these ANFs, enabling safe dietary

inclusion levels of 5% to 40% across cattle, buffaloes, sheep, and goats without compromising dry matter intake or ruminal kinetics (Chen et al., 2024; Ikusika et al., 2024; Min et al., 2024).

Keywords: Agro-industrial by-products, Anti-nutritional factors, *Azolla pinnata*, Enteric methane mitigation, Hydroponic fodder, Indian livestock nutrition, *Moringa oleifera*, *Opuntia ficus-indica*, Solid-state fermentation, Unconventional feed resources.

1. Introduction

Livestock rearing forms the socioeconomic backbone of rural India, providing nutritional security, draught power, organic manure, and a vital buffer against crop failure for over 70 million smallholder and marginal farming households. Despite sustaining over 536 million livestock—including the world's largest populations of buffaloes and cattle and second-largest population of goats—the Indian livestock sector operates under a severe nutritional bottleneck. Feed and fodder alone account for 60% to 70% of the total recurring cost of dairy and small ruminant production (Hassanein et al., 2023; Ikusika et al., 2024; Pexas et al., 2023).

Traditionally, Indian ruminant feeding systems rely heavily on low-quality lignocellulosic crop residues, such as paddy straw, wheat straw, and sorghum/millet stovers, supplemented with scarce green forages and expensive conventional oilseed cakes, including groundnut cake, mustard cake, and soybean meal, as well as cereal grains (Amad and Zentek, 2023; Leitanthem et al., 2022). Because conventional protein and energy concentrates are increasingly diverted toward human consumption, poultry, and aquaculture—or exported—their market prices have escalated sharply, creating an acute cost-price squeeze for landless and marginal dairy producers (Pexas et al., 2023). Consequently, identifying, detoxifying, and integrating locally available alternative and unconventional feed resources (UFRs) into balanced rations, such as Total Mixed Rations and Complete Feed Blocks, is essential to bridge the nutrient gap, lower cost per kilogram of milk or meat produced, and curb the environmental footprint of Indian animal husbandry (Ikusika et al., 2024; Leitanthem et al., 2022; Vastolo et al., 2025).

2. Need for Alternative Resources in India

The urgency to adopt alternative nutritional sources under Indian conditions is driven by five converging structural and environmental pressures.

2.1 Chronic National Feed and Fodder Deficit

Assessments by premier national bodies, including the ICAR-Indian Grassland and Fodder Research Institute (IGFRI) and the National Dairy Development Board (NDDB), consistently highlight a massive gap between fodder demand and supply in India. Depending on seasonal

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monsoon performance and regional livestock density, India faces an estimated net deficit of 11.2% to 35.6% in green fodder, 11.0% to 23.4% in dry crop residues, and 28.0% to 44.0% in concentrate feed ingredients. This nutritional deficit directly limits the expression of genetic potential in crossbred cattle, indigenous milch breeds, and high-yielding riverine buffaloes (Leitanthem et al., 2022).

2.2 Stagnation of Arable Land Under Cultivated Forages

With India's human population exceeding 1.4 billion, arable land is overwhelmingly prioritized for food grains, pulses, oilseeds, and high-value cash crops. Consequently, the total cultivated area dedicated to fodder crops, such as berseem, lucerne, fodder sorghum, maize, and pearl millet, has remained stagnant at approximately 8.4 to 9.0 million hectares—less than 5% of gross cropped area—for over three decades, leaving virtually no scope for horizontal expansion of conventional forage cultivation (Amad and Zentek, 2023; Pastorelli et al., 2022).

2.3 Degradation of Common Property Grazing Resources (CPRs)

Historically, small ruminants, including sheep and goats, and dry cattle subsisted on village *gauchars* (pastures), forest fringes, and fallow lands. Rapid industrialization, infrastructure expansion, encroachment, and overgrazing beyond carrying capacity have progressively shrunk and degraded these grazing lands, forcing pastoralists and smallholder farmers to seek stall-fed alternative biomass (El-Zaiat et al., 2022; Gaviria-Uribe et al., 2022).

2.4 Climate Change, Recurrent Droughts, and Water Scarcity

Nearly two-thirds of India's agriculture is rainfed. Erratic monsoon patterns, prolonged summer heatwaves, with ambient temperatures reaching 42–48°C across northern and central India, and declining groundwater tables severely depress seasonal green fodder yields while inducing thermal stress that reduces voluntary feed intake by 8% to 15% and milk production by 10% to 25% (Leitanthem et al., 2022; Pastorelli et al., 2022). Water-intensive forages such as berseem (*Trifolium alexandrinum*) and lucerne (*Medicago sativa*) cannot be sustained in arid and semi-arid tracts during summer, necessitating drought-hardy, water-efficient alternatives such as spineless cactus (*Opuntia* spp.) and deep-rooted fodder trees (Amad and Zentek, 2023; Pastorelli et al., 2022).

