Review Article

Journal of Advanced Veterinary Research
(2026) Volume 16, Issue 2, 283-291

Organic acids as promising alternatives to antibiotics in livestock production: Mechanisms and applications

Mohammad Sukmanadi[1*], Aswin R. Khairullah[2], Imam Mustofa[3], Bima P. Pratama[4], Adeyinka O. Akintunde[5], Riza Z. Ahmad[2], Latifah Latifah[6], Ulvi F. Handayani[6], Lili Anggraini[6], Desi L.H. Utomo[7], Bantari W.K. Wardhani[8], Ilma F. Ma'ruf[8], Dea A.A. Kurniasih[9], Ikechukwu B. Moses[10], Mutasem Abuzahra[6], Syahputra Wibowo[11]

[1]Division of Basic Veterinary Medicine, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[2]Research Center for Veterinary Science, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia
[3]Division of Veterinary Reproduction, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[4]Research Center for Process Technology, National Research and Innovation Agency (BRIN), South Tangerang, Banten 15314, Indonesia.
[5]Department of Agriculture and Industrial Technology, Babcock University, Ilishan Remo, Ogun, 121003, Nigeria.
[6]Research Center for Animal Husbandry, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia.
[7]Profession Program of Veterinary Medicine, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[8]Research Center for Pharmaceutical Ingredients and Traditional Medicine, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia.
[9]Research Center for Public Health and Nutrition, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia
[10]Department of Applied Microbiology, Faculty of Science, Ebonyi State University, Abakaliki Rd, Abakaliki, Ebonyi, 481101, Nigeria.
[11]Eijkman Research Center for Molecular Biology, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia.

ARTICLE INFO

Received: 02 October 2025

Accepted: 29 October 2025

*Correspondence:

Corresponding author: Mohammad Sukmanadi
E-mail address: moh-s@fkh.unair.ac.id

Keywords:

Alternative antibiotics, Animal husbandry, Antimicrobial resistance, Medicine, Organic acids.

ABSTRACT

Livestock production has increased due to the use of antibiotics as growth promoters in livestock farming; nevertheless, this practice has resulted in serious issues with antimicrobial resistance and has an adverse effect on both human health and the environment. Therefore, the search for safe and effective alternatives becomes very important. Conventional antibiotics may eventually be replaced by organic acids such as butyric, propionic, acetic, and formic acids. These substances reduce the number of harmful microorganisms without affecting the good intestinal flora by lowering the pH of the gastrointestinal tract, breaking down the cell membranes of harmful bacteria, and preventing the action of crucial enzymes. Numerous studies have demonstrated that adding organic acids to livestock feed or drink can enhance the immune system, growth performance, and digestive health of animals, particularly pigs, cattle, and chickens. Its effectiveness is influenced by the type of acid, dose, dosage form, and digestive environmental conditions. In practice, organic acids can be used alone or in combination, as well as in conjunction with probiotics or prebiotics to maximize their synergistic effects. Although encouraging, obstacles still need to be addressed, including the stability of organic acids in feed, individual animal response variations, and production costs. Further research is needed to optimize effective usage strategies, dosages, and formulations. Therefore, organic acids present a potentially secure, effective, and sustainable substitute to lessen the livestock industry's need on antibiotics.

Introduction

The use of antibiotics in the livestock industry has been standard practice for decades to improve livestock growth, feed utilization efficiency, and prevent bacterial infections (Kasimanickam *et al*., 2021). Although growth-promoting antibiotics increase the output of meat, milk, and eggs, their overuse and unchecked use can have detrimental effects, such as the development of antibiotic resistance (Manyi-Loh *et al*., 2018). Antibiotic-resistant pathogenic bacteria can proliferate through the food chain, water, livestock habitats, and direct animal-human interaction (Pandey *et al*., 2024). Given that resistant bacteria can result in diseases that are challenging to treat, raise the possibility of therapeutic failure, and result in a substantial financial burden, this phenomena poses a threat not only to the health of cattle but also to human health (Ferraz, 2024). Antimicrobial resistance concerns around the world have prompted limitations on the non-therapeutic use of antibiotics in cattle production and highlighted the pressing need to identify sustainable, safe, and effective substitutes (Salam *et al*., 2023).

