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Postbiotic and Parabiotic Feed Additives in Livestock and Poultry Nutrition: Review on Mechanisms, Health Effects, and Performance Outcomes

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Abstract

The livestock and poultry industries need antibiotic growth promoter alternatives that remain effective during feed processing and storage, where live probiotics may lose viability under heat and pressure. Postbiotics - preparations of inanimate microorganisms and/or their components - and parabiotics (paraprobiotics) have therefore emerged as promising non-live feed additives. This review summarizes evidence on the mechanisms of action and applications of postbiotics and parabiotics in poultry and ruminants, emphasizing microbiota modulation, intestinal barrier function, immunomodulation and performance outcomes, and comparing these products with conventional probiotics. Lactic acid bacteria, *Bifidobacterium*, *Saccharomyces cerevisiae* and *Aspergillus oryzae* are producer strains that generate bioactive metabolites. In poultry, dietary postbiotics typically increase lactic acid bacteria, reduce Enterobacteriaceae counts and gut pH, and improve villus height and villus:crypt ratio, often accompanied by improved weight gain and feed conversion, particularly under heat stress or enteric challenge. In layer pullets orally challenged with 1 mL of a 10^6 CFU/mL *Salmonella Enteritidis* inoculum, a *Saccharomyces*-derived postbiotic reduced cecal colonization from about 4.49 to 3.35 log CFU/g, demonstrating a measurable pre-harvest food safety benefit. In ruminants, *Lactiplantibacillus plantarum* RG14 postbiotics increased ruminal propionic acid concentration by about 18% (31.81 vs. 37.56 mM), enhanced cellulolytic bacteria, and improved rumen papillae development and expression of antioxidant and tight junction genes in post-weaning lambs. The review also considers safety and regulation, highlights the need for harmonized ISAPP-aligned definitions and product characterization, and notes that non-replicating preparations are intrinsically safer and more stable than live probiotics but remain strongly dependent on source strain, inactivation method, dose and delivery matrix. Overall, postbiotics and parabiotics are promising tools to support sustainable, antibiotic-reduced animal production when integrated into well-designed feeding programs.

Keywords: Postbiotics; parabiotic; non-viable microbial products; immunomodulation; intestinal barrier function; antibiotic growth promoter alternatives; sustainable livestock production.

Introduction

The intestinal microbiota is a central determinant of animal health, productivity and welfare because it influences nutrient digestion, immune maturation, epithelial integrity and resistance to enteric disturbances (Ducatelle et al., 2023; Kogut & Arsenault, 2016). In parallel, precision nutrition and Precision Livestock Farming are directing increasing attention towards feed interventions that can modulate host physiology and microbiome function in a more targeted and consistent manner (Pomar & Remus, 2023).

A key challenge in modern livestock and poultry nutrition is therefore to identify microbiome-directed feed additives that remain functional during feed manufacture, storage and delivery, while still producing predictable biological effects under commercial conditions. Probiotics can improve microbiota balance, barrier function and immune responses (Binda et al., 2020), but their efficacy depends on maintaining viable cells at adequate levels throughout processing, shelf life and gastrointestinal transit (Binda et al., 2020). This dependence may contribute to variable responses, particularly under commercial feeding conditions where thermal and mechanical stresses can impair viability (Morán et al., 2025).

In this context, postbiotics and parabiotic are attracting increasing interest not only because they are non-viable, but also because they offer the prospect of improved product characterization, more reproducible delivery of bioactive microbial fractions, and greater stability during processing and storage when properly formulated and characterized (Morán et al., 2025; Salminen et al., 2021; Vinderola et al., 2022, 2025). According to the 2021 ISAPP consensus, postbiotics are “preparations of inanimate microorganisms and/or their components that confer a health benefit on the host” (Salminen et al., 2021), whereas parabiotic mainly denote inactivated cells and cell-wall-associated structures (Abd El-Ghany, 2020).

These preparations are increasingly investigated as functional tools for immunomodulation, intestinal barrier support, microbiota modulation and pathogen control, rather than simply as substitutes for live probiotics (Peluzio et al., 2021; Teame et al., 2020). Studies in poultry and ruminants indicate that they can influence growth performance, intestinal morphology, oxidative status, immune responses and resilience under challenge conditions (Chae et al., 2024; Humam et al., 2019, 2020; Izuddin et al., 2019, 2020; D. Li et al., 2024). However, interpretation across studies remains constrained by inconsistent terminology, differences in source strain, inactivation method, formulation and dose, and the continuing need for improved product characterization and quantification

(Salminen et al., 2021; Vinderola et al., 2025).

Against this background, the objective of this review is to provide a focused synthesis of postbiotics and parabiotics in livestock and poultry nutrition. Specifically, the review aims to clarify their definitions within the current nomenclature framework, summarize their biogenesis and principal mechanisms of action, critically evaluate evidence from poultry and ruminant studies on health, performance and product quality, compare them with probiozics and other feed additives, and identify key priorities for standardization, characterization and commercial application**.**

Definitions, Biogenesis and Mechanisms of Action

Probiotics, postbiotics and related terminology

Probiotics are defined by ISAPP as "live microorganisms that, when administered in adequate amounts, confer a health benefit on the host" (Binda et al., 2020). Because viability is integral to this definition, probiotic efficacy depends on survival during manufacture, storage and gastrointestinal transit, which may contribute to variable responses under practical feeding conditions(Binda et al., 2020). In practice, this also underlies continuing safety discussions around opportunistic infection and transferable resistance determinants in vulnerable hosts (Kothari et al., 2019; Merenstein et al., 2023).

Postbiotics are defined by the 2021 ISAPP consensus as "preparations of inanimate microorganisms and/or their components that confer a health benefit on the host" (Salminen et al., 2021). Under this framework, the active entity is the preparation itself, which may contain intact or fragmented inanimate cells, cell-associated structures and, where present, associated metabolites(Salminen et al., 2021; Vinderola et al., 2022). In earlier literature, the term parabiotic was commonly used for non-viable intact or disrupted microbial cells and crude cell extracts (Abd El-Ghany, 2020). In the present review, however, the ISAPP term postbiotic is used throughout, and preparations are distinguished, where relevant, according to whether the dominant bioactive fraction is primarily cellular or acellular (Salminen et al., 2021; Vinderola et al., 2023). Accordingly, cell-free supernatants or purified microbial metabolites that lack inanimate cells or cell components are referred to as culture supernatants or microbial metabolites rather than postbiotics unless the cited study demonstrates that the preparation meets the ISAPP definition.

Biogenesis and producing microorganisms

The biogenesis of postbiotic preparations begins with careful strain selection, which is critical for safety, consistency and downstream functionality (Binda et al., 2020; Salminen et al., 2021; Vinderola et al., 2022). Candidate strains should be non-pathogenic and non-toxin-producing, and safety should be supported by appropriate taxonomic identification, genomic assessment and, where relevant, GRAS or QPS status (Binda et al., 2020; de Melo Pereira et al., 2018). Whole-genome sequencing is strongly recommended to exclude virulence factors and mobile resistance determinants and to characterize metabolic potential (Vinderola et al., 2022). Functionally, strain selection should be guided not only by the capacity to generate bioactive metabolites or cell-associated structures, but also by the physiological target in the host species (Peluzio et al., 2021; Teame et al., 2020).