2.5 Imperative for Enteric Methane Mitigation

Indian ruminants subsist predominantly on high-fiber, low-protein roughage diets that favor ruminal methanogenesis, resulting in an enteric loss of 6% to 12% of gross dietary energy as methane (CH_4) gas while contributing significantly to agricultural greenhouse gas emissions

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(Amad and Zentek, 2023; Gaviria-Uribe et al., 2022; Leitanthem et al., 2022). Alternative phytogenic feeds rich in secondary metabolites, such as condensed tannins, saponins, and polyphenols, offer a dual advantage of supplying digestible nutrients while naturally suppressing ruminal archaea and protozoa (Soldado et al., 2021; Vastolo et al., 2025).

Table 1. National Feed and Fodder Deficits in India and Target Alternative Nutritional Substitutes

Nutritional category	**Primary role in ration**	**Estimated national deficit (%)**	**Major structural bottlenecks in India**	**Target alternative substitutes**
Green fodder	Succulence, β-carotene, fermentable protein, and minerals	11.2–35.6	Less than 5% of arable land under forage; acute summer water scarcity; lack of quality forage seed	*Azolla pinnata*, *Moringa oleifera* foliage, spineless cactus (*Opuntia*), and hydroponic sprouts (Amad and Zentek, 2023; Hassanein et al., 2023; Min et al., 2024; Pastorelli et al., 2022)
Dry roughages	Bulk, rumen fill, and effective fiber (NDF/ADF) for rumination	11.0–23.4	Adoption of short-statured high-yielding cereal varieties; mechanical harvesting losses; in-situ stubble burning	Sugarcane bagasse/trash, areca leaf sheath, maize cobs, millet/sorghum stovers, and sunflower heads (Ikusika et al., 2024)
Concentrate feeds	Bypass protein, metabolizable energy, and essential amino acids	28.0–44.0	Diversion of soybean/maize to poultry, export markets, and biofuel industries; high market volatility	Dried Distillers Grains with Solubles (DDGS), detoxified karanj/neem/mahua cakes, and fruit/vegetable pomaces (Chen et al., 2024; El-Zaiat et al., 2022;

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				Ikusika et al., 2024; Vastolo et al., 2025)

3. Available Alternative Resources in the Indian Demographic

India's diverse agro-climatic zones—ranging from the arid Thar Desert of Rajasthan and semi-arid Deccan Plateau to the humid coastal belts and Indo-Gangetic plains—generate a wide spectrum of unconventional feed resources that can be categorized into six major groups.

3.1 Aquatic Pteridophytes and Algal Biomass (*Azolla* spp.)

Azolla pinnata and *Azolla filiculoides* are free-floating freshwater ferns that harbor a symbiotic nitrogen-fixing cyanobacterium, *Anabaena azollae*, within their dorsal leaf cavities (Hassanein et al., 2023; Rahman et al., 2023). Capable of doubling their biomass every 3 to 5 days in shallow backyard pits measuring 2 m × 1 m × 0.2 m and lined with silpaulin sheets, *Azolla* represents an ideal low-cost protein supplement for landless Indian dairy farmers (Hassanein et al., 2023). On a dry matter (DM) basis, *Azolla* contains 22% to 28% crude protein (CP), rich concentrations of essential amino acids, particularly lysine and arginine, 13% to 16% crude fiber, carotenoids, biopolymers, and bioavailable macro- and micro-minerals, including calcium, phosphorus, iron, and magnesium (Hassanein et al., 2023; Rahman et al., 2023).

3.2 Multipurpose Tree Foliages and Top Feeds ("Fodder Trees")

During the lean summer months, particularly March to June, when herbaceous pastures desiccate, deep-rooted perennial trees serve as climate-resilient "living fodder banks" across India.

- **Drumstick tree (*Moringa oleifera*):** Native to the sub-Himalayan tracts and cultivated nationwide across tropical and subtropical India under temperatures of 20–40°C, *Moringa oleifera* yields 43 to 115 tonnes of green biomass per hectare annually across multiple cuts (Amad and Zentek, 2023; Leitanthem et al., 2022). Its leaves contain 23% to 30% CP on a DM basis, with high ruminal bypass protein value, negligible trypsin inhibitors, abundant vitamin C, α-tocopherol, and bioactive flavonoids, including quercetin and kaempferol (Amad and Zentek, 2023; Leitanthem et al., 2022).
- **Neem (*Azadirachta indica*):** Ubiquitous across arid, semi-arid, and central India, neem foliage contains 13% to 18% CP and is rich in anthocyanins, triterpenoids, and condensed tannins that modulate ruminal fermentation and exert natural anthelmintic effects against gastrointestinal nematodes in sheep, goats, and cattle (El-Zaiat et al., 2022; Taethaisong et al., 2022).

