



From Feed to One Health: Nutritional Modulation of the Gut Microbiome and its Implications for Animal, Human and Environmental Health: Review Article

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ABSTRACT

The gut microbiome has emerged as a biological interface through which diet, host physiology, animal productivity, food safety and environmental processes become interconnected. In livestock, microorganisms inhabiting the rumen and intestinal tract transform dietary substrates into short-chain fatty acids, microbial protein, vitamins and other metabolites that influence nutrient capture, immune function and host metabolism. At the same time, microbial activity can generate methane, ammonia and other nitrogenous losses, while disruption of microbial communities may facilitate pathogen colonization and antimicrobial resistance (AMR). This review develops a feed-to-One-Health framework in which nutritional inputs are considered upstream determinants of microbial structure and function, with downstream consequences extending from animal health and productivity to food safety, human exposure and environmental sustainability. Particular attention is given to fibre and carbohydrate supply, protein and nitrogen nutrition, probiotics, prebiotics, synbiotics, postbiotics, phytochemical feed additives, mycotoxin control, antimicrobial stewardship and precision nutrition. Recent literature indicates that microbiome-directed nutrition can improve nutrient-use efficiency and support animal resilience, but responses are context dependent and may vary with species, diet, host genotype, production system and baseline microbiome. In ruminants, manipulating hydrogen flow and rumen fermentation offers opportunities to reduce methane, although reductions in emissions do not consistently translate into proportional improvements in feed efficiency. The review also examines the rumenofaecobiome as a potential AMR reservoir and emphasizes the need to connect feed, microbiome and resistome surveillance. For India, where livestock systems are diverse and crop residues, agro-industrial by-products and region-specific feed resources are important, a One Health nutrition strategy should combine feed safety, local resource optimization, microbial ecology and farmer-oriented precision feeding. Future progress will depend on multi-omics, longitudinal studies, standardized microbiome endpoints, causal validation and integration of animal, food and environmental surveillance.

Keywords: gut microbiome; rumen microbiome; animal nutrition; One Health; probiotics; prebiotics; antimicrobial resistance; feed safety; methane; mycotoxins; precision nutrition; livestock.

1. Introduction

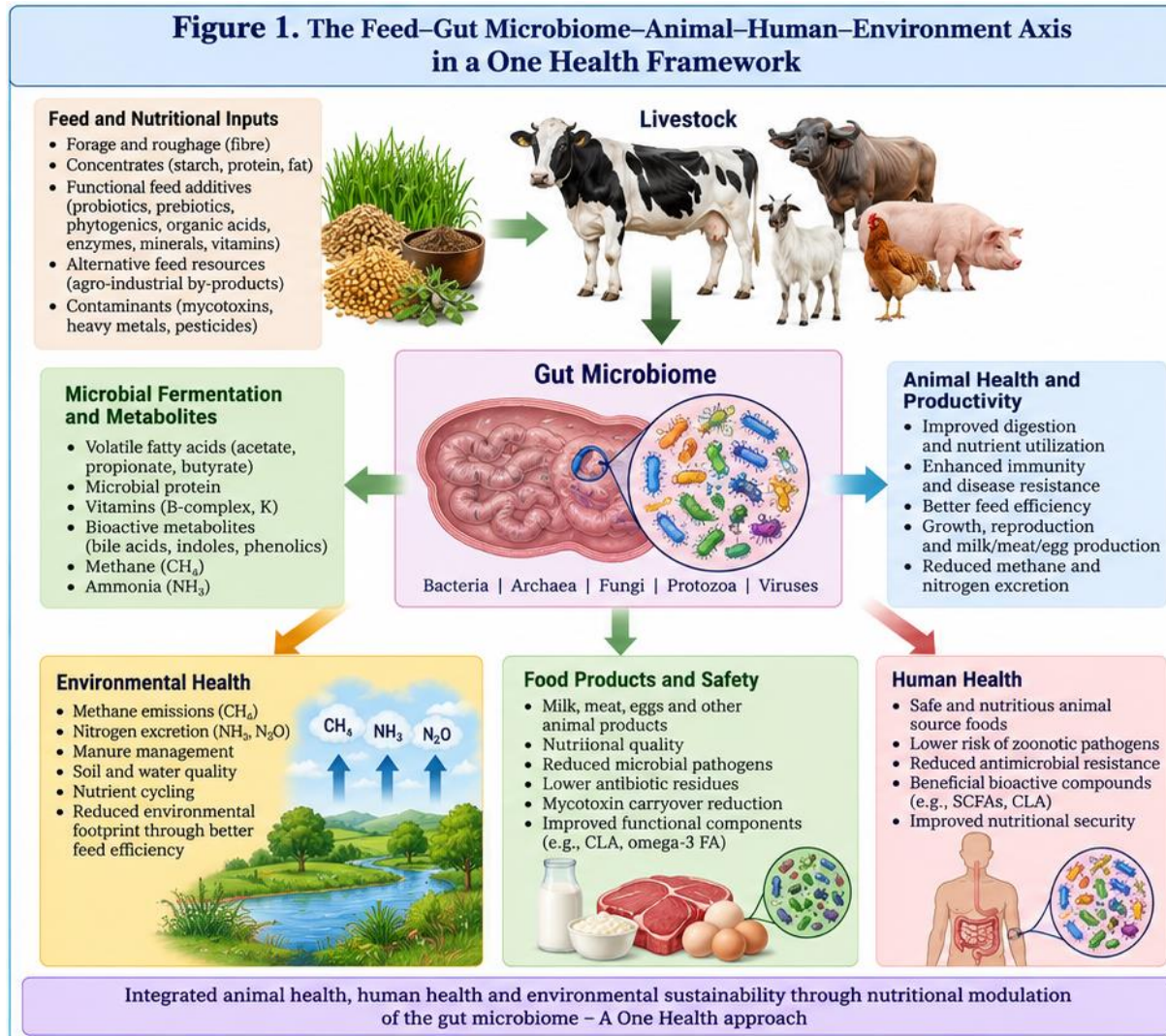
One Health recognizes that the health of humans, animals and ecosystems is interconnected. The microbiome provides a particularly useful biological framework for understanding this interconnection because microbial communities participate in host metabolism, immune regulation, nutrient cycling and the movement of resistance determinants across ecological compartments. A recent One Health review proposed that microbiomes contribute to co-metabolism and co-regulation among hosts and environments and highlighted antibiotic-resistance genes as an important cross-sector concern (Ma *et al.*, 2023). In livestock production, the feed supplied to an animal is therefore more than a source of energy, protein, minerals and vitamins; it is also an ecological input that selects for microbial functions in the gastrointestinal tract.

