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Nutrition Induced Gut Microbiota Modulation in Food Animals: Implications for Viral Susceptibility, Shedding and Transmission Dynamics for Sustainable Development

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Abstract

The gut microbiota has emerged as a central mediator linking host nutrition, immune competence, and vulnerability to viral pathogens in food animals. Diet is a primary driver of microbial community structure and function, influencing metabolite production, intestinal barrier integrity, and systemic antiviral immunity. Accumulating evidence indicates that nutrition induced modulation of the gut microbiota can substantially alter viral susceptibility, replication, and shedding patterns, with downstream effects on transmission dynamics within and between animal populations. This review synthesizes current knowledge on the tripartite interactions among diet, gut microbiota, and viral infections in major food animal species including poultry, swine, and ruminants. It critically evaluates how macronutrients, micronutrients, and functional feed additives shape microbial ecosystems and related immune pathways that govern host responses to viral challenge. Mechanistic insights into microbiota derived metabolites, mucosal immunity, and gut barrier regulation are integrated with empirical findings on viral load, shedding duration, and environmental persistence. The review further explores how nutrition mediated microbial modulation can be strategically leveraged to reduce disease burden, enhance vaccine responsiveness, and improve farm level biosecurity. Key knowledge gaps are identified, particularly the need for longitudinal, multi-omics, and field-based studies that bridge experimental models with commercial production systems. Overall, this synthesis highlights the potential of precision nutrition and microbiota targeted interventions as sustainable tools to mitigate viral risks while supporting productivity, health, and resilience in food animal production systems.

Keywords: Animal health, gut microbiota, nutrition, sustainability, viral infection, viral shedding, viral transmission

INTRODUCTION

Viral diseases remain among the most persistent constraints to efficient and sustainable food animal production worldwide, imposing substantial economic losses, welfare concerns, and public health risks through zoonotic transmission and food security disruptions [1–4]. Despite advances in vaccination, biosecurity, and therapeutics, many viral pathogens continue to circulate within and between animal populations, highlighting the need for complementary, preventive, and systems-based approaches to disease control [4–6]. In this context, host nutrition has gained increasing attention as a modifiable determinant of disease susceptibility, immune competence, and infection outcomes in livestock and poultry.

Concurrently, the gut microbiota has emerged as a critical regulator of host physiology, metabolism,

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and immune homeostasis in food animals [7, 8]. This complex microbial ecosystem interacts dynamically with dietary inputs, shaping nutrient utilization, metabolite production, and mucosal barrier function [7–9]. A growing body of evidence demonstrates that diet induced alterations in gut microbial composition and activity can profoundly influence host responses to infectious agents, including viruses. These interactions form a bidirectional network in which nutrition modulates the microbiota, the microbiota regulates immune defenses, and viral pathogens exploit or are constrained by this microbial immune interface [10, 11].

Recent studies indicate that specific dietary components, such as fermentable fibers, amino acids, fatty acids, vitamins, minerals, probiotics, prebiotics, and phytogenic compounds, can modify gut microbial communities in ways that affect viral susceptibility, replication efficiency, and shedding intensity. Microbiota derived metabolites, particularly short chain fatty acids, have been implicated in maintaining intestinal integrity, modulating inflammatory responses, and influencing systemic antiviral immunity [1, 5, 8, 12]. Furthermore, nutrition driven microbial shifts may alter the gut virome, competitive microbial interactions, and receptor availability for viral entry, thereby shaping infection dynamics.

Understanding these interconnected relationships is particularly relevant for food animals, where high stocking densities, intensive feeding systems, and continuous pathogen exposure amplify the risk of viral transmission [10, 11, 13, 14]. Nutritional strategies that promote a resilient and balanced gut microbiota offer a promising, non-antimicrobial avenue to reduce disease burden, limit viral shedding, and mitigate farm level transmission.