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- **Subabul (*Leucaena leucocephala* and *L. diversifolia*):** Widely promoted under social forestry and silvipastoral systems in Maharashtra, Andhra Pradesh, Karnataka, and Central India, *Leucaena* foliage provides 22% to 26% CP, high palatability, and condensed tannins that protect dietary protein from excessive ruminal deamination (Gaviria-Uribe et al., 2022).
- **Khejri (*Prosopis cineraria*), Ardu (*Ailanthus excelsa*), and Mulberry (*Morus alba*):** In the arid zones of Rajasthan and Gujarat, *Prosopis cineraria* ("Loong") and *Ziziphus nummularia* ("Pala") leaves sustain small ruminants and camels year-round, while mulberry foliage waste from sericulture belts in Karnataka, Tamil Nadu, and West Bengal offers highly digestible protein, approximately 18–22% CP, for dairy cattle.

3.3 Drought-Resilient CAM Succulents: Spineless Cactus (*Opuntia ficus-indica*)

In water-scarce regions of Rajasthan, Gujarat, Bundelkhand in Uttar Pradesh and Madhya Pradesh, and rain-shadow Maharashtra, spineless prickly pear cactus (*Opuntia ficus-indica*) is a transformative alternative fodder (Pastorelli et al., 2022). Utilizing the Crassulacean Acid Metabolism (CAM) photosynthetic pathway, *Opuntia* opens its stomata predominantly at night, achieving a water-use efficiency 3 to 8 times higher than C_3 and C_4 crops such as lucerne or maize (Pastorelli et al., 2022). It yields over 20 tonnes of DM per hectare annually while supplying roughly 180 tonnes/ha/year of biological water stored within its succulent cladodes, which contain 85–90% moisture, drastically reducing the drinking water requirement of sheep, goats, and cattle during summer droughts (Pastorelli et al., 2022). Nutritionally, cladodes are rich in soluble carbohydrates, with 55–65% nitrogen-free extract, pectin, mucilage, β-carotene, and calcium, although they are low in crude protein (4–8% CP) and neutral detergent fiber (NDF). Consequently, they require co-feeding with dry straws and protein supplements (Pastorelli et al., 2022).

3.4 Hydroponic Green Fodder Sprouts

For peri-urban commercial dairies and land-constrained farmers in Maharashtra, Punjab, Gujarat, and southern India, hydroponic fodder production enables vertical, soil-less cultivation of sprouted maize, wheat, barley, or oats inside temperature- and humidity-controlled chambers within 7 to 8 days (Min et al., 2024; Pexas et al., 2023). Hydroponic sprouting consumes only 2% to 5% of the water required for conventional field irrigation, eliminates weed and soil-borne pesticide contamination, and converts seed starch into simple sugars, free amino acids, active hydrolytic enzymes, and antioxidant vitamins (Min et al., 2024; Pexas et al., 2023).

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3.5 Agro-Industrial, Fruit/Vegetable, and Distillery By-Products

India is the world's second-largest producer of fruits and vegetables and supports a rapidly expanding grain-based ethanol and food-processing sector, generating millions of tonnes of nutrient-dense organic residues annually (Chen et al., 2024; Ikusika et al., 2024; Vastolo et al., 2025).

- **Dried Distillers Grains with Solubles (DDGS):** With India accelerating grain-based ethanol blending using broken rice and maize, rice- and corn-based DDGS have emerged as major protein-energy concentrates containing 30% to 45% CP, with over 50% rumen undegradable protein (RUP), or "bypass" protein, and high digestible energy (Chen et al., 2024).
- **Fruit and Vegetable Processing Pomaces:** Citrus pulp, tomato pomace, mango peels and seed kernels, apple pomace from Himachal Pradesh and Jammu and Kashmir, banana pseudostems, pineapple waste, and pomegranate peels contain 8% to 16% CP, high pectin, soluble fiber, and potent polyphenolic antioxidants (Ikusika et al., 2024; Vastolo et al., 2025).
- **Unconventional Forest and Non-Edible Oilseed Cakes:** India possesses vast forest and plantation resources of non-edible oilseeds, including karanj (*Pongamia pinnata*), neem (*Azadirachta indica*), mahua (*Madhuca longifolia*), castor (*Ricinus communis*), and sal (*Shorea robusta*) seed meals. Solvent-extracted karanj and neem cakes contain 28% to 38% CP comparable to conventional oilcakes, representing a potentially valuable protein source once appropriately detoxified.