A wide range of microorganisms has been investigated as postbiotic progenitors in livestock and poultry, but their relevance is not uniform across production systems. In poultry and other monogastrics, lactic acid bacteria such as *Lactiplantibacillus plantarum*, *Lacticaseibacillus rhamnosus*, *Lactococcus lactis*, *Enterococcus faecium*, *Streptococcus thermophilus* and *Leuconostoc* spp., together with some *Bifidobacterium* spp. and *Bacillus* spp., are studied mainly for intestinal acidification, pathogen exclusion, epithelial integrity and immune modulation (Danladi et al., 2022; D. Li et al., 2024). These microorganisms can contribute organic acids, exopolysaccharides, bacteriocins, peptides and cell-associated immunomodulatory structures that are relevant to villus architecture, microbial balance and mucosal defence (Peluzio et al., 2021; Teame et al., 2020). In ruminants, by contrast, *Saccharomyces cerevisiae* and *Aspergillus oryzae* are valued more for their effects on rumen fermentation stability, fiber utilization, papilla development and resilience to heat or transition stress (Chae et al., 2024; Dias et al., 2018; Kaufman et al., 2021). This host-oriented distinction is important because postbiotic design in broilers is commonly directed towards intestinal morphology and pathogen control, whereas in cattle and sheep it is more often directed towards rumen function and metabolic resilience (Chae et al., 2024) The principal progenitor microorganisms, their dominant bioactive fractions and their primary livestock applications are summarized in Table 1.

Multistrain or multispecies fermentations are increasingly explored because co-culturing can broaden the diversity and concentration of bioactive compounds, but compatibility testing remains essential because strain interactions may also alter or dilute the final functional profile (Pimentel et al., 2023). Following fermentation, cells are inactivated using heat, high pressure, radiation, pH shock, drying or chemical agents. Importantly, inactivation is not simply a termination step, but a major determinant of the final postbiotic profile because it influences which cell-associated structures and soluble compounds are retained, exposed, fragmented or lost (Pimentel et al., 2023; Zhu et al., 2025). Thermal inactivation remains the most practical and scalable approach for feed and food applications, but its biological consequences depend strongly on intensity (Pimentel et al., 2023; Zhu et al., 2025).

Table 1. Updated microorganism names, principal bioactive components, primary livestock applications, and representative references

Microorganism name (updated)	**Main bioactive components**	**livestock application**	**References**
Lactiplantibacillus plantarum, *Lacticaseibacillus rhamnosus*, *Lacticaseibacillus casei*, *Lacticaseibacillus paracasei*, *Lactobacillus acidophilus*, *Lactobacillus gasseri*, *Limosilactobacillus fermentum*, *Ligilactobacillus salivarius*, *Lactococcus lactis*, *Enterococcus faecium*, *Streptococcus thermophilus*, *Leuconostoc* spp.	Organic acids, exopolysaccharides, bacteriocins, bioactive peptides, peptidoglycan- and teichoic-acid-rich structures	Poultry and other monogastrics: pathogen exclusion, gut-barrier support, villus architecture and immune modulation	(Danladi et al., 2022; D. Li et al., 2024; Teame et al., 2020)
Bifidobacterium bifidum, *Bifidobacterium breve*, *Bifidobacterium animalis* subsp. *Lactis*	Acetate and other organic acids, exopolysaccharides, peptides, cell-associated immunomodulatory structures	Mainly monogastrics: gut-health support, inflammatory control and pathogen resistance	(Peluzio et al., 2021; Vinderola et al., 2022)
Saccharomyces cerevisiae	β-glucans, mannans/mannoproteins, nucleotides, antioxidants, organic acids and fermentation metabolites	Calves and dairy cows: rumen development, immune support and transition resilience; also some poultry applications	(Chae et al., 2024; Gingerich et al., 2021; Gong et al., 2025; Harris et al., 2017)
Aspergillus oryzae	Glucan- and galactomannan-rich fractions, extracellular enzymes, extracellular polymeric substances and fermentation metabolites	Ruminants: rumen pH support, fiber digestion and heat-stress resilience	(Basson et al., 2025; Kaufman et al., 2021)

Microorganism name (updated)	**Main bioactive components**	**livestock application**	**References**
Bacillus spp. (mainly *Bacillus subtilis*)	Enzymes, peptides/lipopeptides, cell-wall fragments and fermentation metabolites	Broilers: growth performance, gut health, immunity and skeletal integrity	(D. Li et al., 2024)

Mild heating may preserve functional activity, whereas excessive heating can alter the chemical profile of the preparation and reduce heat-sensitive bioactive compounds (Sun et al., 2023; Zhu et al., 2025). For example, postbiotics derived from *Lacticaseibacillus paracasei* ET-22 and *Bifidobacterium animalis* subsp. *lactis* BL-99 retained antioxidant and anti-inflammatory activity after heating below 100°C, whereas treatment at 121°C significantly altered their chemical profile and reduced several bioactive constituents (Sun et al., 2023).

By contrast, non-thermal physical methods such as high-pressure processing, pulsed electric fields and ultrasound are generally considered when greater preservation of heat-sensitive structures or metabolites is desired, although their effects remain highly strain- and parameter-specific (Pimentel et al., 2023; Zhu et al., 2025). Chemical or pH-based inactivation may also modify surface chemistry and cell-envelope integrity, and therefore requires product-specific validation rather than assumption of equivalence to heat-derived preparations (Pimentel et al., 2023; Zhu et al., 2025)). This is illustrated by the observation that heat and sonication caused different patterns of membrane injury and morphological disruption in *Lactobacillus gasseri* and *Lactiplantibacillus plantarum*, indicating that the same progenitor strain can yield materially different postbiotic preparations depending on the inactivation route (Gholian et al., 2024) These differences are especially relevant when immunomodulation is an intended endpoint, because the retention or exposure of immune-active surface structures helps determine how the preparation interacts with host pattern-recognition receptors (Rocha-Ramírez et al., 2020; Zhu et al., 2025) For instance, heat-killed *Lacticaseibacillus casei* IMAU60214 stimulated macrophage nitric oxide and cytokine production through TLR2-dependent signaling (Rocha-Ramírez et al., 2020). In a livestock-relevant model, heat-inactivated *Lactobacillus gasseri* LA806 showed lower anti-adhesion activity against *Staphylococcus aureus* than the live strain, but its anti-inflammatory properties were largely preserved in bovine mammary epithelial cells (Blanchet et al., 2021). Taken together, these findings indicate that inactivation conditions should be selected according to the intended mode of action, particularly whether the target activity depends mainly on preserved cell-associated ligands or on soluble bioactive compounds. The major inactivation routes and their likely implications for postbiotic composition, structural integrity and biological activity are summarized in Table 2.