This review synthesizes current knowledge on nutrition induced gut microbiota modulation in food animals, with specific emphasis on its implications for viral susceptibility, shedding patterns, and transmission dynamics. By integrating insights from microbiology, immunology, nutrition, and virology, this synthesis aims to provide a conceptual framework for developing microbiota informed nutritional interventions that enhance disease resilience while supporting productivity and sustainability in modern animal production systems.

GUT MICROBIOTA IN FOOD ANIMALS

Composition and Functional Characteristics Across Species

The gut microbiota of food animals comprises diverse bacteria, archaea, fungi, protozoa, and viruses whose composition varies markedly among poultry, swine, and ruminants. These communities are structured along the gastrointestinal tract with distinct profiles in the crop, stomach, small intestine, caecum, and colon [15–17]. Functional capacities also differ across species, reflecting variations in digestive physiology, feed type, and fermentation patterns. Ruminants harbor highly specialized microbial consortia for fiber degradation, whereas monogastric animals exhibit communities adapted to starch and protein metabolism, collectively supporting nutrient extraction and metabolic homeostasis [18–20].

Factors Shaping Microbial Communities Including Diet, Age, and Environment

Gut microbial assembly in food animals is dynamic and influenced by multiple interacting determinants. Diet represents the primary driver, with macronutrient composition, feed processing, and bioactive additives altering microbial diversity and activity. Age related succession patterns occur from hatch or birth through maturity, reflecting developmental changes in the gut and immune system. Environmental factors, such as housing conditions, hygiene, stocking density, antimicrobial exposure, and maternal microbial transfer, further shape community structure, creating substantial interindividual and farm level variability in microbial profiles [1, 2, 21–23].

Role of Gut Microbiota in Host Physiology and Immunity

The gut microbiota performs essential functions in digestion, energy harvest, and synthesis of key metabolites that support host physiology. Microbial fermentation generates short chain fatty acids that nourish intestinal cells, regulate inflammation, and strengthen barrier integrity. The microbiota also educates the immune system by stimulating mucosal defenses, maintaining tolerance to commensals, and enhancing resistance to pathogens. Through continuous cross talk with epithelial and immune cells, gut microbes influence systemic metabolic and immune pathways that determine overall health, productivity, and disease resilience in food animals [1, 24–28].

DIETARY DETERMINANTS OF GUT MICROBIOTA

Influence of Macronutrients Including Protein, Lipids, and Carbohydrates

Macronutrient composition of the diet exerts a dominant influence on gut microbial structure and metabolic activity in food animals. Varying levels and sources of dietary protein shape proteolytic fermentation and nitrogen recycling, often altering the balance between beneficial and potentially harmful taxa [29]. Lipid type and inclusion rate can modify bile acid profiles and microbial lipid metabolism, thereby influencing community composition. Carbohydrates, particularly fermentable fibers and resistant starches, provide substrates for saccharolytic microbes, promoting production of short chain fatty acids and enhancing microbial diversity and stability across the gastrointestinal tract [30–32].

Role of Micronutrients such as Vitamins and Minerals

Micronutrients play critical roles in modulating gut microbial ecology by serving as cofactors for microbial enzymes and host metabolic pathways. Adequate vitamin supply supports both microbial growth and immune mediated regulation of the intestinal ecosystem. Minerals, such as zinc, iron, selenium, and copper, influence microbial competitiveness, oxidative balance, and barrier integrity within the gut [32–34]. Imbalances or deficiencies in these micronutrients can disrupt microbial homeostasis, impair mucosal function, and predispose animals to dysbiosis, inflammation, and increased susceptibility to enteric pathogens [33–35].

Impact of Feed Additives Including Probiotics, Prebiotics, Synbiotics, and Phytogenics

Functional feed additives represent strategic tools for targeted modulation of gut microbiota in food animals. Probiotics introduce beneficial live microorganisms that can enhance competitive exclusion, barrier function, and immune responses [14, 36]. Prebiotics selectively stimulate growth of favorable commensals through provision of fermentable substrates. Synbiotics combine both approaches to achieve synergistic effects on microbial balance. Phytogenic compounds derived from herbs and plant extracts exhibit antimicrobial, antioxidant, and immunomodulatory properties that can beneficially reshape microbial communities while supporting intestinal health and overall performance [37].