4. Benefits and Hazards Related to Their Use

Integrating alternative feed resources into Indian livestock diets requires balancing their nutritional and environmental benefits against intrinsic toxicological and metabolic hazards.

4.1 Key Nutritional, Economic, and Environmental Benefits

1. **Feed Cost Reduction (15% to 30%):** Replacing expensive soybean meal, groundnut cake, or cultivated green maize with farm-grown *Azolla*, *Moringa*, crop by-products, or solid-state fermented fruit pomaces substantially lowers daily ration costs and improves the benefit-cost ratio for smallholder farmers (Hassanein et al., 2023; Ikusika et al., 2024; Leitanthem et al., 2022).
2. **Ruminal Bypass Protein and Improved Nitrogen Efficiency:** Moderate concentrations of condensed tannins (CT, 20 to 40 g/kg DM) present in tree leaves, including *Leucaena*,

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Moringa, and neem, and fruit by-products form reversible hydrogen bonds with dietary proteins at neutral ruminal pH (6.0–7.0), protecting them from microbial proteolysis into wasteful ammonia (NH_3-N) (Gaviria-Uribe et al., 2022; Soldado et al., 2021; Vastolo et al., 2025). In the acidic abomasum (pH < 3.5), the tannin-protein complex dissociates, increasing post-ruminal amino acid absorption in the small intestine and shifting nitrogen excretion from volatile urinary urea to environmentally stable fecal nitrogen (El-Zaiat et al., 2022; Gaviria-Uribe et al., 2022).

3. **Enteric Methane (CH_4) Mitigation:** Bioactive secondary metabolites, specifically saponins, condensed tannins, flavonoids, and essential oils, directly inhibit ruminal methanogenic archaea, such as *Methanobrevibacter* spp., and defaunate hydrogen-producing protozoa. This can reduce enteric methane emissions by 12% to 32% per unit of digestible organic matter while redirecting metabolic hydrogen toward propionate synthesis (Amad and Zentek, 2023; Gaviria-Uribe et al., 2022; Leitanthem et al., 2022; Vastolo et al., 2025).
4. **Systemic Antioxidant Status and Product Shelf-Life:** Polyphenols, anthocyanins, and carotenoids transferred from *Moringa*, purple neem foliage, *Azolla*, and fruit pomaces elevate endogenous antioxidant enzymes—superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH-Px)—while depressing lipid peroxidation, measured through malondialdehyde (MDA), in blood plasma, milk, and meat (Leitanthem et al., 2022; Soldado et al., 2021; Taethaisong et al., 2022).
5. **Natural Anthelmintic and Antiprotozoal Action:** Phytochemicals in *Moringa* and *Azadirachta indica* suppress gastrointestinal nematode egg output, including that of *Haemonchus contortus*, potentially reducing reliance on synthetic chemical dewormers (Amad and Zentek, 2023; El-Zaiat et al., 2022).

4.2 Anti-Nutritional Factors (ANFs), Contaminants, and Health Hazards

Conversely, indiscriminate or unprocessed feeding of unconventional resources exposes livestock to metabolic and toxicological hazards.

- **Excessive Tannins and Phenolics:** When dietary condensed tannins exceed 50 g/kg DM (5%), they bind salivary mucoproteins, depressing palatability and voluntary intake, inhibit ruminal fibrolytic bacteria such as *Fibrobacter succinogenes* and *Ruminococcus albus*, and inactivate host digestive enzymes, reducing fiber and protein digestibility (Gaviria-Uribe et al., 2022; Ikusika et al., 2024; Soldado et al., 2021).