Ruminants depend on a complex microbial ecosystem to degrade structural carbohydrates and convert dietary nitrogen into microbial protein. The resulting fermentation products support host energy metabolism, but fermentation also determines the production of methane and nitrogenous wastes. The rumen microbiome is shaped primarily by diet but also by host genetics, rumen volume, passage rate, rumination and physiological state (Sasson *et al.*, 2017; recent synthesis in the Journal of Dairy Science, 2025). Consequently, nutrition is a practical entry point for changing microbial function without treating the microbiome as an isolated target.

The One Health relevance becomes broader when animals are viewed as part of a food and environmental system. Foodborne pathogens can move through livestock production chains, while antimicrobial-resistant organisms and resistance genes may circulate among animals, food, people and environmental

compartments. Feed contamination by mycotoxins creates another feed-to-fork pathway: contaminated ingredients can affect animal health and productivity and, for some toxins or metabolites, contribute to residues in animal-derived foods (Zhou *et al.*, 2020; recent feed-to-fork risk assessment, 2025). Thus, nutritional interventions that improve gut stability, reduce pathogen carriage, optimize nutrient use or prevent contaminant exposure may have benefits extending beyond the individual animal.

Figure 1- Feed-to-One-Health pathways connecting nutritional inputs, livestock gut microbiomes, animal health and productivity, animal-derived foods, human health and environmental outcomes.



2. The Gut Microbiome as the Nutritional Interface

Recent dairy-cattle studies reinforce that the microbiome is not merely an outcome of nutrition but can contribute measurably to phenotype. In 448 mid-lactation Holstein cows, inclusion of rumen microbial information in models of feed efficiency improved model fit, and microbiability for some traits reached values up to 26% for milk energy; the authors also found evidence for genome-by-microbiome interaction effects (Cavaco-Gonçalves *et al.*, 2024). A companion mediation analysis identified structural relationships between host genotype, rumen microbial features and feed-efficiency phenotypes, supporting the concept of the animal as a host–microbiome holobiont (Cavaco-Gonçalves *et al.*, 2024).

Short-chain fatty acids (SCFAs), particularly acetate, propionate and butyrate, are important examples of diet-derived microbial products. Their concentrations reflect substrate availability and microbial metabolism and can influence epithelial energy supply, signalling and inflammatory responses. Recent work has expanded interest in SCFA physiology in livestock and aquatic animals, including their production, absorption and metabolic fate (2026 review in *The Journal of Nutrition*). The nutritional objective is therefore not simply to increase microbial diversity, but to promote a stable community with desirable functions under a defined production system.

A major methodological distinction is between taxonomic association and functional causation. A microbial taxon may correlate with feed efficiency, milk yield or disease resistance without being the causal driver. Conversely, functionally important organisms may be poorly represented in reference databases or remain uncultured. This issue is particularly relevant to AMR research in the rumen, where recent work argues for simultaneous

characterization of the rumen and faecal microbiomes—the proposed 'rumenofaecobiome'—because faecal samples alone may not capture the full resistome (Wu *et al.*, 2025).

Table 1. Major nutritional inputs and potential microbiome-mediated outcomes

Sr.No.	Nutritional input	Primary microbial response	Potential animal outcome	One Health relevance
1	Fermentable fibre	Expansion/activity of fibre-degrading communities; SCFA production	Improved fermentation and gut function	Better nutrient capture; potentially lower waste intensity
2	Rapidly fermentable starch	Shift toward amylolytic fermentation; altered pH	Can support energy supply but excessive supply may cause dysbiosis/acidosis	Animal health and productivity; manure nutrient consequences
3	Protein and degradable N	Proteolysis, peptide/amino-acid metabolism, ammonia formation	Microbial protein synthesis; excess N may be lost	Ammonia/N ₂ O emissions and nutrient pollution
4	Probiotics	Competitive exclusion and signalling effects	Gut stability, immune support, pathogen control	Potential reduction in reliance on antimicrobials
5	Prebiotics	Selective substrate supply to beneficial microbes	Barrier function and fermentation products	Reduced pathogen pressure; circular use of agro-industrial residues
6	Phytogenics	Changes in microbial ecology and fermentation; bioactive signalling	Digestive, immune and production responses	Potential antibiotic-alternative role; emission effects
7	Mycotoxin mitigation	Reduced toxin bioavailability or microbial transformation	Improved intake, immunity and productivity	Feed safety and reduced feed-to-food exposure

3. Nutritional Modulation of the Microbiome

3.1 Carbohydrates and dietary fibre

A recent review of dietary fibre in poultry emphasized that fibre influences gut development, feed intake, passage rate, nutrient absorption, microbiome taxonomy and function, gut pH and environmental sustainability, but also noted that definitions and analytical methods vary substantially across studies (Animal Nutrition, 2024). Thus, fibre should be considered a functional component of the diet rather than only a diluent of dietary energy.