MECHANISTIC LINKS BETWEEN NUTRITION AND GUT MICROBIOTA

Nutrient Fermentation and Metabolite Production

Dietary components that escape host digestion become substrates for microbial fermentation, generating a wide spectrum of bioactive metabolites that shape gut ecosystem function. Carbohydrates are converted into organic acids, gases, and secondary metabolites that influence microbial competition and host physiology [30, 32]. Protein fermentation yields amines, phenols, and indoles with variable biological effects, while lipid derived metabolites interact with bile acids and microbial signaling pathways. The balance between saccharolytic and proteolytic fermentation determines overall metabolic output, microbial stability, and host nutritional status across food animal species.

Short Chain Fatty Acids and Immune Signaling

Short chain fatty acids, particularly acetate, propionate, and butyrate, represent key microbial metabolites that link nutrition to immune regulation. These compounds act as energy sources for intestinal epithelial cells while modulating inflammatory pathways and immune cell differentiation [38–40]. Butyrate strengthens mucosal defense by enhancing regulatory immune responses and reducing excessive inflammation. Through receptor mediated and epigenetic mechanisms, short chain fatty acids coordinate local and systemic immunity, influencing host resistance to infectious agents and overall immunological homeostasis in food animals.

Microbial Metabolite Mediated Modulation of Intestinal Barrier

Microbiota derived metabolites play a central role in maintaining and regulating intestinal barrier integrity. Butyrate and other fermentation products enhance tight junction protein expression, mucin production, and epithelial cell turnover, thereby limiting pathogen translocation. Secondary bile acids and microbial peptides further contribute to barrier function and antimicrobial defense [15, 19, 41–45]. Disruption in metabolite profiles due to dietary imbalance or dysbiosis can weaken the epithelial barrier, increase gut permeability, and heighten susceptibility to enteric inflammation and viral invasion in food animal production systems.

GUT MICROBIOTA AND ANTIVIRAL IMMUNITY

Interaction Between Microbiota and Innate Immune Responses

The gut microbiota interacts continuously with innate immune components, shaping the first line of defense against viral pathogens in food animals. Microbial associated molecular patterns stimulate pattern recognition receptors on epithelial and immune cells, priming antiviral signaling pathways and interferon responses [15, 19, 41–45]. Commensal microbes also regulate inflammatory tone by balancing pro and anti-inflammatory mediators, preventing excessive tissue damage while maintaining readiness against infection. This dynamic interplay enhances mucosal surveillance, limits viral colonization, and contributes to rapid containment of early-stage viral challenges within the gastrointestinal tract.

Microbiota Driven Regulation of Adaptive Immunity

Gut microbial communities play a pivotal role in educating and modulating adaptive immune responses that determine long term antiviral protection. Commensals influence the development and differentiation of T and B lymphocytes, promoting balanced cellular and humoral immunity. Microbial metabolites and antigenic stimulation enhance immunoglobulin production, particularly secretory IgA, which neutralizes viruses at mucosal surfaces. Through continuous immune training, the microbiota supports immune memory, improves vaccine responsiveness, and strengthens host resilience to recurrent viral exposures in food animals [40, 46].

Cross Talk Between Gut Microbes and Systemic Antiviral Defense

Signals originating from the gut microbiota extend beyond the intestine to shape systemic antiviral immunity in food animals. Microbial metabolites and immune mediators enter circulation, influencing distant organs including the respiratory and reproductive tracts. This gut systemic axis modulates interferon production, natural killer cell activity, and antiviral gene expression throughout the body [32]. Disruption of this cross talk through dysbiosis or poor nutrition can weaken whole body antiviral defenses, whereas a balanced microbiota supports coordinated, organism wide protection against viral pathogens.