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- **Alkaloids, Amino Acid Analogues, and Terpenoids:**
    - **Mimosine in *Leucaena leucocephala*:** A toxic non-protein amino acid comprising 2–6% of dry leaf weight. It is degraded in the rumen to 3,4-dihydroxypyridine (3,4-DHP), a potent goitrogen that chelates essential trace minerals (Zn, Cu, and Fe), inhibits thyroid hormone synthesis, and can cause alopecia, salivation, esophageal ulcers, goiter, and poor weight gain in unadapted ruminants (Gaviria-Uribe et al., 2022).
    - **Karanjin and Pongamol in Karanj Cake:** These furanoflavonoids impart bitter astringency and may cause hepatotoxicity and depressed rumen fermentation if fed without appropriate processing.
    - **Azadirachtin, Nimbin, and Salannin in Neem Seed Cake:** These limonoid triterpenoids can cause severe bitterness, anorexia, and reproductive or spermatogenic suppression at high levels (El-Zaiat et al., 2022).
    - **Mowrin (Saponins) in Mahua Seed Cake:** These saponins can damage gastrointestinal mucosa and cause gastroenteritis.
- **Soluble Oxalates in *Opuntia* Cladodes and Napier/Paddy Forages:** High concentrations of soluble oxalates bind dietary calcium in the gut and bloodstream to form insoluble calcium oxalate crystals, potentially precipitating hypocalcemia, secondary nutritional hyperparathyroidism, and urolithiasis/nephrosis if fed as a sole diet (Pastorelli et al., 2022). High pectin and mucilage, coupled with low NDF in *Opuntia*, can also cause wet, laxative feces and depressed milk fat if fed above 50–60% of DM without dry roughage (Pastorelli et al., 2022).
- **Non-Starch Polysaccharides (NSPs) and Mycotoxins in Agro-Byproducts:** DDGS and fruit pomaces contain cellulose, lignin, mannans, and xylans that limit direct digestibility. High moisture in fresh wet pomaces and poorly drained hydroponic mats can encourage proliferation of *Aspergillus* and *Fusarium* molds producing aflatoxins (AFB_1, excreted in milk as AFM_1) and zearalenone (Chen et al., 2024; Ikusika et al., 2024; Pexas et al., 2023).
- **Heavy Metal Bioaccumulation in *Azolla*:** Because *Azolla* possesses exceptional phytoremediation capacity and can accumulate heavy metals, including lead, cadmium, chromium, and arsenic, as well as textile dyes, cultivating it using contaminated sewage or industrial runoff poses a severe bioaccumulation hazard to livestock and human milk consumers (Pexas et al., 2023; Sundararaman et al., 2021).

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- **High Energy Footprint and Dry Matter Loss in Hydroponics:** Sprouting grains without light or soil nutrition often results in a 7% to 15% loss in total dry matter due to seed respiration. Climate-controlled hydroponic units may consume up to 60% more electrical energy per tonne of protein than conventional field crops if air-conditioning is required during Indian summers (Min et al., 2024; Pexas et al., 2023).

Table 2. Nutritional Benefits, Anti-Nutritional Factors (ANFs), and Detoxification Protocols for Alternative Feeds

Alternative feed resource	Key bioactive/nutritional benefits	Primary ANFs and hazards	Detoxification/amelioration strategy
Azolla pinnata / *A. filiculoides*	22–28% CP; rich in lysine, carotenoids, Ca, P, and trace minerals; rapid 3–5-day doubling time (Hassanein et al., 2023; Rahman et al., 2023)	High moisture (90–94%), acid detergent lignin buildup in over-mature mats, and heavy metal accumulation from polluted water (Sundararaman et al., 2021)	Cultivate strictly in clean potable/borewell water; harvest every 5–7 days; wash thoroughly to remove cow-dung odor and sun-dry for concentrate mixing (Hassanein et al., 2023)
Moringa oleifera foliage	23–30% CP, high bypass protein, flavonoids, and vitamins A/C/E; reported reduction in enteric CH_4 (Amad and Zentek, 2023; Leitanthem et al., 2022)	Moderate tannins (12–20 g/kg), saponins, phytates, and oxalates at high inclusion levels	Shade-drying or ensiling with molasses; restrict inclusion to 15–25% of DM or concentrate mixture (Amad and Zentek, 2023; Leitanthem et al., 2022)
Subabul (*Leucaena* spp.) foliage	22–26% CP; condensed tannins may enhance post-ruminal amino acid flow and reduce	Mimosine (2–6% DM) and its ruminal metabolite 3,4-DHP, which is	Wilting/sun-drying, ensiling, supplementation with $FeSO_4$/$ZnSO_4$ mineral mixture,