In this context, organic acids have emerged as promising alternative candidates. Organic acids, such as butyric, propionic, acetic, and formic acids, are carboxylic substances having short to medium carbon chains (Huang *et al*., 2011). These substances can be added straight to drinking water or animal feed, or they can be produced spontaneously during microbial fermentation (Siddiqui *et al*., 2023). Organic acids have a variety of antimicrobial properties, such as lowering the pH of the gastrointestinal tract to make the environment less favorable for harmful bacteria, rupturing cell membranes, and preventing the activity of enzymes that are necessary for the pathogens' metabolism (Anumudu *et al*., 2024). This activity is selective, allowing beneficial gut flora to persist and support digestive health (Waghmare *et al*., 2025). Thus, without leaving harmful residues or increasing the chance of long-term resistance, organic acids can partially replace the function of conventional antibiotics in enhancing the health and performance of animals (Abd El-Hack *et al*., 2022).

Supplementing with organic acid has been demonstrated in numerous studies to enhance immunological response, growth, and digestive efficiency in a variety of livestock species, including cattle, pigs, and chickens (Adil *et al*., 2010; Fontoura *et al*., 2023; Nhara *et al*., 2024). Its effectiveness is influenced by the type of acid, dose, dosage form (liquid, solid, or microencapsulated), and gastrointestinal environmental conditions (Khan *et al*., 2022). Organic acids can be used singly or in combination, and for maximum synergistic benefits, they are occasionally paired with probiotics or prebiotics (Bozkurt *et al*., 2009). This approach not only inhibits the growth of harmful bacteria but also fortifies the intestinal mucosa and enhances livestock's overall metabolic efficiency (Chukwudi *et al*., 2025).

The use of organic acids is promising, but it also has drawbacks, including production costs, feed component stability, and individual livestock's varying responses (Broom, 2015). Therefore, more research is required to identify the best combination strategy, the ideal dosage, and the most effective formulation. The safety and sustainability of using organic acid also depend on long-term assessments of the health of cattle and the quality of food products (Rahman *et al*., 2024).

The aim of this review was to comprehensively analyze the role of organic acids as an alternative to antibiotics in animal husbandry, with a focus on their mechanisms of action, effectiveness, and applications. It is anticipated that a comprehensive grasp of the potential, benefits, and drawbacks of organic acids will support international efforts to lower antibiotic resistance and offer scientific direction to researchers and livestock industry practitioners in the development of safe, effective, and sustainable pathogen control methods.

ISSN: 2090-6277/2090-6269/ © 2011-2026 Journal of Advanced Veterinary Research. All rights reserved.

Classification and types of organic acids

Organic acids used in animal husbandry generally include compounds such as formic acid, acetic acid, propionic acid, and butyric acid, which can be obtained from natural or synthetic sources and are provided in various forms, including pure, mixed, solid, and liquid; differences in the chemical properties of each acid, such as acid strength, carbon chain length, and solubility, directly affect its antimicrobial activity and effectiveness in suppressing the growth of pathogenic bacteria in the digestive tract of livestock. Table 1 presents a classification of the types of organic acids commonly used in livestock, including their source (natural or synthetic), dosage form, chemical characteristics, antimicrobial mechanism of action, and additional benefits for livestock health and performance.

Commonly used types of organic acids

Organic acids used in livestock generally include carboxylic compounds with short to medium carbon chains, which have antibacterial properties and play a role in improving the digestive health of livestock (Tugnoli *et al*., 2020). The most prevalent kinds are butyric acid, propionic acid, acetic acid, and formic acid. Formic acid is one of the most commonly utilized organic acids due to its potent ability to lower the pH of the gastrointestinal tract, which makes the intestinal environment less conducive to the growth of harmful bacteria like *Salmonella* and *Escherichia coli* (Luise *et al*., 2020). Formic acid can also enhance nutrition absorption and boost the activity of digestive enzymes (Abd El-Hack *et al*., 2024).