NUTRITION INDUCED MICROBIOTA CHANGES AND VIRAL SUSCEPTIBILITY

Evidence from Poultry, Swine, and Ruminant Models

Experimental and field studies across poultry, swine, and ruminants demonstrate that nutrition induced shifts in gut microbiota are closely associated with altered viral susceptibility. In poultry, dietary fiber, probiotics, and phytogenics have been linked to microbial profiles that reduce enteric and respiratory viral impacts. In swine, protein level and fermentable carbohydrates modify microbial communities that correlate with outcomes of viral enteric infections. In ruminants, forage to concentrate ratios shape rumen and intestinal microbiota, influencing systemic immune status and susceptibility to viral pathogens [15, 41, 42, 47].

Effects of Diet Composition on Host Vulnerability to Viral Infection

Diet composition directly influences host vulnerability to viral infection by modulating microbial structure, metabolite production, and immune competence. Diets rich in fermentable substrates enhance beneficial microbial populations and short chain fatty acid production, strengthening mucosal defenses [38, 48, 49]. High protein or high fat diets may promote dysbiosis, impair barrier integrity, and increase inflammatory responses that favor viral persistence. Balanced nutrient formulations support microbial stability, optimize antiviral immune pathways, and reduce viral replication, shedding, and disease severity in food animals [50, 51].

Species Specific Responses and Variability

Responses to nutrition induced microbiota modulation vary substantially among poultry, swine, and ruminants due to differences in digestive physiology, feeding systems, and baseline microbial ecology. Monogastric animals exhibit rapid microbial shifts in response to dietary changes, whereas ruminants display more buffered responses due to complex foregut fermentation. Genetic background, production stage, and management practices further contribute to variability. Understanding these species-specific patterns is essential for designing targeted nutritional strategies that effectively mitigate viral susceptibility and transmission risk [52, 53].

IMPLICATIONS FOR VIRAL SHEDDING IN FOOD ANIMALS

Relationship Between Gut Microbiota and Viral Load

The composition and functional activity of the gut microbiota are closely associated with viral load in infected food animals. Certain microbial communities can restrict viral replication through competitive exclusion, enhancement of mucosal immunity, and production of antiviral metabolites. Conversely, dysbiotic microbiota may weaken barrier defenses and facilitate viral persistence within the gastrointestinal tract. The balance between beneficial and opportunistic microbes, therefore, plays a decisive role in determining intestinal viral burden, systemic dissemination, and overall infection intensity during acute and subclinical disease states [6, 54–56].

Dietary Strategies Influencing Viral Shedding

Targeted nutritional interventions can modify gut microbial profiles in ways that reduce both the duration and magnitude of viral shedding [46, 56, 57]. Diets enriched with fermentable fibers, probiotics, and bioactive phytochemicals promote microbial communities that strengthen mucosal defenses and limit viral replication. Balanced protein and lipid formulations prevent dysbiosis and excessive inflammation that may prolong shedding. Strategic feeding programs, therefore, represent practical tools to minimize environmental viral contamination and lower transmission risk within production systems [31, 58, 59].

Consequences for Farm Level Biosecurity

Nutrition mediated control of gut microbiota and viral shedding has significant implications for farm level biosecurity and disease management. Reduced viral shedding decreases environmental contamination, lowers infection pressure, and limits animal to animal transmission within densely stocked facilities [33, 60, 61]. Integrating microbiota supportive diets with vaccination, hygiene, and biosecurity protocols can enhance overall disease resilience. Such approaches contribute to more sustainable production systems by reducing outbreak frequency, antimicrobial dependence, and economic losses associated with viral diseases.

IMPACT ON VIRAL TRANSMISSION DYNAMICS

Role of Nutrition and Microbiota in Environmental Viral Persistence

Nutrition induced alterations in gut microbiota can indirectly influence environmental viral persistence through effects on faecal composition and shedding characteristics. Diets that promote beneficial microbial communities may reduce viral load and stability in excreta by enhancing mucosal immunity and limiting viral replication. Conversely, dysbiosis associated with imbalanced nutrition can increase viral excretion and survival in litter, manure, or water systems. Microbial metabolites and organic matter content in waste further affect viral stability, highlighting the interconnected role of diet, microbiota, and environmental contamination dynamics [50, 62, 63].