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	CH_4 (Gaviria-Uribe et al., 2022)	goitrogenic and can cause alopecia and thyroid enlargement	or ruminal inoculation with *Synergistes jonesii* bacteria
Spineless cactus (*Opuntia ficus-indica*)	Biological water yield reported at 180 t/ha/year; rich in soluble carbohydrates and calcium; extreme drought resilience (Pastorelli et al., 2022)	Oxalates bind calcium; low CP (4–8%) and low effective fiber (NDF), potentially causing laxative diarrhea and low milk fat	Chop and wilt cladodes for 24 hours; co-feed in a Total Mixed Ration (TMR) with dry cereal straw (minimum 30–40%) and a protein/phosphorus source
Neem (*Azadirachta indica*) leaves and cake	13–18% CP in leaves; 30–36% CP in cake; natural anthelmintic activity (El-Zaiat et al., 2022; Taethaisong et al., 2022)	Azadirachtin, nimbin, and salannin; bitterness and reduced palatability; possible reproductive effects from raw cake	Neem leaves may be included at 4–6% DM in the cited studies; detoxify raw neem seed cake by water washing or 1.5–2.0% urea/alkali ammoniation before feeding
Karanj (*Pongamia*) and mahua cakes	28–34% CP in karanj and 16–20% CP in mahua; forest-origin protein (Ikusika et al., 2024)	Karanjin and pongamol in karanj; mowrin/saponins and high tannins in mahua	Complete solvent extraction followed by alkali treatment or *Saccharomyces* solid-state fermentation (Ikusika et al., 2024)
Fruit pomaces and DDGS	High rumen-undegradable protein in DDGS (30–45% CP); antioxidant polyphenols in fruit	High NSPs, lignin, rapid mold/mycotoxin spoilage in wet	Solid-state fermentation (SSF) with suitable fungi and bacteria, plus cellulase/xylanase enzymes; polyethylene glycol

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	pomaces (Chen et al., 2024; Vastolo et al., 2025)	pomaces, and high condensed tannins	(PEG) may be used to neutralize excess tannins

5. Possible Inclusion Levels in Livestock Rations

Determining precise, scientifically validated dietary inclusion thresholds is critical so that farmers capture the nutritional and economic benefits of alternative feeds without crossing into toxicity or depressing ruminal cellulolysis. Based on controlled in vivo metabolism trials and in vitro fermentation studies, the recommended inclusion levels for Indian livestock species are summarized below.

- **Azolla pinnata Meal/Fresh Biomass:** In lactating dairy cattle and buffaloes, fresh washed *Azolla* can be supplemented at 1.5 to 2.0 kg/animal/day, mixed 1:1 with commercial concentrate, or sun-dried *Azolla* meal can replace 15% to 25% of the concentrate mixture. This is equivalent to 10% to 20% of total diet DM in dairy goats and sheep, according to the cited research (Hassanein et al., 2023).
- **Moringa oleifera Foliage/Leaf Meal:** In growing goat kids, sheep, buffalo calves, and lactating cows, *Moringa* leaf meal is optimally included at 15% to 25% of the concentrate mixture or used to replace 20% to 50% of conventional green berseem/fodder on a DM basis (Amad and Zentek, 2023; Leitanthem et al., 2022).
- **Spineless Cactus (*Opuntia ficus-indica*) Cladodes:** Chopped spineless cactus cladodes can constitute 30% to 40% of total dietary DM in lactating cattle and buffaloes, and up to 40% to 50% of dietary DM in sheep and goats in arid zones, provided the remaining ration contains dry cereal straw and a nitrogen supplement (Pastorelli et al., 2022).
- **Hydroponic Wheat/Maize Sprouts:** In growing ewes, lambs, and dairy cattle, hydroponic sprouts should be included at 10% to 15% of total dietary DM, with a cited maximum of 20% DM. Exceeding this level may dilute dry matter intake because of excessive intracellular water and accelerate ruminal passage rate (Min et al., 2024).
- **Neem (*Azadirachta indica*) and *Leucaena* Foliage:** Dried neem leaf powder functions as a phytogenic modifier at 4% to 6% of total diet DM (40–60 g/kg DM) in sheep and goats (El-Zaiat et al., 2022; Taethaisong et al., 2022), while *Leucaena leucocephala* or *L. diversifolia* foliage is reported to be incorporated at 20% to 30% of dietary DM (Gaviria-Uribe et al., 2022).

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- **Agro-Industrial By-Products:** Polyphenol-rich fruit and vegetable by-products, including citrus pulp, pomegranate peel, tomato pomace, and grape/olive pomace, can be incorporated at 10% to 20% of the concentrate mixture, or up to 30% after solid-state fermentation (Ikusika et al., 2024; Vastolo et al., 2025). Probiotic- and enzyme-fermented DDGS can replace 20% to 30% of soybean/groundnut meal in concentrate mixtures, while water-washed or alkali-detoxified karanj and neem seed cakes may be included at 10% to 20% of the concentrate mixture, depending on residual toxins and ration composition (Chen et al., 2024; Ikusika et al., 2024).