Acetic acid, which is the main component of vinegar, has effective antimicrobial properties against both Gram-positive and Gram-negative bacteria, and can modulate the intestinal flora to support the growth of beneficial microbes (Ryssel *et al*., 2009). Propionic acid is well-known for its capacity to inhibit the growth of harmful bacteria and fungus as well as for being stable in feed (Bücher *et al*., 2021). Furthermore, propionic acid is frequently combined with other acids to increase their antibacterial activity in a synergistic manner (Antone *et al*., 2023).

Butyric acid, a compound with a longer carbon chain, plays an important role in gut health because it is an energy source for intestinal epithelial cells and can strengthen mucosal integrity (Kalkan *et al*., 2025). Additionally, butyric acid helps to reduce inflammation in the digestive tract and modulate the immune system, which enhances livestock development and digestive efficiency (Chen *et al*., 2025).

These kinds of organic acids can be used in single or combination forms, and their application can be customized to meet certain objectives like enhancing gut health, reducing infections, or boosting growth performance (Waghmare *et al*., 2025). Furthermore, its efficacy, stability in the feed, and release in the gastrointestinal tract can all be impacted by the dosage form—liquid, solid, or microencapsulated (Feye *et al*., 2020). The secret to getting the best outcomes in sustainable and healthful animal production is choosing the appropriate kind and blend of organic acids.

Sources and forms of use

Organic acids used in animal husbandry can come from natural or synthetic sources. Synthetic sources are derived from chemical techniques that enable large-scale production with regulated uniformity, whereas natural sources include metabolites produced by probiotic microbes, agricultural by-products, and microbial fermentation products (Fitsum *et al*., 2025). The choice of source is important because it affects the purity, stability, and antimicrobial effectiveness of the compound used (Teshome *et al*., 2022).

Organic acids come in a variety of dose forms, such as liquid, solid, blended, and pure. The mixed form of organic acids, which contains multiple types, is used to increase the synergistic action against pathogenic bacteria and widen the spectrum of antimicrobial activity, while the pure form allows for precision dosing and control of its biological effects (Sorathiya *et al*., 2025). Solid forms are generally applied in dry feeds due to their better stability and easier handling, while liquid forms are more suitable for mixing into drinking water or wet feed, facilitating rapid release in the early digestive tract (Bakshi *et al*., 2023). Furthermore, certain formulations increase the total antibacterial activity by preventing the acid from degrading before it reaches the distal gut through the use of microencapsulation techniques (Nguyen *et al*., 2020).

Livestock practitioners can select the appropriate formulation based on the desired use, such as pathogen management, digestive health enhancement, or supporting optimal livestock growth performance, by being aware of the sources and types of organic acid formulations. Organic acids can be used in a safe, effective, and sustainable manner because proper selection guarantees compound stability, equal distribution in the digestive tract, and consistent antibacterial activities (Gómez-García *et al*., 2019).

Differences in chemical characteristics that affect antimicrobial activity

The effectiveness of organic acids to inhibit the growth of harmful bacteria in livestock is greatly impacted by differences in their chemical properties (Yoon *et al*., 2024). Chemical characteristics including solubility, dissociation ability, pKa value, and carbon chain length all affect an acid's antibacterial activity (Sorathiya *et al*., 2025). Short-carbon acids, including acetic and formic acid, can more readily pass through bacterial cell membranes and reduce intracellular pH, which can cause disruptions in pathogen growth, enzyme activity, and cell metabolism (Ji *et al*., 2023). On the other hand, medium to long chain acids, such propionic acid and

Table 1. Classification, sources, and characteristics of organic acids used in animal husbandry.