Structural carbohydrates favour cellulolytic and hemicellulolytic processes, whereas readily fermentable carbohydrates rapidly change substrate availability and fermentation kinetics. In ruminants, a shift toward highly fermentable diets can lower ruminal pH and contribute to subacute ruminal acidosis, with consequences for intake, milk production and animal health. The challenge is therefore to formulate diets that synchronize fermentable energy with fibre, maintain rumen function and support productive microbial pathways Jiao *et al.* (2025).

3.2 Protein and nitrogen nutrition

Microbial protein synthesis is a major route by which ruminants obtain amino acids. Dietary protein degradation produces peptides, amino acids and ammonia, which are subsequently incorporated into microbial biomass or lost from the system. Excessive ruminal nitrogen relative to fermentable energy can increase ammonia losses and downstream nitrogen excretion. A systems review of amino-acid metabolism in rumen microbes emphasized that diet and microbial ecology jointly determine nitrogen utilization and that nutritional and ecological interventions can reduce nitrogen emissions (Wang *et al.*, 2024).

3.3 Probiotics, prebiotics, synbiotics and postbiotics

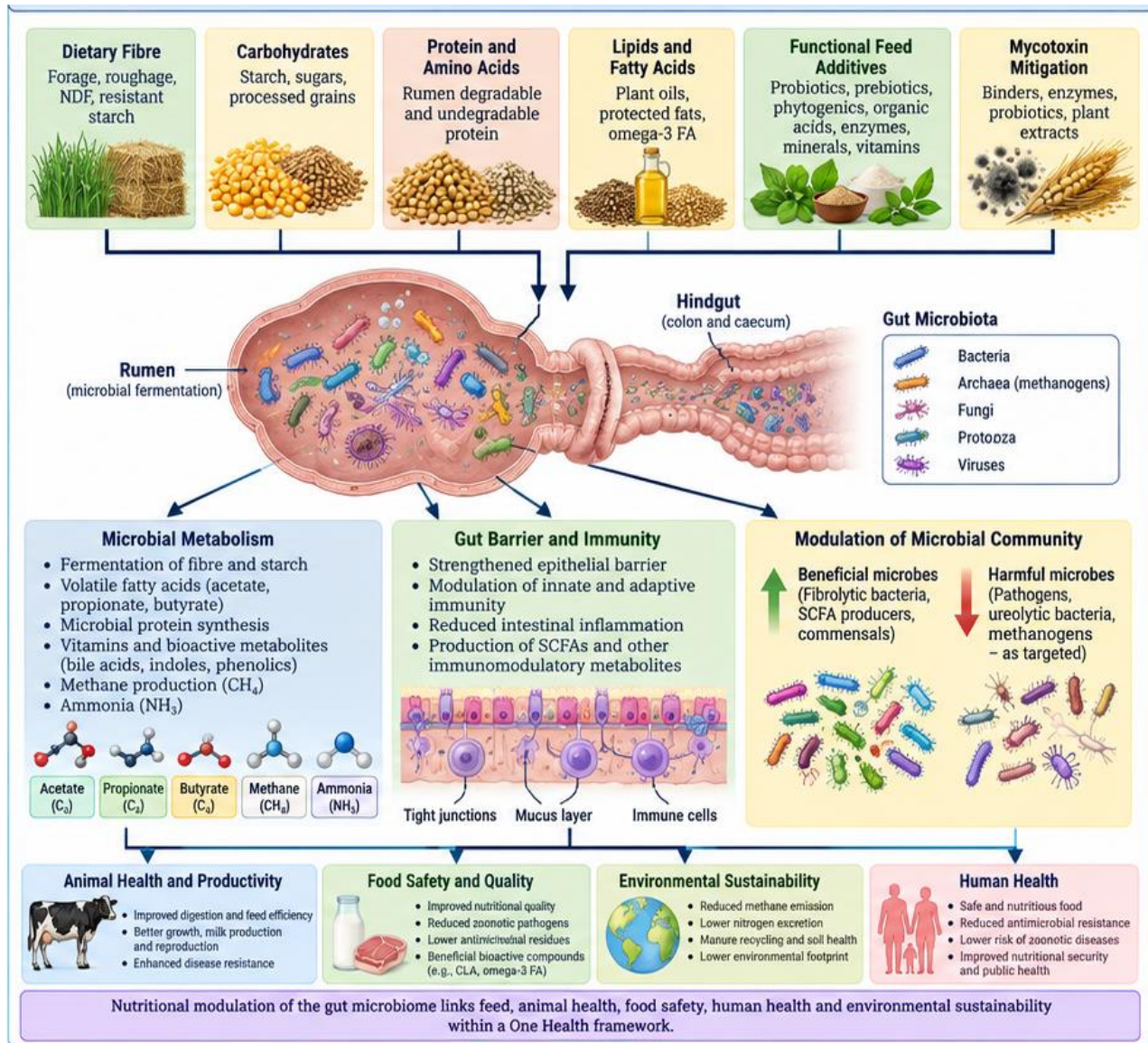
The most recent quantitative evidence is informative but also cautions against generic probiotic claims. Bilal *et al.* (2026) synthesized 53 studies comprising 106 independent broiler trials and found significant pooled differences for body weight, feed intake and feed conversion ratio. However, I^2 was 95.67%, indicating marked between-study heterogeneity; probiotic genus, trial duration and regional economic status were significant moderators of FCR. This supports a formulation-, strain- and context-specific approach rather than assuming that all probiotics act equivalently. Synbiotics combine

complementary probiotic and prebiotic components, while postbiotics use non-viable microorganisms or their components/metabolites. A 2025 review of prebiotics highlighted agro-industrial residues as potential sources of functional substrates and emphasized their capacity to alter gastrointestinal microbiota, suppress pathogens and modulate immune responses (Ravanal *et al.*, 2025).