Table 3. Scientifically Validated Dietary Inclusion Levels and Upper Thresholds for Indian Livestock

Alternative feed resource	Target livestock species	Recommended inclusion level	Basis of inclusion	Upper threshold and limiting factor
Sun-dried/fresh *Azolla pinnata*	Dairy cattle, buffaloes, goats, sheep	15–20% for goats/sheep; 15–25% for cattle/buffaloes	Percentage of concentrate mixture, or 10–20% of total diet DM	Above 25–30%: high ash/acid-insoluble ash and moisture may reduce energy density and voluntary intake (Hassanein et al., 2023)
Moringa oleifera leaf meal/silage	Cattle, buffaloes, goat kids, sheep	15–25% in concentrate; 25–50% replacement of green fodder	Percentage of concentrate mixture or green-fodder DM	Above 50% of diet DM: excess saponins and tannins may impart bitterness and depress fiber digestion (Amad and Zentek, 2023; Leitanthem et al., 2022)
Spineless cactus (*Opuntia ficus-indica*)	Cattle, buffaloes, sheep, goats in arid/semi-arid areas	30–40% for cattle/buffaloes; 40–50% for sheep/goats	Percentage of total diet DM in a TMR with dry straw	Above 50–60% DM: risk of osmotic diarrhea, ruminal acidosis, and oxalate load (Pastorelli et al., 2022)

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Hydroponic wheat/maize sprouts	Dairy cattle, growing sheep and goats	10–15%; optimal range 10–15% DM	Percentage of total dietary DM	Above 20% DM: high moisture may limit total DM intake and reduce NDF retention time (Min et al., 2024)
Neem (*Azadirachta indica*) leaf powder	Sheep, goats, growing calves	4–6% (40–60 g/kg DM)	Percentage of total diet DM	Above 10% DM: bitter limonoids may depress palatability and ruminal cellulolytic activity (El-Zaiat et al., 2022; Taethaisong et al., 2022)
Subabul (*Leucaena* spp.) foliage	Cattle, buffaloes, goats, sheep	20–30%	Percentage of total diet DM	Above 30–40% DM in unadapted stock: mimosine/3,4-DHP toxicity and alopecia risk (Gaviria-Uribe et al., 2022)
Fruit pomaces (citrus, tomato, pomegranate)	Dairy cattle, sheep, goats	10–15% raw dried; 20–30% after SSF	Percentage of concentrate mixture	Above 30%: high lignin/pectin and condensed tannins may affect fermentation (Ikusika et al., 2024; Vastolo et al., 2025)
Fermented DDGS and detoxified karanj/neem cake	Cattle, buffaloes, growing small ruminants	20–30% DDGS; 10–15% detoxified karanj/neem cake	Percentage of concentrate mixture	Above 15–20% for unconventional cakes: residual karanjin/triterpenoids may depress intake and affect liver enzymes (Chen et al., 2024; Ikusika et al., 2024)

6. Effectiveness on Livestock Production, Metabolism, and Environment

Experimental and field studies under tropical and Indian farming conditions indicate that strategic incorporation of alternative feed resources within appropriate inclusion ranges can

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improve productive, metabolic, and environmental outcomes. Responses depend on the feed resource, processing method, animal species, basal ration, and management conditions.

6.1 Enhancement of Milk Yield, Milk Composition, and Offspring Growth

- **Dairy Production with *Azolla*:** In lactating Zaraibi dairy goats, replacing 10% and 20% of the concentrate feed mixture with sun-dried *Azolla pinnata* reportedly increased daily milk yield by 11.8% to 18.5%, 4% fat-corrected milk (FCM), milk fat percentage, and total solids. The study also reported improvements in the weaning weight and average daily gain (ADG) of suckling offspring and reductions in feed cost per kilogram of milk (Hassanein et al., 2023). Similar improvements of 10% to 15% in milk yield and feed conversion efficiency have been reported in Indian crossbred cows and Murrah buffaloes supplemented with 1.5–2.0 kg fresh *Azolla* daily.
- **Lactation and Growth with *Moringa oleifera*:** Supplementation with *Moringa oleifera* foliage or leaf meal at 15–25% of concentrate in dairy cows, buffaloes, and goats can enhance apparent digestibility of dry matter (DM), organic matter (OM), crude protein (CP), and neutral detergent fiber (NDF) (Amad and Zentek, 2023; Leitanthem et al., 2022). A controlled trial at ICAR-National Dairy Research Institute (NDRI), Karnal, India, reported that feeding *Moringa oleifera* leaves to male goat kids increased total volatile fatty acid (VFA) and propionate concentrations, average daily body weight gain, plasma superoxide dismutase (SOD) and catalase (CAT) activities, and immunity (Leitanthem et al., 2022).
- **Milk Sustainability and Water Conservation with *Opuntia*:** Incorporating spineless cactus cladodes at 30% to 40% of diet DM alongside dry roughages can maintain or increase milk yield in dairy cattle and small ruminants. Studies have also reported changes in beneficial polyunsaturated fatty acids, including conjugated linoleic acid (CLA), in milk and meat fat. Claims regarding reduced drinking-water requirements should be interpreted in the context of animal species, environmental conditions, and the water supplied by the total ration (Pastorelli et al., 2022).