Table 2. Likely influence of inactivation route on postbiotic composition, bioactivity, and representative references

Inactivation route	**Main molecular consequence**	**Likely functional implication**	**References**
Mild heat treatment	Inactivates cells while retaining many heat-stable cell-associated structures; some soluble bioactive compounds remain	Suitable for scalable production of cell-associated postbiotics; some immunomodulatory activity retained	(Sun et al., 2023); (Zhu et al., 2025)
Severe heat treatment	Greater membrane disruption and stronger alteration of chemical profile	May reduce antioxidant and anti-inflammatory activity and shift the functional profile	(Sun et al., 2023); (Zhu et al., 2025)
Sonication / mechanical disruption	Membrane injury, fragmentation and release of intracellular material	Favors lysate-like or fragment-rich preparations; not equivalent to heat-derived products	(Gholian et al., 2024)
Non-thermal physical methods	May preserve some heat-sensitive structures or metabolites better than severe heat	Promising for sensitive products but requires strain-specific validation	(Pimentel et al., 2023); (Zhu et al., 2025)
pH-based / chemical inactivation	Alters membrane structure and surface chemistry in a strain-dependent manner	Potentially useful, but requires product-specific optimization	(Pimentel et al., 2023); (Zhu et al., 2025)

From a feed manufacturing perspective, this distinction is especially important because broiler pelleting studies commonly evaluate steam-conditioning temperatures in the 71-88°C range, and conditioning can reach about 90°C under practical or experimental conditions (Rueda et al., 2022; Teixeira Netto et al., 2019). Unlike probiotics, whose efficacy depends on survival of viable cells during processing, postbiotics are not defined by cell viability and are therefore less constrained by steam-conditioning and pelleting temperatures used in compound-feed manufacture (Morán et al., 2025). Recent evidence supports this technological advantage but also indicates that thermostability remains product specific: high-temperature short-time treatment at approximately 105°C for 7 s caused only minor changes in the metabolomic profile of a *Lactobacilli*-derived postbiotic, whereas heating below 100°C for 10 min preserved antioxidant and anti-inflammatory activity in other postbiotic preparations, while 121°C significantly altered their chemical profile and reduced antioxidant activity (Jansseune et al., 2025). Thus, the practical advantage of postbiotics for feed millers is not absolute heat indifference, but greater functional compatibility with conditioning and pelleting processes that commonly challenge live microbial additives.

Mechanisms of Action

The mechanisms of action of postbiotics are multifactorial and interrelated, operating not only at microbiota, epithelial and immune levels within the gut, but also through gut-organ axes that influence systemic metabolism. Key mechanisms include:

Modulation of gut microbiota and fermentation

Postbiotic preparations typically contain organic acids, SCFAs, EPS and bacteriocins that shape the composition and metabolic output of the microbiota. Organic acids and SCFAs lower luminal pH and create an environment that disfavors acid-sensitive pathogens such as *Escherichia coli*, *Salmonella spp.* and *Clostridium perfringens*, while promoting acid-tolerant beneficial genera such as *Lactiplantibacillus* and *Bifidobacterium* (Johnson et al., 2019; Kareem et al., 2016; Lamas et al., 2019). EPS from *Lactiplantibacillus* and *Bifidobacterium* act as fermentable substrates for commensals, enhance cross-feeding interactions and increase SCFA production, particularly propionate and butyrate (Bengoa et al., 2020; Peluzio et al., 2021). Beyond these local luminal effects, acetate, propionate and butyrate can enter the portal circulation and act as signaling molecules through G-protein-coupled receptors such as GPR41 (FFAR3) and GPR43 (FFAR2), thereby linking microbial fermentation to hepatic energy metabolism and broader nutrient partitioning (Lee et al., 2024). Figure 1. depicts how microbial fermentation-derived short-chain fatty acids enter the portal circulation and act through gut-liver and gut-brain signaling pathways to influence hepatic metabolism, feed intake regulation, feed efficiency and overall production performance.

This systemic signaling is increasingly relevant in animal production because microbial metabolites are now recognized as mediators of the gut-liver and gut-brain axes, with implications for hepatic function, neuroendocrine regulation and production performance in poultry, and acetate-mediated hepatic AMPK-PPARA signaling has recently been implicated in postpartum energy metabolism in dairy ruminants (Beldowska et al., 2023; S. Wang et al., 2025). In poultry and pigs, postbiotic supplementation has repeatedly been associated with increased lactic acid bacteria, reduced Enterobacteriaceae, lower intestinal pH and improved villus morphology (Danladi et al., 2022; Humam et al., 2019, 2020). In ruminants, *Lactiplantibacillus plantarum* RG14 postbiotics increased ruminal VFA and cellulolytic bacteria and improved rumen papillae development, thereby enhancing fermentative efficiency and nutrient absorption in post-weaning lambs (Izuddin et al., 2018, 2019, 2020). Taken together, these observations indicate that modulation of gut fermentation may contribute not only to local microbial balance and epithelial health, but also to metabolic regulation beyond the intestine.

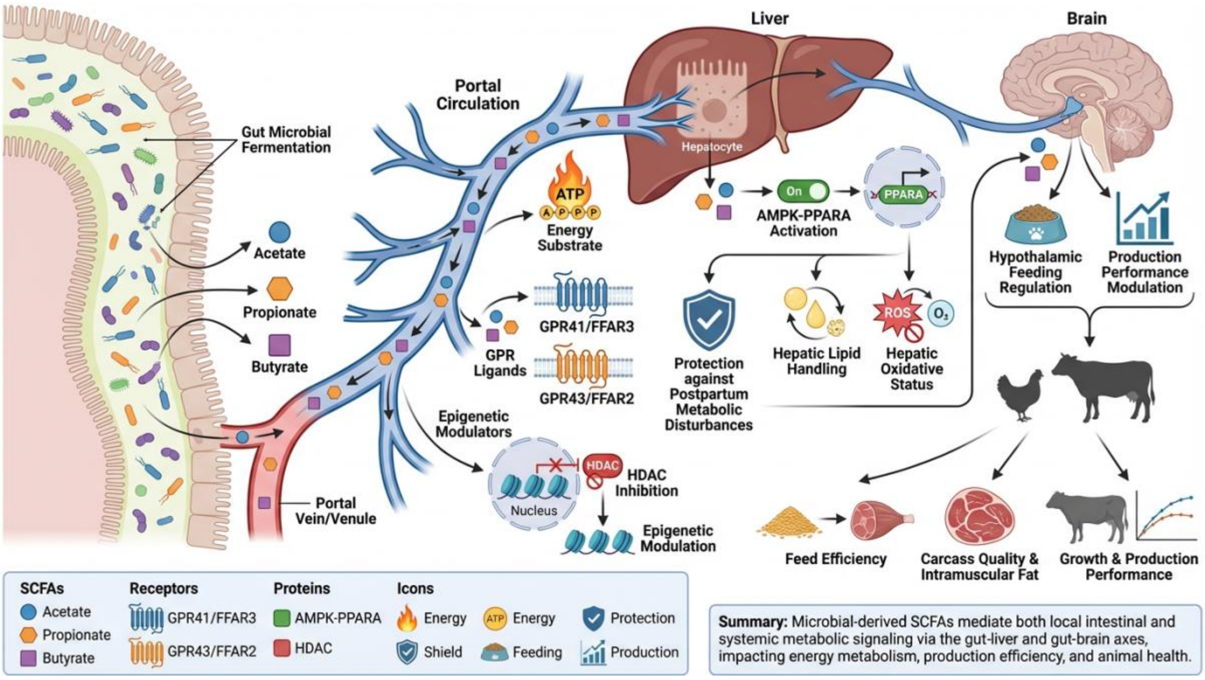


Figure 1. Systematic metabolic signaling and gut-organ axes mediated microbiota driven short chain fatty acids in livestock