3.4 Phytogetic feed additives

Plant-derived compounds—including essential oils, saponins, tannins and polyphenols—can alter microbial growth, fermentation pathways, oxidative status and host signalling. A recent review concluded that phytogetic additives have multifunctional potential but also noted variability related to plant source, extraction, dose, diet and production system (Wang *et al.*, 2024). In ruminants, some phytogetic interventions have been associated with changes in ruminal bacterial and archaeal communities and with altered methane or ammonia production.

Figure 2- Nutritional modulation of livestock gut microbiomes: dietary substrates and functional feed additives alter microbial metabolism, barrier and immune responses, and downstream One Health outcomes.



4. Gut Microbiome and Animal Health

An expanding area is the nutrition–gut microbiome–mammary health connection. Wang *et al.* (2024) reviewed evidence linking nutritional status and gastrointestinal microbial metabolites with bovine mastitis and highlighted potential roles for probiotics, high-fibre diets, inulin and other nutritional approaches. This provides a useful One Health bridge because udder inflammation can influence milk quality and antimicrobial use, even though causal pathways between intestinal microbes and mammary infection remain incompletely resolved.

A stable microbial ecosystem contributes to nutrient digestion, colonization resistance and immune homeostasis. Disruption may increase susceptibility to enteric disease, alter intestinal permeability or shift metabolic signalling. The nutritional interpretation is important: a microbial shift is not inherently beneficial or harmful; its significance depends on function, host physiology and production context.

5. From Animal Health to Food Safety and Human Health

The food chain creates direct opportunities for microbial and chemical exposures to move between livestock systems and people. Pathogens such as *Salmonella* and *Campylobacter* can contaminate animal-derived foods, while resistant bacteria and resistance genes may circulate between animals, food and environmental compartments. A One Health review of livestock food safety emphasizes that these pathways extend across breeding, production, processing, storage, transport and consumption and that animal and human microbiomes can also interact indirectly through food-associated microbial exposure (Science in One Health, 2023).

Nutrition can influence these pathways by changing intestinal colonization resistance, faecal shedding, immune competence and the physicochemical environment in which pathogens compete. Probiotics and prebiotics have consequently been investigated for reduction of enteric pathogens and improvement of gut health. However, evidence should be interpreted carefully: reductions in a microbial indicator in an animal experiment do not automatically demonstrate a reduction in human disease burden. Field-scale epidemiology and food-chain surveillance are required to establish population-level One Health effects.

6. Antimicrobial Resistance: The Rumen and Intestinal Resistome

The regional evidence is particularly important for India and South Asia. Harun *et al.* (2024) synthesized livestock and poultry evidence from 2014–2023 and estimated pooled prevalences of 74% for *E. coli*, 37% for *Salmonella* spp. and 48% for *Staphylococcus* spp. among the included datasets; common resistance determinants included *tetA*, *blaTEM*, *blaCTX*, *mcr1* and *sul1*. Separately, a 2024 systematic analysis of India-specific data reported resistance patterns across animal, human and environmental compartments, underlining the connected nature of the AMR problem (Heliyon, 2024). AMR is one of the clearest One Health links in animal production. Antimicrobial exposure can select resistant organisms and resistance genes, while manure and farm environments provide opportunities for persistence and dissemination. A 2025 systematic review of antimicrobial growth promoters found that 7 of 10 eligible studies reported statistically significant increases in resistance associated with growth-promoter exposure, although the authors highlighted substantial methodological limitations and risk of bias (Etienne *et al.*, 2025).

The microbiome is central because resistance determinants may reside in commensal organisms as well as pathogens. The 2025 rumenofaecobiome review emphasized the possibility that uncultured rumen organisms contribute to the resistome and that faecal sampling alone may underestimate the complexity of AMR dynamics (Wu *et al.*, 2025). This suggests a nutrition-relevant research agenda: determine how diet, feed additives, antimicrobial exposure and microbial community structure interact to influence resistance selection and transfer.

Table 2. Nutrition-linked approaches relevant to antimicrobial resistance

Sr.No.	Strategy	Proposed mechanism	Potential benefit	Key limitation / research need
1.	Probiotics	Competitive exclusion, bacteriocins, immune and barrier modulation	Support gut stability and pathogen resistance	Strain-specific effects; colonization and field consistency
2.	Prebiotics	Selective microbial substrate	Promote beneficial fermentation and barrier function	Dose and substrate specificity; host/diet dependence
3.	Synbiotics	Combined microbial strain + selective substrate	Potential synergistic microbiome modulation	Optimal combinations remain poorly standardized
4.	Phytogenics	Antimicrobial, antioxidant and signalling effects	Potential alternative to some antibiotic applications	Variable composition, dose-response and safety
5.	Antimicrobial peptides	Membrane targeting and immune activity	Potential pathogen suppression	In vivo evidence, stability and resistance surveillance
6.	Precision feeding	Match nutrient supply to animal requirement and microbial function	Lower excess nutrient supply and reduce selection pressure	Requires sensors, data and validated decision models

7. Environmental Health: Methane, Nitrogen and Nutrient Cycling

For nitrogen, recent work has moved beyond simple crude-protein reduction toward coordinated microbiota–host nitrogen metabolism. Jiao *et al.* (2025) emphasized spatially distinct rumen and intestinal microbial communities, microbial protein synthesis, urea nitrogen salvage and host amino-acid utilization as interacting components of nitrogen-use efficiency.