Animal to Animal Transmission Patterns Under Different Dietary Regimes

Dietary regimes that shape gut microbiota significantly affect patterns of viral transmission among food animals. Balanced, microbiota supportive diets tend to reduce susceptibility, viral shedding, and contact based spread within herds or flocks. In contrast, nutrient imbalances that disrupt microbial homeostasis can elevate infection pressure and facilitate rapid transmission. Variations in feeding strategies, stocking density, and microbial resilience collectively determine how efficiently viruses move between individuals under different nutritional conditions [46, 54, 55, 57].

Implications for Outbreak Risk and Control

Understanding nutrition microbiota interactions provides valuable insights for managing outbreak risk and designing effective control strategies. Diets that enhance microbial stability and antiviral immunity can lower baseline susceptibility and reduce the probability of large scale transmission events. Integrating targeted nutritional interventions with vaccination, sanitation, and surveillance programs can strengthen preventive biosecurity. Such approaches support proactive disease management, minimize production disruptions, and promote long term sustainability in intensive animal production systems [31, 33, 56, 58].

INTERPLAY BETWEEN GUT BARRIER FUNCTION, MICROBIOTA, AND VIRAL INFECTION

Nutritional Modulation of Intestinal Integrity

Diet plays a central role in maintaining and strengthening intestinal integrity in food animals. Adequate levels of fermentable carbohydrates, specific amino acids, fatty acids, vitamins, and minerals support epithelial cell turnover, tight junction stability, and mucus layer development. Nutrient deficiencies or imbalanced formulations can compromise barrier structure, increase intestinal permeability, and trigger inflammatory responses. Optimized nutrition, therefore, sustains a resilient gut lining that limits pathogen entry, maintains homeostasis, and supports overall gastrointestinal health and productivity [2, 33, 64, 65].

Microbiota Mediated Protection Against Viral Translocation

A balanced gut microbiota provides multilayered protection against viral translocation from the intestine into systemic circulation. Beneficial microbes enhance mucin production, strengthen epithelial tight junctions, and produce metabolites that inhibit viral attachment and penetration. Competitive exclusion and antimicrobial peptide induction further limit viral access to epithelial receptors [2, 33, 64, 65]. Through these combined mechanisms, a stable microbial ecosystem acts as a biological barrier that restricts viral movement beyond the gut.

Relevance to Systemic Infection Risk

The integrity of the gut barrier and its microbial regulation directly influence the risk of systemic viral infection in food animals. Compromised barriers allow viral particles and inflammatory mediators to enter circulation, increasing the likelihood of widespread tissue dissemination and clinical disease [2, 33, 64, 65]. Conversely, a well-maintained barrier supported by optimal nutrition and microbiota reduces systemic exposure, limits immune overactivation, and lowers overall infection severity and transmission potential.

PRACTICAL APPLICATIONS IN ANIMAL PRODUCTION

Diet Formulation Strategies to Reduce Viral Susceptibility

Precision diet formulation can enhance gut health and reduce viral susceptibility in food animals. Balancing macronutrients, ensuring adequate protein quality, optimizing fiber content, and supplementing essential vitamins and minerals support microbial stability, mucosal integrity, and immune competence. Tailored feeding programs can target critical growth phases or high-risk periods to strengthen antiviral defenses. By designing nutritionally complete and microbiota supportive diets, producers can reduce infection pressure, limit viral replication, and improve overall resilience against viral challenges in intensive production systems [66, 67].

Use of Functional Feed Additives for Microbiota Modulation

Functional feed additives, such as probiotics, prebiotics, synbiotics, and phytogenics, offer effective tools to modulate gut microbiota and enhance antiviral defenses. Probiotics introduce beneficial microbes that compete with pathogens and stimulate immune responses. Prebiotics selectively feed commensal microbes, promoting metabolite production that supports barrier function [18, 68, 69]. Synbiotics combine both strategies for synergistic effects, while phytogenic compounds provide antimicrobial, antioxidant, and immunomodulatory benefits. Incorporating these additives strategically into diets can stabilize microbial communities, reduce viral shedding, and improve animal health and performance.