Reinforcement of epithelial barrier

SCFAs, EPS and cell-wall components can upregulate tight-junction proteins and stimulate mucin production, thereby strengthening the physical and chemical components of the intestinal barrier (Peluzio et al., 2021; Teame et al., 2020; J. Wang et al., 2018). Importantly, these barrier-protective effects are also supported by in vivo evidence in production animals. In broilers challenged with necrotic enteritis, postbiotic supplementation improved intestinal morphology by increasing the villus height: crypt depth (VH:CD) ratio and enhanced jejunal ZO-1 expression, indicating better preservation of epithelial integrity under enteric challenge (Dong et al., 2025). In a commercial swine production system, supplementation with a *Saccharomyces cerevisiae* fermentation derived postbiotic reduced pre-weaning diarrhea and increased the expression of Claudin-1 and Occludin in piglets, consistent with strengthened epithelial barrier function even in the absence of major changes in small-intestinal morphology (Hung et al., 2025). Similarly, in post-weaning lambs, dietary postbiotic derived from *Lactiplantibacillus plantarum* RG14 upregulated TJP-1, CLDN-1 and CLDN-4 and supported ruminal epithelial development, indicating that barrier-related effects extend beyond monogastrics (Izuddin et al., 2019, 2020). In poultry and swine studies, these barrier-supporting effects are commonly reflected histomorphometrically by an increased VH: CD ratio, a standard index interpreted as indicating a more mature and functionally efficient mucosa with greater absorptive capacity and lower epithelial turnover pressure (Belote et al., 2023; Danladi et al., 2022). In vivo, these barrier-supporting effects translate into improved villus architecture, lower gut permeability and better histological scores in postbiotic-supplemented animals, particularly under challenge or environmental stress (Danladi et al., 2022).

Immunomodulation

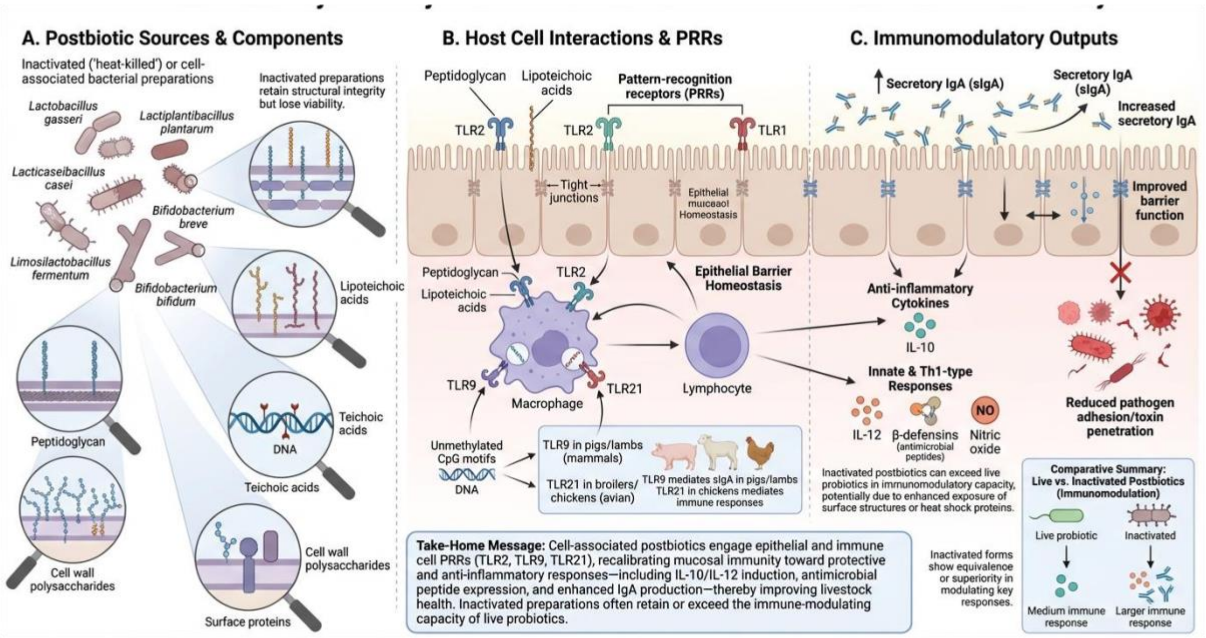
Cell-associated postbiotic components such as peptidoglycan, teichoic acids, lipoteichoic acids, DNA, cell wall polysaccharides and surface proteins interact with pattern-recognition receptors on immune and epithelial cells and modulate cytokine production and immune cell differentiation (Rocha-Ramírez et al., 2020; Teame et al., 2020). In livestock, the best defined pathways for this effect involve TLR2, which recognizes peptidoglycan and lipoteichoic-acid-rich structures from Gram-positive bacteria, together with DNA-sensing receptors of the TLR9 axis. Because receptor repertoires differ among species, this pathway should be interpreted as TLR9 in mammalian livestock, whereas in chickens unmethylated CpG-rich bacterial DNA is sensed mainly through TLR21, the avian functional homologue of mammalian TLR9 (Guabiraba et al., 2024; C. Wang et al., 2024). These signaling routes are particularly relevant to the anti-inflammatory balance described above, because controlled activation of TLR2 and TLR9/TLR21 can recalibrate mucosal immunity toward a regulated response characterized by IL-10 production, antimicrobial peptide expression and improved barrier-associated immune homeostasis, rather than unchecked inflammation Heat-killed *Lacticaseibacillus casei* IMAU60214 stimulated macrophage nitric oxide and cytokine production through TLR2-dependent signaling

At the mucosal level, this discussion should also include secretory IgA, which is the principal antibody of the intestinal mucosa and mediates immune exclusion by limiting pathogen adhesion, toxin access and excessive penetration of luminal antigens. In pigs, TLR9 has been shown to be a critical mediator of intestinal IgA production, providing a direct mechanistic link between microbial DNA sensing and mucosal antibody responses in a livestock species (C. Wang et al., 2024). Likewise, postbiotic supplementation in post-weaning lambs has been evaluated using mucosal IgA concentration together with barrier- and immune-related gene expression, underscoring that postbiotic immunomodulation in vivo should be assessed not only by systemic cytokines but also by local mucosal readouts (Izuddin et al., 2019). In broilers, continuous intake of the paraprobiotic *Lactiplantibacillus plantarum* ABG0050 altered avian β-defensin expression and increased Th1-type cytokine responses after immune stimulation, further indicating that inactivated microbial preparations can shape mucosal as well as systemic immunity under production conditions (Kondo et al., 2025). Cell-associated preparations from *Limosilactobacillus fermentum* regulate IL-10 and β-defensin expression, while those from *Bifidobacterium breve* and *Bifidobacterium bifidum* increase IL-10 secretion, supporting anti-inflammatory balance (Abd El-Ghany, 2020) Comparative studies suggest that inactivated microbial preparations can possess equal or even superior immunomodulatory potential compared with live probiotics, possibly due to enhanced exposure of immune-active surface structures during inactivation (Abd El-Ghany, 2020; Teame et al., 2020) Figure 2. illustrates the proposed immunomodulatory mechanism of cell-associated postbiotics.