Environmental health is not an external issue to animal nutrition; it is partly generated by microbial metabolism. In ruminants, methanogenic archaea use hydrogen and carbon dioxide to produce methane. This represents an energy loss to the animal and a greenhouse-gas emission. Recent synthesis indicates that methane-mitigation additives can reduce enteric methane substantially in controlled studies, but the expected improvement in feed efficiency is not always proportional (Journal of Dairy Science, 2025).

7.1 Evidence from Published Meta-Analyses and Systematic Reviews

Quantitative syntheses are particularly valuable in One Health nutrition because individual feeding studies are often small and heterogeneous. Importantly, the estimates below are not a new meta-analysis conducted for this review; they are pooled findings reported in peer-reviewed systematic reviews and meta-analyses. Their interpretation must therefore retain the species, dose, diet, study design and outcome definitions of the original analyses.

For methane mitigation, Kebreab *et al.* (2023) pooled 13 articles covering 14 experiments and 48 treatment means and estimated mean reductions of 32.7% in methane production, 30.9% in methane yield and 32.6% in methane intensity at an average 3-NOP dose of 70.5 mg/kg DM. The authors also demonstrated that dietary NDF and crude fat modified efficacy, showing why methane interventions cannot be evaluated independently of the basal diet. A broader meta-analysis of 108 refereed papers covering eight dietary interventions likewise identified substantial quantitative potential for reducing enteric methane, with the strongest efficacy in the dataset for macroalgae and 3-NOP (Arndt *et al.*, 2022/2021 publication record).

A newer 2026 meta-analysis of nitrate supplementation in dairy cattle included nine publications and ten studies. It reported an approximately 20% reduction in methane emissions across nitrate doses of 5.3–21.1 g/kg DM, a reduction in dry matter intake of up to 1.04 kg/d without a significant reduction in milk yield or milk fat content, and an estimated 3.21% improvement in feed efficiency. Blood methemoglobin increased at higher doses but remained below the concentration considered clinically harmful in the dataset (Dicks *et al.*, 2026). These results demonstrate both the environmental opportunity and the importance of monitoring intake and safety when nitrate is used as a nutritional methane-mitigation strategy.

Evidence for microbiome-oriented additives is similarly quantitative. Abdelli *et al.* (2022) analyzed 99 trials from 49 peer-reviewed studies and found yeast-product supplementation associated with +0.69 kg/d milk yield, +0.06 percentage units milk fat content, +0.04 kg/d milk-fat yield and +0.02 kg/d milk-protein yield, without an associated increase in dry matter intake; responses varied with lactation stage and diet. In beef cattle, a 2024 meta-analysis of 14 studies found essential oils increased dry matter intake, average daily gain and gain:feed ratio while shifting ruminal VFA patterns and reducing ruminal ammonia, although the authors emphasized heterogeneity across formulations and experimental conditions.

For poultry, a 2026 PRISMA-based meta-analysis included 53 studies and 106 independent trials. Random-effects models indicated increases in body weight and feed intake and an improvement in feed conversion ratio, but heterogeneity was very high ($I^2 = 95.67\%$), and probiotic genus, trial duration and regional economic status were important moderators of FCR. The study therefore supports probiotic use as a potential antibiotic-alternative nutrition tool while illustrating why pooled averages should not be transferred directly across farms, breeds or formulations (Bilal *et al.*, 2026).

Table 3. Selected published systematic reviews and meta-analyses relevant to microbiome-directed animal nutrition and One Health outcomes

Sr. No.	Evidence area	Evidence base	Findings	Interpretation or limitation	Reference
1	3-NOP in dairy cattle	13 articles; 14 experiments; 48 means	CH ₄ production –32.7%; yield –30.9%; intensity –32.6% at mean dose 70.5 mg/kg DM	Diet NDF, crude fat and starch modified efficacy; dose mattered	Kebreab <i>et al.</i> , 2023
2	Nitrate in dairy cattle	9 publications; 10 studies	≈20% CH ₄ reduction; DMI ↓ up to 1.04 kg/d; milk yield/fat not significantly changed; feed efficiency +3.21%	Dose-dependent safety monitoring needed; milk-protein responses can decline	Dicks <i>et al.</i> , 2026
3	Yeast products in dairy cows	99 trials; 49 peer-reviewed studies	Milk yield +0.69 kg/d; milk fat +0.06%; milk-fat yield +0.04 kg/d; milk-protein yield +0.02 kg/d	Response modified by parity, lactation stage and diet	Abdelli <i>et al.</i> , 2022