Types of organic acids	Source	Dosage form	Chemical characteristics	Mechanism of action / Antimicrobial effect	Additional functions / Benefits for livestock
Formic acid	Natural (microbial fermentation) and synthetic	Pure, mixed, solid, and liquid	Short carbon chain, low pKa, and water soluble	Lowers gastrointestinal pH, penetrates bacterial cell membranes, disrupts metabolism, and enzyme activity of pathogens	Increases digestive enzyme activity, improves nutrient absorption, and suppresses *Eschericia coli* and *Salmonella*
Acetic acid	Natural (vinegar) and synthetic	Pure, mixed, solid, and liquid	Short carbon chain and water soluble	Lowers pH, disrupts the metabolism of Gram-positive, and Gram-negative bacteria	Modulates gut flora and supports the growth of beneficial microbes
Propionic acid	Natural (fermentation) and synthetic	Pure, mixed, solid, liquid, and microencapsulated	Medium carbon chain and stable in feed	Inhibits the growth of pathogenic bacteria and fungi, works slower but lasts longer	Used in combination for synergistic effect and stable in feed
Butyric acid	Natural (fermentation) and synthetic	Pure, mixed, solid, liquid, and microencapsulated	Longer carbon chains, stable, and soluble	Local effects in the distal intestine, supporting the integrity of the intestinal mucosa, and epithelium	Energy source for epithelial cells, modulation of the immune system, reducing inflammation, and increasing digestive efficiency

butyric acid, enhance intestinal epithelial health and mucosal integrity while having slower membrane penetration and longer-lasting local effects (Tian *et al*., 2020).

The tendency of an acid to ionize in the gastrointestinal environment is indicated by its pKa value, which influences the quantity of free H^+ ions to reduce pH and prevent the growth of harmful bacteria (Carpenter and Broadbent, 2009). Higher pKa acids are more stable and can withstand into the distal portion of the colon, increasing the spectrum of antibacterial activity, but lower pKa acids are better at decreasing pH in the early portion of the digestive tract (Mustafa *et al*., 2021). The distribution of organic acids along the digestive system is also influenced by solubility and chemical stability; acids that are chemically stable can sustain effective concentrations for extended periods of time, which improves the capacity to control pathogenic bacteria in a sustainable manner (Tugnoli *et al*., 2020).

Combinations of several kinds of organic acids are frequently employed to produce a wider spectrum of action since their chemical properties differ. In addition to boosting antimicrobial efficacy, this combined approach reduces resistance risk, promotes the development of healthy bacteria, and enhances livestock's general digestive health (Qui, 2023). Organic acid compositions can be tailored for a variety of uses, such as preventing infections, enhancing animal performance, or boosting the immune system, by comprehending the variations in these chemical characteristics.

Mechanism of action of organic acids

Organic acids suppress the growth of pathogenic bacteria through multifaceted mechanisms, including lowering gastrointestinal pH, disrupting cell membrane integrity, and inhibiting metabolic enzymes, thereby limiting the proliferation of pathogens such as *Escherichia coli* and *Salmonella* without harming the beneficial microbiota, and offering a safer alternative to conventional antibiotics by reducing the risk of antimicrobial resistance.

How antibacterials work

Organic acids actively disrupt the survival and growth of harmful bacteria in livestock's digestive tracts by exhibiting antibacterial activity through a number of interconnected ways (Ji *et al*., 2023). The first major mechanism is a decrease in gastrointestinal pH (Tugnoli *et al*., 2020). The intracellular pH can be lowered by non-ionized organic acids because they can pass through the bacterial cell membrane and release H+ ions into the cytoplasm (Warnecke and Gill, 2005). Bacterial growth and proliferation are disrupted by this pH drop because it throws off the internal acid-base balance of cells, stops important enzymes from working, and lowers the capacity of cell metabolism to generate energy (Atasoy *et al*., 2024).