Antimicrobial, antibiofilm and quorum-sensing interference

Cell-associated and metabolite-rich postbiotic preparations often contain organic acids, bacteriocins, antimicrobial peptides, hydrogen peroxide, SCFAs, EPS and enzymes with antimicrobial and anti-adhesion properties (Che et al., 2024; Pimentel et al., 2023). These components can lower pH, disrupt bacterial membranes, inhibit surface adhesion and interfere with quorum sensing systems that coordinate virulence expression and biofilm maturation (Che et al., 2024; Mi et al., 2024). In this respect, postbiotics may attenuate pathogen behaviour by disrupting bacterial communication rather than relying solely on direct killing; when such effects occur at sub-inhibitory concentrations, they are better interpreted as anti-virulence activity and may impose less selective pressure for resistance than bactericidal interventions (Alum et al., 2025). Culture supernatants from *Lactobacillus acidophilus* LA5 and *Lacticaseibacillus casei* 431, for example, inhibit planktonic growth and biofilm formation of *Staphylococcus aureus* (Koohestani et al., 2018). LAB-derived postbiotic preparations have also shown antibacterial and antibiofilm activity against bovine mastitis pathogens such as *S. aureus* and *Streptococcus agalactiae* (Özdemir, 2026). while yeast- and LAB-based postbiotics reduced *Salmonella* colonization in poultry (Gingerich et al., 2021; Guan et al., 2024).

In cattle, the rumen is a large fermentative chamber, and in pigs the lengthy colon continues fermentation as digesta progress toward the distal colon; in such dynamic compartments, active compounds are likely to be diluted, buffered and adsorbed to digesta, making it difficult to reproduce uniformly the inhibitory concentrations observed in vitro (Fregulia et al., 2021; Moran & Bedford, 2022) Accordingly, the practical significance of antibiofilm postbiotics in livestock may lie less in complete luminal biofilm eradication than in reducing adhesion, disrupting quorum-sensing-regulated virulence and lowering colonization pressure at the mucosal surface (Che et al., 2024; Mi et al., 2024).



Inactivated postbiotics can exceed live probiotics in immunomodulatory capacity, potentially due to enhanced exposure of surface structures or heat shock proteins.

Take-Home Message: Cell-associated postbiotics engage epithelial and immune cell PRRs (TLR2, TLR9, TLR21), recalibrating mucosal immunity toward protective and anti-inflammatory responses—including IL-10/IL-12 induction, antimicrobial peptide expression, and enhanced IgA production—thereby improving livestock health. Inactivated preparations often retain or exceed the immune-modulating capacity of live probiotics.

Inactivated forms show equivalence or superiority in modulating key responses.

Figure 2. Immunomodulatory pathways of cell-associated postbiotics in livestock and poultry

Postbiotics in Poultry Nutrition

Poultry is the species in which postbiotics have been most intensively studied. Broilers and layers face strong regulatory and market pressure to reduce antibiotic use, and postbiotics are being evaluated as tools to stabilize gut health, improve performance and mitigate food-safety risks.

Gut microbiota, intestinal morphology and performance

A primary objective of postbiotic supplementation in poultry is to modulate gut microbiota and improve intestinal morphology. Broiler trials using postbiotics from *Lactiplantibacillus plantarum* and related LAB have consistently shown increased lactic acid bacteria, reduced Enterobacteriaceae and lower cecal or fecal pH, reflecting organic acid production (Humam et al., 2019; Kareem et al., 2016) These microbial shifts are accompanied by increased villus height, reduced crypt depth and higher villus: crypt ratios in the small intestine, indicating enhanced absorptive surface and better mucosal integrity (Danladi et al., 2022; Humam et al., 2019).

In layers and pullets, *Saccharomyces cerevisiae* fermentation-based postbiotics improved cecal microflora and supported intestinal health under pathogen challenge (Gingerich et al., 2021) Collectively, these findings support the view of postbiotics as microbiota modulators that shift the intestinal ecosystem towards a more favorable configuration.

In many broiler studies, these effects translate into increased body weight gain, improved feed conversion ratio and better carcass traits, though responses vary with strain, dose, basal diet and health (Atan Çırpıcı & Kırkpınar, 2025; Biagini et al., 2026; Fang et al., 2024; Mahlangu et al., 2026). Under heat stress, postbiotics improved growth performance and gut morphology (Hashemitabar & Hosseinian, 2024; Riaz & Nouman, 2025; Sirisopapong et al., 2026). while replacing AGPs with combined postbiotic preparations yielded performance comparable to or better than antibiotic-fed controls (Danladi et al., 2022).

Control of enteric pathogens, coccidiosis and necrotic enteritis

Postbiotics have been intensively studied as tools for controlling *Salmonella spp.*, a major foodborne hazard associated with poultry meat and eggs. Organic acids, SCFAs and bacteriocins in postbiotics create an unfavorable intestinal environment for *Salmonella* by lowering pH, disrupting membranes and interfering with adhesion and biofilm formation (Chaney et al., 2022; Lamas et al., 2019). In layer pullets challenged with *Salmonella Enteritidis*, *S. cerevisiae* fermentation-based postbiotics reduced cecal *Salmonella* loads by approximately 1-1.5 log CFU/g compared with positive controls, demonstrating substantial colonization resistance (Gingerich et al., 2021). In broilers challenged with *Salmonella*, *Lactiplantibacillus plantarum* postbiotic reduced bacterial colonization and modulated gut inflammatory and barrier-related responses, indicating improved host defence against enteric invasion (Guan et al., 2024). These findings are consistent with broader evidence that postbiotics reduce colonization by *Salmonella* and *Clostridium perfringens*, contributing to lower disease risk and improved food safety (Liu et al., 2022).

Coccidiosis remains one of the most important diseases in the broiler industry, and *Eimeria* infection is widely recognized as a major predisposing factor for *Clostridium perfringens* associated necrotic enteritis (Feng et al., 2022; Mathis et al., 2025). This link is important because postbiotics may help interrupt the coccidiosis-necrotic enteritis cascade by limiting epithelial damage, supporting barrier repair and reducing the opportunity for secondary *C. perfringens* overgrowth. In a recent subclinical necrotic enteritis model, in ovo and drinking-water supplementation with a *Saccharomyces cerevisiae* based postbiotic improved average daily gain during the post-challenge period, reduced jejunal and ileal lesion scores, increased villus height: crypt depth ratio, and enhanced jejunal ZO-1 expression (Dong et al., 2024, 2025). Most recently, work with *Lactobacillus reuteri* (LR) postbiotics on broilers also showed enhanced jejunal cell-growth/survival and immune signaling during necrotic enteritis challenge (Wu et al., 2025). Direct evidence in *Eimeria* only postbiotic challenge models is limited which remains an important research gap. Taken together, these findings indicate that postbiotics in poultry should be considered not only as pre-harvest food-safety tools against *Salmonella*, but also as candidates for integrated nutritional support against coccidiosis-associated intestinal damage and necrotic enteritis.

Barrier function, heat stress resilience and product quality

Postbiotics support epithelial restitution and barrier integrity, which is especially relevant during heat stress. In broilers, high ambient temperature induces panting and peripheral vasodilation, which can reduce splanchnic perfusion, promote oxidative stress and destabilize tight junctions (Brugaletta et al., 2022; Prates, 2025). In heat-stressed broilers, *Lactiplantibacillus plantarum* RI11 postbiotic increased glutathione peroxidase, catalase and glutathione activity, upregulated ileal zonula occludens-1 and mucin 2, and downregulated IL-8, TNF-α, HSP70 and α1-acid glycoprotein, indicating that its protective effect involves both antioxidant defense and preservation of epithelial integrity (Humam et al., 2021).

This barrier-centered mechanism is also relevant to enteric disease. Heat stress can predispose birds to necrotic enteritis by favoring epithelial disruption and *Clostridium perfringens* overgrowth (Tsiouris et al., 2018). Consistent with this, postbiotic supplementation reduced lesion scores, improved villus height: crypt depth ratio and enhanced jejunal ZO-1 expression in subclinical necrotic enteritis models (Dong et al., 2024, 2025). A related concept applies to coccidiosis, because *Eimeria* induced epithelial damage facilitates secondary bacterial proliferation. Direct evidence for postbiotics in pure coccidial challenge models remains comparatively limited and should be treated as an important research gap.