Sr. No.	Evidence area	Evidence base	Findings	Interpretation or limitation	Reference
4	Essential oils in beef cattle	14 studies	DMI +0.2862 kg/d; ADG +0.1148 kg/d; gain:feed +0.0060; ruminal NH ₃ reduced	Formulation, dose and diet explain variability	Meta-analysis, Animal Feed Science and Technology, 2024
5	Probiotics in broilers	53 studies; 106 trials	BW +66.61 g; FI +29.80 g; FCR pooled MD 0.058	Very high heterogeneity (I ² 95.67%); genus and trial duration moderated FCR	Bilal <i>et al.</i> , 2026
6	Mycotoxin binders in dairy cows	28 papers; 131 data points	AFM1 reduction in milk ≈25–40% depending on binder	Effect strongly affected by binder:toxin ratio and experimental design	Kihal <i>et al.</i> , 2023
7	Bovine feed mycotoxin contamination	97 studies	Aflatoxins prevalence 59%; DON 74%; ZEN 70%; fumonisins 65%	Marked geographic/climatic heterogeneity; upper-tail concentrations can exceed guidance values	Chhaya <i>et al.</i> , 2024
8	AMR in South Asian livestock/poultry	Systematic review/meta-analysis, 2014–2023 literature	Pooled prevalence: E. coli 74%; Salmonella 37%; Staphylococcus 48%	High heterogeneity and regional differences; resistance genes included tetA, blaTEM, blaCTX, mcr1 and sul1	Harun <i>et al.</i> , 2024
9	Enteric methane strategies in dairy cows	218 studies; 1963–2022 literature	Nitrate: CH ₄ production –18.5% ±1.9%; yield –17.6% ±1.6%; intensity –13.0% ±0.2%. Lipids reduced methane metrics by up to 14.8% ±2.3%; condensed tannins reduced CH ₄ yield 11.3% ±2.9%.	Effect depended on dose, dietary fibre/starch, additive type and supplementation period; direct-fed microbials were not effective for methane in this synthesis.	Martins <i>et al.</i> , 2024
10	Nitrate in lactating dairy cattle	9 publications; 10 studies; nitrate 5.3–21.1 g/kg DM	At the most frequently tested dose (~10 g/kg DM): CH ₄ production –21.5%; yield –15.6%; intensity –20.2%; feed efficiency +3.21% in Model 1.	Milk-protein responses declined at some doses; methemoglobin increased but remained below reported animal-health risk levels. Dose above ~10 g/kg DM did not provide additional methane reduction in dose-response analysis.	Dicks <i>et al.</i> , 2026
11	Bromoform/seaweed cattle diets	14 studies; 39 treatment mean differences	At ~28.3 mg CHBr ₃ /kg DM: CH ₄ production –47.3%; yield –43.3%; intensity –39.0%. DMI fell 6.45% in dairy cattle and 3.26% in beef cattle.	Methane mitigation was strongly influenced by cattle type, carrier, diet composition and measurement method; milk yield declined 4.60% at the average dose in dairy cattle.	Kebreab <i>et al.</i> , 2025
12	Global non-antibiotic feed additives	71 papers; 1,035 effect sizes; 9 species; 7 additive classes	Overall, dietary additives improved production and immune outcomes across species; effect sizes were larger in herbivores than omnivores.	Dose-response estimates suggest strong context dependence; the analysis supports customized rather than universal dosing.	Liu <i>et al.</i> , 2026

Sr. No.	Evidence area	Evidence base	Findings	Interpretation or limitation	Reference
13	Mycotoxins in bovine feed	97 studies; 2011–2022 evidence base	Aflatoxins: prevalence 59%, concentration 2.58–3.92 µg/kg; DON: prevalence 74%, 233.17–327.73 µg/kg; ZEN: 70%, 42.47–66.19 µg/kg; fumonisins: 65%, 232.19–393.07 µg/kg.	Global estimates show substantial heterogeneity; climate, region and sample size affect risk estimates. Country-level data for India should not be treated as national prevalence.	Chhaya <i>et al.</i> , 2024

8. Feed Safety and Mycotoxins: A Feed-to-Fork One Health Pathway

The quantitative burden is substantial. Chhaya *et al.* (2024) synthesized 97 studies and reported global prevalences of 59% for aflatoxins, 74% for deoxynivalenol, 70% for zearalenone and 65% for fumonisins in bovine feed and feed components. The authors also reported substantial heterogeneity associated with climate and region. A 2024 systematic review further highlighted the occurrence of emerging mycotoxins such as enniatins, beauvericin, nivalenol and fusaric acid and emphasized the need to consider co-occurrence rather than evaluating each toxin in isolation.

Aflatoxin B1 is especially important because dairy cattle can metabolize it to aflatoxin M1, which can appear in milk. A 2026 One Health review described feed contamination as a route connecting fungal ecology, livestock health, animal products and public welfare and highlighted prevention, biocontrol, storage management and advanced detection as complementary measures.

Table 4. Feed-borne hazards and One Health implications

Sr. No.	Hazard	Animal consequence	Human/food-chain concern	Nutrition/feed-management response
1.	Aflatoxin B1	Hepatotoxicity, immunosuppression, lower performance	Aflatoxin M1 carry-over into milk	Ingredient screening, storage control, validated binders/biotransformation approaches
2.	Fusarium toxins	Reduced intake, gut and immune effects; species-dependent sensitivity	Potential exposure through animal-derived foods	Source control, analytical monitoring, appropriate detoxification strategies
3.	Salmonella/Campylobacter contamination	Enteric colonization and disease risk	Foodborne illness	Biosecurity, feed hygiene, pathogen control and gut-health strategies
4.	Antimicrobial residues	Possible toxicity and regulatory non-compliance	Consumer exposure and stewardship concern	Veterinary oversight, withdrawal compliance, responsible use
5.	AMR bacteria/genes	Altered microbiota and resistance reservoir	Potential transmission through food/environment	Antimicrobial stewardship, surveillance and microbiome-aware feeding

9. Relevance to Indian Livestock Systems

India also provides a particularly relevant One Health setting for AMR surveillance. Mahindroo *et al.* (2024) reported antimicrobial resistance in food-borne pathogens at the human–animal interface in India, while a separate 2024 One Health systematic analysis included animal, human and environmental data from India. Together, these studies support integrating nutritional antimicrobial stewardship with veterinary diagnostics, food-safety surveillance and environmental monitoring rather than treating feed interventions as a stand-alone solution.