The second mechanism is disruption of the bacterial cell membrane (Soares-Silva *et al*., 2020). The lipid bilayer of the membrane may interact with lipophilic organic acid molecules or medium carbon chains, leading to enhanced permeability, cell contents leakage, and ion imbalance that ultimately results in cell death (Lin *et al*., 2021). The beneficial gut flora can endure because of the process's selectivity against a broad variety of pathogenic bacteria, including both Gram-positive and Gram-negative ones (Jandhyala *et al*., 2015).

Furthermore, organic acids have the ability to block metabolic enzymes (Wu *et al*., 2021). Organic acids enter the cell and disrupt the activity of enzymes that are essential in energy metabolism, DNA replication, and protein synthesis, which prevents the bacteria from reproducing (Ji *et al*., 2023). These mechanisms are often synergistic, meaning the combination of pH reduction, membrane disruption, and enzyme inhibition produces a stronger antibacterial effect than either mechanism alone.

Activity against pathogenic and probiotic bacteria

Organic acids have a significant impact on microbial control in livestock's digestive tracts because they selectively inhibit harmful bacteria while promoting the development of healthy microbiota (Fathima *et al*., 2022). Compounds such as formic acid, acetic acid, propionic acid, and butyric acid effectively suppress the population of pathogens such as *Escherichia coli*, *Salmonella* spp., and *Clostridium* spp. through complex mechanisms, including decreasing intracellular pH, disrupting cell membrane integrity, and inhibiting the activity of metabolic enzymes essential for bacterial growth and proliferation (Liu *et al*., 2021). Pathogen-unfriendly conditions are produced by a drop in pH, and pathogenic bacteria's capacity to proliferate is suppressed by membrane rupture and enzyme inhibition, which also prevent cellular activity and protein synthesis (Yoon *et al*., 2024).

Conversely, probiotic bacteria, like *Lactobacillus* species and *Bifidobacterium* species, have internal adaption mechanisms that enable them to maintain pH homeostasis and regular metabolic activity, making them comparatively more tolerant to acidic environments (Dempsey and Corr, 2022). This selectivity improves the health and digestive efficiency of livestock by maintaining the stability of good gut flora, which supports the fermentation of fiber, the generation of short-chain fatty acids, and the absorption of nutrients (Guan *et al*., 2021). Through food competition and the generation of naturally occurring antimicrobial compounds, preserving a population of beneficial bacteria also contributes to preventing pathogen colonization (Pickard *et al*., 2017).

Organic acids provide a safe and sustainable way to enhance animal health and growth performance while lowering dependency on traditional antibiotics and the risk of antibiotic resistance. They do this by suppressing infections while preserving the balance of the gut microbiota (Ma *et al*., 2021). Determining the best kind, concentration, and composition of acid for contemporary cattle management requires an understanding of this selection behavior.

Comparison with conventional antibiotic mechanisms

Organic acids and conventional antibiotics both have the ability to suppress the growth of pathogenic bacteria, but their mechanisms of action are fundamentally different. Conventional antibiotics typically target particular biological processes in bacterial cells, like DNA replication (fluoroquinolones), protein synthesis (tetracyclines, macrolides), or cell wall building (β-lactams) (Muteeb *et al*., 2023). Antibiotics can quickly eradicate or stop the growth of germs thanks to this particular mechanism, but it also produces selective pressure that may cause antimicrobial resistance to develop (Gauba and Rahman, 2023).

Organic acids, on the other hand, function via a complex process that is more sensitive to environmental factors and physical-chemical interactions (Batista-Silva *et al*., 2018). These substances alter the integrity of cell membranes, decrease the pH of the gastrointestinal tract, and non-specifically suppress the activity of metabolic enzymes (Ebeid and Al-Homidan, 2021). The ability of beneficial probiotic bacteria to maintain internal homeostasis and adapt to low pH makes this mechanism more likely to be selective against pathogens (El-Garhi *et al*., 2025). Thus, organic acids are able to suppress the pathogen population while maintaining the balance of the gut microbiota, in contrast to conventional antibiotics which often reduce the entire bacterial population, both pathogenic and probiotic (Pickard *et al*., 2017).