Broilers and layers should, however, be considered separately. In broilers, the main priority is rapid intestinal development during the first week after hatch, which makes early-life postbiotic delivery conceptually attractive (Gaweł et al., 2025)). Emerging studies indicate that in ovo postbiotic administration can modulate intestinal development and health, although direct evidence that it specifically accelerates yolk sac utilization is still limited (Cinar et al., 2025; Dong et al., 2025). However, in layers, the emphasis shifts toward long-term intestinal function, calcium-phosphorus utilization, eggshell quality and skeletal integrity (Fu et al., 2025; Sinclair-Black et al., 2023). Moreover, in post-peak laying hens, *Saccharomyces cerevisiae* fermentation product improved eggshell ratio together with villus height: crypt depth ratio, occludin, ZO-1, MUC-2 and jejunal secretory IgA, suggesting that part of the egg-quality response may be mediated through improved intestinal health and mineral absorption (Gong et al., 2025).

Postbiotics may also improve product quality through effects on systemic oxidative and inflammatory status. In broilers, supplementation has been associated with lower drip loss, cooking loss, shear force and lipid peroxidation under heat stress (Humam et al., 2020). This is relevant because woody breast and white striping are increasingly linked to oxidative stress, inflammatory dysregulation and impaired muscle metabolism in modern broilers (Barbut et al., 2024). Although direct evidence for postbiotic mitigation of these myopathies is not yet available, the observed improvement in antioxidant defenses provides a biologically reasonable basis for future study.

From a commercial perspective, however, these responses must justify additive cost. Poultry production operates on narrow margins, and direct cost-benefit comparisons between postbiotics and live probiotics are still scarce (Beal et al., 2023). Responses also remain heterogeneous across broiler postbiotic studies, particularly for growth and gut-morphology outcomes (Biagini et al., 2026). At present, postbiotics are most likely to justify inclusion where birds face heat stress, enteric disease pressure or feed-processing conditions that compromise live probiotic viability, rather than as a universally superior option in all low risk production systems (Morán et al., 2025).

Applications in Ruminant Nutrition

Rumen fermentation and intestinal morphology

In ruminants, postbiotic research has focused mainly on post-weaning lambs and dairy cattle. The rumen is an anaerobic fermentation chamber whose microbial community is central to fiber digestion and energy supply. Postbiotics derived from *Lactiplantibacillus plantarum* RG14 have shown promising effects on rumen fermentation and epithelial development.

In vitro, RG14 postbiotics increased total VFA and promoted the growth of total bacteria, cellulolytic bacteria and protozoa, indicating enhanced fermentative capacity (Izuddin et al., 2018). In vivo, post-weaning lambs supplemented with RG14 postbiotics for 60 days showed improved growth and more developed rumen papillae, increasing absorptive surface area (Izuddin et al., 2020). Gene expression analyses revealed upregulation of tight junction proteins and antioxidant enzymes in the rumen epithelium and intestine, indicating improved barrier integrity and oxidative defense and Jejunal cytokine profiles shifted towards a more balanced state, with increased IL-6 and reduced IL-1β, TNF-α and IL-10, suggesting fine-tuned immune modulation rather than broad suppression or activation. (Izuddin et al., 2019, 2020).

These findings are relevant beyond small ruminants because they show that postbiotics can influence fermentation and epithelial integrity simultaneously. This dual role is especially important in dairy cows during the transition period, when animals move from a controlled-energy, high-forage dry diet to a more fermentable fresh-cow ration. Such dietary change increases acid load in the rumen and hindgut and can compromise epithelial integrity. In a recent pilot study, post-ruminal starch infusion in dairy cows induced hindgut acidosis, gut damage and increased intestinal permeability, illustrating how rapidly fermentable carbohydrate delivery can contribute to a “leaky gut” phenotype in cattle (Sanz-Fernandez et al., 2024). In this context, postbiotics may be valuable not only for supporting fermentation, but also for reducing the epithelial and inflammatory consequences of dietary transition.

This point is supported by transition cow work with *Saccharomyces cerevisiae* fermentation products. Supplementation during the transition period reduced the range of ruminal pH variation in fresh cows fed high starch diets, increased nadir rumen pH, and shortened the daily duration below pH 5.8, indicating improved rumen stability under conditions relevant to subacute acidosis (Shi et al., 2019). From a metabolic perspective, such stabilization is important because propionate remains the major gluconeogenic precursor in dairy cows, whereas acetate and other fermentation products can influence hepatic lipid and glucose metabolism indirectly through gut-liver signaling. Thus, postbiotics in ruminants should be viewed not only as modifiers of rumen fermentation, but also as potential modulators of barrier function and whole-animal metabolic adaptation during periods of nutritional stress.

Dairy calves and cows

In dairy calves, yeast fermentation products based on *Saccharomyces cerevisiae* have been widely evaluated as postbiotics. direct *Saccharomyces cerevisiae* fermented-derived postbiotics supplementation to calves during the preweaning period improved growth performance and health and modified rumen fermentation and microbial composition (S. Li et al., 2026).

In dairy cows, however, the main question is whether postbiotics can reduce the inflammatory and metabolic stress that defines the transition period, particularly the risk of ketosis and fatty liver. Recent studies suggest that this is a realistic target. In transition cows supplemented from 21 to 56 d relative to calving, *Saccharomyces cerevisiae* fermentation products increased ECM yield and reduced plasma β-hydroxybutyrate, ceruloplasmin, haptoglobin, IL-1β and serum amyloid A, while improving glucose and mineral status, supporting the interpretation that postbiotics can modulate both immunity and liver-associated metabolism during early lactation (Dai et al., 2024). These responses are mechanistically consistent with emerging gut-liver axis evidence in dairy ruminants. A recent multi-omics study linked reduced hindgut acetate availability with postpartum energy-metabolism disorders and showed that sodium acetate suppressed hepatic lipid accumulation and β-hydroxybutyrate production through the hepatic AMPK-PPARA axis in bovine hepatocytes (S. Wang et al., 2025). Although this does not prove that all postbiotics act through the same pathway, it provides a plausible mechanistic framework for interpreting how postbiotic-supported fermentation and barrier protection could reduce the combination of leaky gut, systemic inflammation and hepatic fat accumulation that characterizes transition-cow dysfunction.

Milk fat responses also deserve attention because milk fat depression remains a major concern in dairy nutrition. High-starch diets can promote a trans-10 shift in ruminal biohydrogenation, increasing trans-10 18:1 and trans-10,cis-12 CLA at the expense of the usual trans-11 pathway, and this shift is closely associated with depressed milk fat synthesis (Vahmani et al., 2025). Direct evidence that postbiotics consistently prevent this shift or modify milk fatty acid profiles is still limited. Nevertheless, products that stabilize the rumen environment may indirectly reduce the conditions that favor milk fat depression. In one transition-cow study, *Saccharomyces cerevisiae* fermentation products increased milk fat content and yield (Dai et al., 2024), while an *Aspergillus oryzae* fermentation product tended to increase milk fat content in pasture-based Jersey cows while maintaining rumen conditions compatible with microbial function (Basson et al., 2025). At present, therefore, the most defensible conclusion is that postbiotics may support milk fat synthesis indirectly through rumen stabilization and reduced inflammatory stress, but direct work on ruminal biohydrogenation intermediates and milk fatty acid profiles remains a clear research priority.