A One Health nutrition framework is particularly relevant to India because livestock systems range from smallholder dairy and mixed crop-livestock farms to specialized poultry, pig, goat and commercial dairy operations. Feed availability, quality and cost differ markedly among regions. Earlier ICAR literature emphasized the importance of crop residues and the persistent gap between quantitative feed availability and feed quality in Indian livestock systems. This context means that microbiome-directed nutrition cannot simply import high-input feeding strategies from temperate production systems.

Crop residues, cereal straws, agro-industrial by-products, tree leaves and region-specific unconventional feeds may provide substrates for microbial fermentation but can also carry variable fibre, protein, mineral and contaminant profiles. Their use should therefore be linked to chemical characterization, digestibility assessment, mycotoxin surveillance and appropriate processing. Prebiotic research on agro-industrial residues provides a useful conceptual bridge: residues may become functional feed ingredients when their fermentable carbohydrate fractions and safety are characterized (Ravanal *et al.*, 2025).

Indian research should also account for breed and genotype, seasonal heat stress, water availability, smallholder management, variable forage quality and local disease pressure. A practical precision-nutrition model for India may therefore need low-cost feed testing, smartphone or sensor-supported record keeping, region-specific feed databases and simple decision-support tools rather than expensive laboratory infrastructure alone.

Table 5. Priority research questions for Indian One Health animal nutrition

Sr.No.	Research domain	Priority question	Potential method	Expected One Health value
1.	Feed resources	Which local residues consistently support productive microbial fermentation?	Chemical profiling + digestibility + metagenomics	Lower feed cost and improved resource efficiency
2.	Feed safety	How common are co-occurring mycotoxins in region-specific feed chains?	LC-MS/MS or validated rapid assays + surveillance	Reduced animal and food-chain exposure
3.	AMR	How do diet and antimicrobial exposure shape livestock resistomes?	Metagenomics + culture + AMR phenotyping	Better stewardship and transmission-risk assessment
4.	Rumen methane	Which diets reduce methane without compromising productivity?	Respiration chambers/SF6/GreenFeed + rumenomics	Lower emissions per unit product
5.	Gut health	Which locally available pre-/probiotic combinations are reproducible?	Controlled feeding + microbiome + immune endpoints	Reduced pathogen pressure and improved resilience
6.	Precision nutrition	Can low-cost sensors and feed analysis predict nutrient intake?	AI/ML + field validation	Better nutrient-use efficiency for smallholders

9.1 India-specific quantitative context for a One Health nutrition framework

India's livestock-nutrition context makes the One Health framework quantitatively important. The Department of Animal Husbandry and Dairying (DAHD) reports that national milk production reached 247.87 million tonnes in 2024–25, up from 239.30 million tonnes in 2023–24, while per-capita milk availability reached 485 g/day in 2024–25. The latest completed national livestock census is the 20th Livestock Census (2019), which recorded 535.78 million livestock and 851.81 million poultry birds; the 21st Livestock Census was launched in October 2024 and is being conducted with digital enumeration (DAHD, 2026; DAHD, 2019). These figures indicate a very large animal-derived food system in which changes in feed quality, gut health and microbial metabolism can scale into food-safety and environmental outcomes.

Feed-resource constraints remain a central Indian specificity. Recent ICAR-IIMR communication has highlighted a 32% green-fodder deficit and a 23% dry-fodder deficit, while earlier IGFR-based national assessments reported approximately 35.6% green-fodder, 10.95% dry-crop-residue and 44% concentrate-feed-ingredient gaps. These estimates should not be treated as interchangeable national constants because they arise from different years, demand assumptions and assessment methods (ICAR-IIMR, 2026; IGFR Vision 2050). For a microbiome-oriented nutrition strategy, the practical implication is that diet formulation must use locally characterized crop residues, cereal straws, cultivated fodders, silages and agro-industrial by-products, with attention to fermentability, digestibility and safety rather than nutrient percentages alone.

India also has a direct climate–nutrition connection. A 2026 high-resolution inventory estimated 37.79 Tg CH₄/year from 25 natural and anthropogenic sources in India for 2023; agriculture contributed about 49% of national methane emissions, and livestock enteric fermentation accounted for about one-third of agricultural methane. Within livestock enteric methane, cattle accounted for 6.03 Tg/year (approximately 51%), indigenous cattle for about 37%, crossbred cattle for about 14%, and buffaloes for roughly 40% (Mishra *et al.*, 2026). The inventory identified Uttar Pradesh as the largest state contributor to livestock methane, followed by Rajasthan, Madhya Pradesh, Bihar and Gujarat, supporting region-specific nutritional interventions rather than a single national ration strategy.

The public-health dimension is also measurable. In a 2025 cross-sectional survey of 691 veterinarians in Gujarat, 77% considered farmer misuse of antimicrobials to contribute significantly to AMR and 78% considered inappropriate antimicrobial use in food-producing animals to contribute to AMR; 92% agreed that culture and antimicrobial susceptibility testing should be used as frequently as possible, but only 4% reported always sending samples for susceptibility testing (Thakar *et al.*, 2025). These findings do not estimate AMR prevalence in livestock; rather, they indicate an implementation gap relevant to antimicrobial stewardship and justify pairing nutritional alternatives with diagnostics, biosecurity and surveillance.