In addition, organic acids have the advantage of reducing the risk of long-term resistance because their mechanism does not target a single metabolic pathway that is easily modified by genetic mutations (Zhang and Cheng, 2022). The use of organic acids as a supplement or substitute for traditional antibiotics is a sustainable approach in animal husbandry because of their diverse and non-specific qualities, which hinder the development of disease resistance (Rahman *et al*., 2022). Ultimately, creating the best feed supplementation programs, enhancing animal performance and gut health, and lowering dependency on traditional antibiotics all depend on a knowledge of these mechanistic variations.

Figure 1 provides a schematic representation of the multifaceted mechanisms through which organic acids exert antibacterial effects, including gastrointestinal pH reduction, disruption of bacterial cell membrane integrity, and inhibition of metabolic enzymes, while concurrently maintaining the stability of beneficial microbiota.

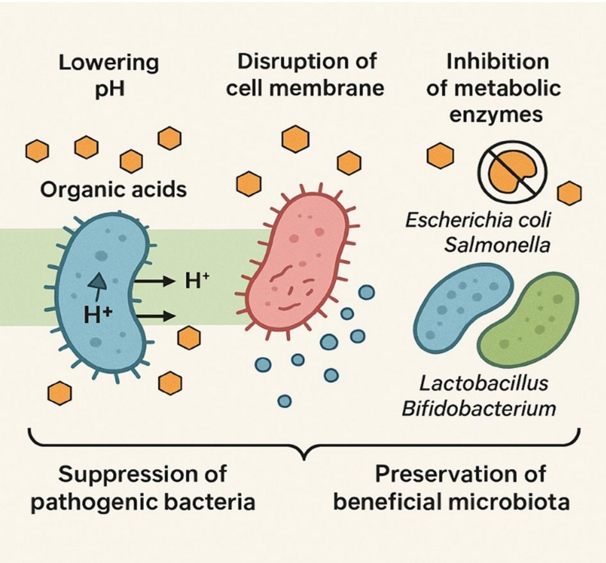

Figure 1. Mechanistic pathways of organic acids in suppressing pathogenic bacteria and preserving beneficial microbiota.

Effectiveness of organic acids in animal husbandry

Organic acids have been shown to be effective in suppressing the growth of pathogenic bacteria, while supporting livestock health by improving digestive efficiency, growth performance, and immune response; this effectiveness has been supported by various studies in livestock species such as chickens (Bagal *et al*., 2016), cattle (Castillo *et al*., 2004), and pigs (Nguyen *et al*., 2020), and is influenced by factors such as dosage, dosage form, combination of acid types, and intestinal environmental conditions that determine the availability and biological activity of the compound.

Effectiveness against the growth of pathogenic bacteria

Organic acids have demonstrated efficacy in inhibiting the growth of harmful bacteria, such as *Salmonella* spp. (Van Immerseel *et al*., 2006), *Clostridium* spp. (Ko *et al*., 2025), and *Escherichia coli* (Raftari *et al*., 2009), which commonly infect the digestive system of animals. The main mechanism of its efficacy is a complex collection of factors, such as suppression of bacterial metabolic enzyme activity, breakdown of cell membrane integrity, and a drop in stomach pH (Dibner and Buttin, 2002). The intracellular pH can be lowered by non-ionized organic acids because they can pass through the pathogen cell membrane and release H^+ ions into the cytoplasm (Slonczewski *et al*., 2009). Pathogen growth and proliferation are inhibited by this pH drop because it upsets the body's natural acid-base balance, inhibits vital enzymes, and lowers the capacity of cell metabolism to generate energy (Atasoy *et al*., 2024).