Udder health and mastitis control

Postbiotics also show promise in mastitis control, but route of administration matters. Intramammary postbiotic preparations should be distinguished from dietary postbiotics because they act through different mechanisms and serve different purposes. The former are local medical interventions delivered directly into the infected quarter, whereas the latter are nutritional additives intended to influence udder health indirectly through modulation of gut or rumen function, epithelial integrity, systemic inflammatory tone and leukocyte readiness (Chae et al., 2024; Mathur et al., 2022).

Evidence for this feed-to-udder connection is emerging. In mid-lactation Holstein cows fed a *Saccharomyces cerevisiae* fermentation product before intramammary *Streptococcus uberis* challenge, supplementation reduced somatic cell score and local inflammatory responses, and mammary transcriptomics indicated enrichment of pathways linked to antibacterial function, epithelial protection and tight-junction integrity (Vailati-Riboni et al., 2021). Likewise, supplementation from before dry-off through early lactation has been associated with lower somatic cell count and fewer new intramammary infections in cows with elevated pre-dry-off SCC, although not all challenge studies show a direct anti-infective effect (Kolar et al., 2025; Mezzetti et al., 2025). These findings suggest that oral postbiotics are best viewed as prophylactic or resilience promoting tools that may improve mammary defense by conditioning the host before challenge, rather than as stand-alone replacements for intramammary therapy.

By contrast, Mathur et al. (Mathur et al., 2022) evaluated a local therapeutic application rather than a dietary one: an emulsion-based formulation containing heat-killed *Lactococcus lactis* DPC3147 was infused directly into udders of cows with chronic mastitis and elicited local IL-8 responses comparable to those induced by viable cells, indicating that cell-associated postbiotics can function as localized immunostimulatory agents in the mammary gland. Postbiotic use in udder health should therefore be considered in two distinct contexts: dietary preparations that support systemic host resilience and mammary immune competence, and topical or intramammary preparations used as direct local interventions.

Comparison with Probiotics and Other Additives

Probiotics, prebiotics and symbiotic remain important tools in animal nutrition, but their limitations have catalyzed interest in postbiotics. From a technological standpoint, the distinction becomes especially relevant during feed manufacture. Published broiler pelleting studies commonly evaluate steam-conditioning temperatures of approximately 71-88°C, and other studies have examined conditioning up to 90°C, exposing additives to heat, steam and mechanical stress (Rueda et al., 2022). Under such conditions, live probiotics may lose viability and therefore often require protective strategies such as encapsulation or dedicated post-pellet liquid application, whereas postbiotics are functionally more thermo-stable because their efficacy is not dependent on survival of live cells (Agriopoulou et al., 2023; Morán et al., 2025). Accordingly, postbiotics can, in principle, be incorporated before the conditioner or pellet mill, provided that product-specific bioactivity has been validated after processing (Jansseune et al., 2025).

From a safety perspective, live probiotics rarely cause adverse events, yet case reports of probiotic-associated bacteremia or fungemia in vulnerable hosts and concern about transferable resistance determinants remain part of the safety discussion (Merenstein et al., 2023; Wombwell et al., 2021; Yelin et al., 2019). A further manufacturing and regulatory distinction concerns shelf life and dosing. To qualify as probiotics, microorganisms must remain alive in adequate numbers throughout shelf life, and commercial quality frameworks commonly express dose as colony-forming units. Postbiotics remove this end-of-shelf-life viability requirement and can instead be standardized using non-viable cell, biomass or compositional markers, together with analytical measurement of relevant metabolites where appropriate (Binda et al., 2020; Vinderola et al., 2025). However, no single system postbiotic metric equivalent to colony forming units yet exists, so standardization still depends on product-specific marker selection rather than simple plate counts (Vinderola et al., 2025).

Mechanistically, there is considerable overlap: both probiotics and postbiotics can modulate microbiota, reinforce barrier function and regulate immune responses. In some cases, inactivated microbial preparations have shown equal or greater immunostimulatory activity than their live counterparts (Rocha-Ramírez et al., 2020; Teame et al., 2020). Probiotics retain unique advantages such as transient colonization and dynamic in situ metabolite production, which may be advantageous for longer-term microbiota engineering. Postbiotics, by contrast, offer more reproducible delivery of preformed bioactive fractions and avoid uncertainty associated with survival and colonization. Direct head-to-head cost comparisons are still scarce, so economic superiority cannot yet be assumed for either category. In practice, probiotics may require added expenditure for viability protection, shelf-life management and post-pellet delivery, whereas postbiotics require inactivation, drying/concentration and robust compositional characterization; cost-effectiveness is therefore product- and process-specific (Agriopoulou et al., 2023; Guglielmetti et al., 2025).

Postbiotics also interact with other additives. They can be combined with prebiotics, organic acids, phytobiotics and enzymes in multi-target programs aimed at gut health and performance (Yue et al., 2025). Because ISAPP defines symbiotic as mixtures comprising live microorganisms and substrate(s) selectively utilized by host microorganisms, combinations of postbiotics with prebiotics are referred to here as postbiotic-prebiotic blends rather than synbiotics blends (Swanson et al., 2020). Taken together, postbiotics should be viewed as complementary rather than competing agents within the broader biotics toolbox, with particular value where thermal processing, storage stability and viability-independent dosing are major practical priorities. The major technological, safety and standardization differences between probiotics and postbiotics are summarized in Table 3.

Table 3. Comparison of probiotics and postbiotics for animal-feed application

Feature	**Probiotics**	**Postbiotics**	**Practical implication**	**References**
Biological status	Live microorganisms that must remain viable	Inanimate microbial preparations and/or their components	Viability is essential for probiotics but not for postbiotics	(Binda et al., 2020); (Salminen et al., 2021)
Pelleting / thermal stability	Heat-, steam- and moisture-sensitive	Functionally more thermo-stable, though excessive heat may alter composition	Postbiotics are generally more compatible with pre-pellet inclusion	(Teixeira Netto et al., 2019) (Rueda et al., 2022); (Morán et al., 2025); (Jansseune et al., 2025)
Feed-mill incorporation	May require encapsulation or post-pellet addition	Often suitable for pre-pellet inclusion if bioactivity is validated	Greater manufacturing flexibility	(Agriopoulou et al., 2023); (Morán et al., 2025); (Jansseune et al., 2025)
Shelf life / dose declaration	Commonly managed as viable counts	Standardized using biomass or compositional markers	Removes end-of-shelf-life viability constraint	(Binda et al., 2020); (Vinderola et al., 2025)
Quality-control metric	Colony-forming units are conventional	No universal colony-forming-unit-equivalent metric yet	Postbiotics simplify some QC risks but still require analytical standardization	(Vinderola et al., 2025)
Safety / AMR risk	Rare infection risk in vulnerable hosts; AMR transfer remains part of assessment	No replication; lower infectivity and gene-transfer concern	Safety advantage where live-cell persistence is undesirable	(Salminen et al., 2021); (Merenstein et al., 2023); (Wombwell et al., 2021); (Yelin et al., 2019)

Feature	**Probiotics**	**Postbiotics**	**Practical implication**	**References**
Mechanism	Colonization, competitive exclusion and in situ metabolite production	Delivery of preformed bioactive fractions without colonization	Probiotics may suit microbiota engineering; postbiotics suit more controlled delivery	(Teame et al., 2020); (Peluzio et al., 2021); (Vinderola et al., 2022)
Relative cost	May require viability protection and post-pellet delivery	Requires inactivation, drying/concentration and characterization	No universal cost winner; economics are product-specific	(Mathur et al., 2022); (Guglielmetti et al., 2025)

Safety, Regulation and Commercialization

Safety considerations

Because postbiotics are inanimate, they cannot replicate or colonize the host, which removes the primary concern associated with live microbial persistence and substantially reduces concerns about horizontal transfer of resistance genes by the administered product itself (Salminen et al., 2021; Vinderola et al., 2025). Safety assessment, however, should not be limited to the target animal. It should also consider the user or worker, the consumer and the environment, because these are standard dimensions of feed-additive evaluation in current regulatory practice (Bampidis et al., 2023; Guglielmetti et al., 2025). This is particularly relevant for microbial feed products handled in dry form, where worker exposure may occur through inhalation of dust or small particles (Bampidis et al., 2023).