Feed-to-food mycotoxin transfer is another India-relevant One Health pathway. In the 2024 global systematic review and meta-analysis of bovine feed components, India had a reported country-level ochratoxin A concentration of about 52 µg/kg in dairy feed/feed components in the available evidence base (Chhaya *et al.*, 2024). Because country-level values depend on the underlying studies and are not national surveillance estimates, the value should be interpreted as a risk signal rather than a prevalence statistic. Nevertheless, the combination of heterogeneous feed chains, storage-related fungal growth and the biological carry-over of selected mycotoxins supports stronger ingredient-level surveillance and feed-to-milk monitoring in India.

Table 6. India-specific quantitative indicators relevant to One Health animal nutrition

Sr. No.	Indicator	Quantitative fact	Source / method	One Health significance	Reference
1.	Milk production	247.87 million tonnes (2024–25)	DAHD Basic Animal Husbandry Statistics 2025; national annual estimate	Large feed-to-food system; nutrient efficiency and feed safety have population-level implications	DAHD, 2026
2.	Per-capita milk availability	485 g/person/day (2024–25)	DAHD Basic Animal Husbandry Statistics 2025	Shows scale of the dairy food chain relevant to food safety and nutritional security	DAHD, 2026
3.	Latest completed livestock census	535.78 million livestock; 851.81 million poultry (2019)	20th Livestock Census; 21st census launched Oct 2024	Provides the most recent fully published national population baseline	DAHD/PIB, 2019–2026
4.	Feed-resource gap	32% green-fodder and 23% dry-fodder deficit reported by ICAR-IIMR (recent communication); IGFRI Vision 2050 reports 35.6%, 10.95% and 44% gaps for green, dry and concentrates	Different assessments use different years and demand/supply assumptions	Supports region-specific fodder planning, feed testing and microbiome-aware formulation	ICAR-IIMR, 2026; IGFRI Vision 2050
5.	National methane inventory	37.79 Tg CH ₄ /year total India (2023); agriculture ~49%; livestock enteric ≈ one-third of agricultural methane	0.1° × 0.1° bottom-up inventory using country-specific emission factors	Links feed composition and rumen fermentation with national climate outcomes	Mishra <i>et al.</i> , 2026
6.	Livestock methane within inventory	Cattle 6.03 Tg CH ₄ /year (~51% of livestock enteric); buffalo ~40%	2023 national gridded methane inventory	Highlights cattle/buffalo as major targets for ration and fermentation interventions	Mishra <i>et al.</i> , 2026
7.	AMR stewardship indicator	691 Gujarat veterinarians surveyed; 77% linked farmer misuse with AMR; 78% linked inappropriate food-animal use with AMR; 4% always sent samples for AST	2025 cross-sectional survey	Shows that nutrition-based antibiotic alternatives need to be integrated with diagnostics and stewardship	Thakar <i>et al.</i> , 2025
8.	Mycotoxin risk signal	India: ~52 µg/kg country-level OTA concentration in dairy feed/feed	Global 2024 systematic review/meta-analysis; not a national prevalence estimate	Justifies feed ingredient screening and feed-to-milk risk assessment	Chhaya <i>et al.</i> , 2024

Sr. No.	Indicator	Quantitative fact	Source / method	One Health significance	Reference
		components in available studies			

10. Multi-Omics and Precision Nutrition

Host–microbiome integration is becoming experimentally tractable. Genomic and microbial kernel models in Holstein cows showed that including microbiome information improved prediction of some traits, while mediation analysis suggested that a proportion of the host-genetic effect on feed efficiency may operate through the rumen microbiome (2024 Journal of Dairy Science studies). This supports future precision-nutrition systems in which host genotype, feed composition and microbial phenotype are considered jointly.

The next stage of microbiome research is moving from descriptive taxonomy toward functional systems biology. Amplicon sequencing can describe community composition, metagenomics can identify functional genes, metatranscriptomics can indicate active pathways, metabolomics can quantify microbial products, and proteomics can help connect gene expression with biochemical activity.

11. Knowledge Gaps and Challenges

First, microbiome studies often use different sequencing pipelines, sampling sites and analytical definitions, limiting direct comparison. Second, a single time-point sample may not capture a dynamic microbial ecosystem. Third, taxonomic shifts do not necessarily translate into functional changes. Fourth, responses to feed additives are highly context dependent. The recent dairy literature illustrates this clearly: lower microbial diversity has been associated with better feed efficiency in some studies, whereas other studies found little difference among efficiency phenotypes under the same diet. This cautions against treating diversity as a universal target.

A further challenge is translation. Demonstrating that an additive changes the rumen microbiome is not sufficient to claim a human-health benefit. One Health evidence requires a chain of evidence connecting the intervention to a measurable animal phenotype and then to food, environmental or public-health outcomes. Similarly, reducing methane in a short-term trial does not necessarily prove long-term sustainability if animal productivity, feed sourcing or additive production creates countervailing impacts.

12. Conclusion

The gut microbiome provides a mechanistic bridge between animal nutrition and One Health. Feed determines the substrates entering the gastrointestinal ecosystem; microbial communities transform those substrates into metabolites that influence nutrient capture, immunity and host physiology; and microbial metabolism simultaneously affects food safety, antimicrobial resistance and environmental emissions. This makes nutrition a practical upstream lever for improving animal health while supporting broader public-health and environmental objectives.

The strongest future approach is not to pursue a single 'ideal' microbiome but to design diets and management systems that produce desirable microbial functions under defined production conditions. For ruminants, this includes efficient fermentation, microbial protein synthesis and lower methane and nitrogen losses; for monogastrics, it includes stable intestinal communities, barrier function and pathogen resistance. For India, the One Health opportunity lies in integrating local feed resources, feed safety, microbiome science, antimicrobial stewardship and affordable precision nutrition. Such an approach can move animal nutrition from a feed-input discipline toward an integrated biological and ecological science.

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