Furthermore, the lipid bilayer of bacterial cell membranes is impacted by interactions between lipophilic organic acid molecules or medium carbon chains, which increase permeability, cause cell contents to seep out, and produce ion imbalances that lead to cell death (Ji *et al*., 2023). This mechanism is effective against both Gram-positive and Gram-negative bacteria and often works synergistically with pH reduction and enzyme inhibition, thereby increasing overall antibacterial strength (Zhang *et al*., 2021).

Selectivity for gut bacteria is another benefit of organic acids (Garcia-Gutierrez *et al*., 2019). The beneficial flora population is maintained by probiotic bacteria, such as *Lactobacillus* spp. and *Bifidobacterium* spp., which are comparatively resistant to acidic environments because of their

Table 2. Effectiveness of organic acids on digestive health, growth performance, and gut microbiota in various livestock species.

Livestock species	Types of organic acids	Working mechanism	Result indicators	Practical notes	Reference
Laying hens	Formate, propionate, and butyrate	Lowers gastrointestinal pH, inhibits pathogen growth, and increases beneficial flora	Egg production ↑, shell quality ↑, and *Lactobacillus* spp. population ↑	Microencapsulation improves distribution in the distal intestine and dosage is adjusted according to age and production phase.	(Khan *et al*., 2020)
Broiler chicken	Formate, propionate, and butyrate	Decreased pH, disruption of pathogen membranes, and inhibition of metabolic enzymes	ADG ↑, FCR ↓, and diarrhea incidence ↓	Liquid or microencapsulated forms are more effective for rapid growth	(Song *et al*., 2017)
Laying ducks	Formate and propionate	Decrease in pH and modulation of microbiota	Egg production ↑, skin and feather quality is maintained	The dosage is adjusted according to age and production phase.	(Li *et al*., 2024)
Meat ducks	Formate, propionate, and butyrate	Suppresses pathogens and improves nutrient digestion	ADG ↑, FCR ↓, and optimal digestive health	Combinations of organic acids are more effective than single ones.	(Huang *et al*., 2025)
Dairy cows	Acetate, propionate, and butyrate	Lowers rumen pH, supports fiber fermentation, and VFA production ↑	Milk production ↑, milk quality ↑, rumen health stable	Solid or microencapsulated form maintains acid stability in the digestive tract.	(Sutton *et al*., 2003)
Beef cattle	Propionate and butyrate	Lowering rumen pH and increasing digestive efficiency	↑ weight gain rate and optimal digestive health	The dose is adjusted according to age and body weight	(Rathert-Williams *et al*., 2023)
Pig	Formate, propionate, and butyrate	Suppresses pathogen growth and improves mucosal integrity	ADG ↑, FCR ↓, and *Lactobacillus* spp. population ↑	Combination of organic acids is more effective, liquid or microencapsulated form is recommended	(Zhou *et al*., 2020)
Goat	Formate and butyrate	Lowers rumen pH, supports fiber fermentation, and improves digestive health	ADG ↑, efficient feed consumption, and beneficial microbiota population ↑	The dose is adjusted according to age and body weight, stable solid form for dry feed	(Zhuang *et al*., 2024)
Sheep	Formate, propionate, and butyrate	Decrease in rumen pH, modulation of microbiota, and strengthening of mucosal integrity	↑ weight gain rate, ↑ feed efficiency, and optimal digestive health	The combination of organic acids supports the performance and balance of the microbiota	(Sujani *et al*., 2024)

internal adaptability (Chandrasekaran *et al*., 2024). This selectivity guarantees that pathogen management does not upset the microbiota's equilibrium, promoting the generation of short-chain fatty acids, fiber fermentation, and nutrient absorption, all of which enhance digestive health and animal development.