Integration with Vaccination and Biosecurity Programs

Nutrition and microbiota targeted interventions are most effective when integrated with vaccination and farm level biosecurity measures. Optimized diets and functional feed additives enhance vaccine responsiveness by supporting mucosal and systemic immunity, while reducing viral load and shedding diminishes transmission risks. Coupling these nutritional strategies with sanitation, controlled animal movement, and monitoring programs strengthens preventive health management. Such a holistic approach improves disease resilience, mitigates outbreak risks, and contributes to sustainable, high productivity food animal production systems [36, 68, 69].

KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

Need for Longitudinal and Mechanistic Studies

Current evidence on nutrition induced microbiota modulation and viral susceptibility in food animals is largely derived from short term or cross-sectional studies. Longitudinal investigations are needed to capture temporal dynamics of microbial communities, metabolite production, and host immune responses during different growth phases and infection stages. Mechanistic studies at cellular and molecular levels will clarify causal relationships between diet, microbiota, and viral resistance. Such research is essential to move beyond correlations and develop targeted, evidence based nutritional interventions for disease control.

Multi-Omics Approaches to Link Diet, Microbiota, and Virome

Integrating multi-omics technologies, including metagenomics, metabolomics, transcriptomics, and proteomics, offers comprehensive insights into the interactions between nutrition, gut microbiota, and viral populations. These approaches can identify microbial taxa, metabolic pathways, and host immune networks that influence viral susceptibility and shedding. Multi-omics analyses enable detection of subtle diet induced shifts, uncover virus microbiota cross talk, and facilitate prediction of infection outcomes. Application of these techniques will advance precision nutrition strategies and microbiota targeted interventions in food animal production.

Translation from Experimental Models to Field Conditions

Most current studies are conducted under controlled laboratory or experimental conditions, which may not fully replicate commercial production environments. Variability in genetics, housing, feed quality, and pathogen exposure can affect outcomes in field settings. Translational research is required to validate laboratory findings in practical conditions, assess real world efficacy of dietary and microbiota interventions, and develop cost effective, scalable strategies. Bridging this gap will enable implementation of microbiota informed nutrition programs that improve viral resilience and productivity on commercial farms.

CONCLUSIONS

Nutrition plays a central role in shaping gut microbiota, which in turn influences viral susceptibility, shedding, and transmission dynamics in food animals. Diet composition, macronutrient balance, micronutrients, and functional feed additives can modulate microbial diversity, metabolite production, and immune responses. A stable and balanced gut microbiota enhances intestinal barrier integrity, supports antiviral immunity, and reduces viral replication and environmental contamination. Evidence from poultry, swine, and ruminants highlights the potential of diet driven microbial modulation as a non-antimicrobial strategy to improve animal health and performance.

Integrating nutrition based microbial interventions into production systems offers a sustainable approach to disease management. By reducing viral susceptibility and shedding, these strategies lower the reliance on antimicrobials, improve biosecurity, and minimize economic losses associated with viral outbreaks. Enhancing gut health and immune competence through diet promotes resilience to infections, supports productivity, and contributes to animal welfare. Such approaches align with global priorities for sustainable intensification, environmental stewardship, and responsible livestock management.

Future research should focus on longitudinal and mechanistic studies, multi-omics analyses, and field validation to establish causal links between diet, microbiota, and viral outcomes. Advances in precision nutrition, functional feed additives, and microbiota targeted interventions are likely to transform viral disease management in food animals. Understanding species specific responses, host microbiome variability, and virus microbiota interactions will enable tailored strategies that optimize health, reduce transmission risks, and enhance sustainability. Continued integration of nutrition, microbiology, and virology will shape next generation approaches for resilient animal production systems.

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