From a farm biosecurity perspective, postbiotics offer an additional advantage because they do not introduce viable microbial propagules into litter, manure or effluent. This does not eliminate all occupational or environmental considerations, but it reduces concerns about persistence, dissemination or biological runoff of the additive organism itself. By contrast, live microbial additives may still require explicit user and environmental safety assessment. Accordingly, postbiotics can be viewed as biologically more contained products, even though their non-microbial components must still be assessed for chemical and toxicological safety.

Regulatory categorization and claims

Regulatory approaches to postbiotics differ between jurisdictions, and the key commercial issue is often not only what the product is, but how it is categorized and what claims are made for it (Guglielmetti et al., 2025). In commercial practice, postbiotic products may be positioned as feed additives, complementary feeds, feed materials or more broadly as fermentation derived ingredients, depending on formulation and intended claim. This creates a practical categorization challenge because the evidentiary burden becomes much heavier when a product is promoted with a disease-oriented or pathogen-reduction claim than when it is marketed for nutritional or physiological support, such as digestibility, nutrient utilization or resilience (Guglielmetti et al., 2025). For commercial, this distinction is critical because market access may depend as much on regulatory framing and wording of claims as on the biological efficacy of the product itself.

Commercial adoption, quality control and standardization

Postbiotic-type products are already used commercially in animal nutrition, especially yeast fermentation products and other non-viable fermentation derived ingredients. Their commercial appeal lies not only in biological activity, but also in easier handling, reduced dependence on viable counts and potentially simpler batch standardization than live microbial products (Guglielmetti et al., 2025; Vinderola et al., 2025). For live microbial additives, product identity and dose are closely tied to viable counts, typically expressed as colony-forming units, and maintaining those counts over storage remains a practical quality-control challenge. By contrast, postbiotics can be characterized using non-viable biomass, inanimate-cell markers and selected metabolite or compositional markers, although no single universal gold-standard metric equivalent to colony-forming units yet exists (Vinderola et al., 2025).

This means that postbiotics do not remove the need for rigorous standardization; rather, they shift it from viability assurance to compositional characterization, inactivation process control and fit for purpose quantification. Transparent product description, validated marker selection and claim-appropriate evidence will therefore be central to wider commercialization. At present, the field remains commercially promising but regulatory nomenclature, claim boundaries and analytical standardization are still evolving.

Research Gaps and Future Perspectives

Despite rapid progress, several key gaps remain in the science and application of postbiotics:

1. Many studies reported beneficial outcomes without identifying which components of the postbiotic preparation are responsible. For postbiotics, this is a particularly important limitation because efficacy cannot be inferred simply from the identity of the progenitor strain; unlike live probiotics, whose presence can be tracked by viability and strain recovery, postbiotics must be understood in terms of the molecules and structures that remain in the final inanimate preparation (Vinderola et al., 2025). Accordingly, metabolomics is not merely descriptive but essential for identifying the active molecular determinants of efficacy, while bioactivity-guided fractionation provides a practical route to separate complex preparations into functional subfractions and pinpoint the molecules most closely associated with a biological effect (Nealon et al., 2024; Vinderola et al., 2025).
2. Standardization and comparability. Differences in strains, inactivation methods, formulation and experimental design continue to hinder cross-study comparisons. Future progress will require stronger consensus on minimal compositional characterization, process control and fit for purpose quantification, so that biological findings can be compared across studies and translated more reliably into commercial products (Vinderola

et al., 2025). This is especially important for postbiotics because standardization depends on defining what the finished preparation contains, rather than simply counting viable cells as in probiotics.

3. Species- and life-stage-specific optimization. Responses to postbiotics are influenced by species, breed, age, diet, environment and health status. Future work should refine dose and formulation for specific targets such as broilers under heat stress, layers in extended production cycles, weaned lambs and calves during rumen development, and high-yield dairy cows during transition and early lactation.
4. Methane mitigation and rumen archaeal ecology should become a headline research priority**.** Enteric methane is a major sustainability issue in ruminant production and reflects the activity of methanogenic archaea together with the wider network of hydrogen-producing and hydrogen utilizing microbes in the rumen (Pitta et al., 2022). Accordingly, a major future perspective for postbiotics is whether they can selectively modulate methanogen-associated consortia or redirect reducing equivalents toward alternative sinks without suppressing beneficial fibrolytic bacteria and overall rumen function.
5. Integration with other interventions. Postbiotics are rarely used in isolation. Understanding synergy or antagonism with prebiotics, organic acids, phytobiotics, vaccines and management practices remains essential for designing coherent health and performance programs.
6. Future trials should incorporate not only performance and health endpoints, but also methane emissions, nutrient excretion, manure characteristics and other sustainability metrics, especially in ruminants where the environmental rationale for feed additives is becoming increasingly important.
7. Precision nutrition and predictive targeting. Advances in microbiome profiling, metabolomics and host phenotyping raise the prospect of matching postbiotic preparations to specific physiological states or microbial configurations. In this context, metagenomics and meta-transcriptomics are needed to determine which microbial populations and pathways are altered, whereas metabolomics and fractionation are needed to identify which postbiotic components are actually acting on the host (Nealon et al., 2024; Vinderola et al., 2025).

Addressing these gaps will be essential for moving postbiotics from promising complex preparations toward standardized, mechanism-informed tools for precision livestock and poultry nutrition.

Conclusions

Postbiotics represent more than another antibiotic alternative; they reflect a shift in animal nutrition from microbiological nutrition, centered on live and variably surviving microorganisms, to molecular nutrition, centered on stable microbial effector preparations and, increasingly, a transition from viable cell counts to molecular dosing. Their key advantage is not only biological activity, but viability-independent robustness: they can deliver reproducible gut-health functions without relying on survival through pelleting, storage and gastrointestinal transit. This thermo-stability also has a democratizing value, making advanced gut-health technology more accessible in hot, humid regions where cold-chain logistics are limited. In this broader sense, postbiotics should be viewed not only as feed additives, but as practical One Health tools. By supporting prudent antibiotic reduction, improving villus height: crypt depth ratio, feed conversion and intestinal integrity, they can help lower the environmental resistome and reduce nitrogen and phosphorus excretion per unit of animal product. The immediate priority, however, is standardization: the field should move beyond the current terminology confusion, adopt the ISAPP definition consistently, and characterize products using validated compositional and functional markers so that regulatory, scientific and commercial progress can proceed on a common foundation

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