6.2 Growth Performance, Ruminal Fermentation, and Blood Metabolites

- **Hydroponic Sprouts in Growing Ruminants:** Including hydroponic wheat sprouts at 10% to 15% of dietary DM in growing ewes has been associated with improved average daily gain (ADG), body weight, and feed conversion ratio, alongside changes in blood

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metabolic parameters, serum total protein, and immunoglobulin concentrations (Min et al., 2024).

- **Phytogenic Neem Foliage as a Natural Growth Promoter:** Supplementing growing lambs with 40 g/kg DM (4%) of *Azadirachta indica* leaf powder reportedly increased final body weight, average daily gain, and crude protein digestibility to levels comparable with those observed with the synthetic ionophore antibiotic monensin, without depressing dry matter intake or fiber degradation (El-Zaiat et al., 2022). Similarly, anthocyanin-rich purple neem foliage at 3% to 6% in growing goats was associated with changes in ruminal fermentation, increased plasma antioxidant capacity, including DPPH scavenging and SOD activity, and lower ruminal ammonia-N losses (Taethaisong et al., 2022).
- **Bioconverted Agro-Byproducts (SSF Pomaces and Synergistic DDGS):** Raw distillers grains and fruit pomaces contain lignocellulosic material that can limit digestibility. Solid-state fermentation using suitable fungi, bacteria, and exogenous cellulase/xylanase enzymes has been reported to degrade cellulose and hemicellulose, enrich microbial protein content, and release bound phenolic antioxidants. These changes may improve nutrient digestibility, growth performance, and meat oxidative stability when fermented products are incorporated appropriately into ruminant diets (Chen et al., 2024; Ikusika et al., 2024; Soldado et al., 2021).

6.3 Efficacy in Enteric Methane (CH_4) Abatement

Alternative feeds rich in secondary metabolites may provide a practical nutritional approach to reducing enteric methane emissions from Indian livestock.

- Replacing conventional green fodder or concentrate with *Moringa oleifera* leaves in goat kids at ICAR-NDRI was reported to reduce daily enteric methane emissions, expressed as g/day and g/kg digestible DM intake, by 15% to 24%. The response was associated with changes in the ruminal acetate-to-propionate ratio and methanogenic archaea (Amad and Zentek, 2023; Leitanthem et al., 2022).
- Incorporating *Leucaena leucocephala* or *Leucaena diversifolia* at 25% of a tropical grass diet reportedly decreased in vitro methane production by 14% to 22% while increasing post-ruminal bypass protein supply (Gaviria-Uribe et al., 2022).
- Inclusion of polyphenol-rich agro-industrial by-products, such as pomegranate peel, grape pomace, citrus pulp, and tomato pomace, has been associated with reduced ruminal

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methane production and ammonia-N accumulation through effects on ruminal microbial fermentation and volatile fatty acid pathways (Vastolo et al., 2025).

7. Conclusion

Addressing India's chronic feed and fodder deficit under the dual pressures of shrinking arable land and climate variability requires a shift from traditional cereal-straw-and-oilcake feeding toward regionally tailored, circular livestock nutrition. Aquatic protein sources such as *Azolla pinnata*, perennial fodder trees—including *Moringa oleifera*, *Azadirachta indica*, and *Leucaena leucocephala*—drought-resilient CAM succulents such as *Opuntia ficus-indica*, hydroponic sprouts, and bioprocessed agro-industrial residues, including DDGS, fruit/vegetable pomaces, and detoxified non-edible oilcakes, offer nutritional potential across India's diverse agro-climatic zones (Amad and Zentek, 2023; Hassanein et al., 2023; Ikusika et al., 2024; Pastorelli et al., 2022).

When processed through appropriate detoxification technologies—such as solid-state fermentation, probiotic-enzymatic co-fermentation, water washing, alkali treatment, or ensiling—and incorporated within scientifically supported inclusion thresholds, these alternative resources may replace a proportion of scarce conventional concentrates, reduce ration costs, improve aspects of milk and meat antioxidant quality, and mitigate enteric methane emissions (Chen et al., 2024; Leitanthem et al., 2022; Soldado et al., 2021; Vastolo et al., 2025). Scaling up village-level decentralized feed-processing units, complete-feed-block plants, and extension training through state veterinary departments and farmer producer organizations (FPOs) will be important for translating these nutritional innovations into practical, climate-smart livestock farming across India.

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