Impact on livestock health

Organic acids have been demonstrated to significantly improve livestock's immunological response, growth performance, and digestive health when added to animal feed (Kumar *et al*., 2021). Organic acids work in the digestive tract to reduce the pH of the gastrointestinal tract, which makes it less favorable for harmful bacteria including *Salmonella*, *Clostridium*, and *Escherichia coli* (Paul *et al*., 2007). Additionally, this pH drop promotes the growth of good bacteria, including *Lactobacillus* and *Bifidobacterium* species, which contribute to the fermentation of fiber, the synthesis of short-chain fatty acids, and improved nutrient absorption (Ademosun *et al*., 2025). The availability of nutrients for cattle growth and the effectiveness of energy metabolism is directly improved by this more balanced digestive state.

Organic acids can improve the rate of weight gain and feed conversion in terms of growth performance by enhancing the digestion of proteins and carbohydrates, boosting the activity of digestive enzymes, and promoting better vitamin and mineral absorption (Sharifuzzaman *et al*., 2025). Furthermore, the intestinal wall is strengthened by the integrity of the intestinal mucosa, which is maintained by organic acids, particularly butyric acid. This lowers the danger of infection and local inflammation, which indirectly enhances growth performance (Takiishi *et al*., 2017).

Organic acids also provide immunomodulatory effects (Du *et al*., 2023). This substance can decrease intestinal inflammation by inhibiting the growth of pathogens, which lowers the immunological load and boosts the adaptive immune response to infection (Vinayamohan *et al*., 2024). Some types of organic acids, especially short to medium chains, can stimulate the production of immune cells and signaling molecules such as cytokines, strengthening the body's defenses against pathogens (Duan *et al*., 2023). Through this complex process, organic acids enhance intestinal health, digestive effectiveness, and livestock's immune system in addition to acting as antibacterial agents and physiological modulators.

Research data from various livestock species

Research data from various livestock species shows that organic acid supplementation in feed has a significant impact on digestive health, growth performance, and gut microbiota balance. Table 2 summarizes the effectiveness of organic acids on various livestock species. This data highlights the mechanisms of action of organic acids, measurable outcome indicators, and practical considerations for field application. Organic acids like formic, propionic, acetic, and butyric acids generally function by lowering the pH of the rumen or gastrointestinal tract, rupturing the cell membranes of pathogens, and preventing the activity of metabolic enzymes. This stops the growth of harmful bacteria while promoting the development of beneficial microbiota.

In laying and broiler chickens, organic acid supplementation increases egg production, shell quality, average daily gain (ADG), and feed conversion efficiency (FCR), while reducing the incidence of diarrhea (Khan *et al*., 2020; Song *et al*., 2017). A microencapsulation strategy is recommended for optimal distribution in the distal gastrointestinal tract. Laying and broiler ducks showed similar responses, with improved egg, skin, and feather quality, and more efficient growth (Li *et al*., 2024; Huang *et al*., 2025).

In ruminants such as dairy and beef cattle, as well as goats and sheep, organic acids support fiber fermentation in the rumen, increase short-chain fatty acid (VFA) production, improve digestive efficiency, and reduce the risk of digestive disorders (Sutton *et al*., 2003; Rathert-Williams *et al*., 2023). This is reflected in increased milk production in dairy cattle and improved weight gain rates in beef cattle, goats, and sheep (Zhuang *et al*., 2024; Sujani *et al*., 2024).

In pigs, the use of a combination of organic acids significantly suppressed the growth of intestinal pathogens, increased mucosal integrity, and supported the population of *Lactobacillus* spp., thereby improving ADG, FCR, and overall digestive health (Zhou *et al*., 2020).

Factors that influence effectiveness

The effectiveness of organic acids in animal feed is influenced by several critical factors, including dose, dosage form, combination of acid types, and environmental conditions of the digestive tract. The correct dosage determines the ability of organic acids to lower gastrointestinal or rumen pH, inhibit the growth of pathogenic bacteria, and support beneficial microbiota (Dittoe *et al*., 2018). A dose that is too high can upset the microbiota's equilibrium or irritate the mucosa, while one that is too low usually isn't enough to inhibit infections (Ji *et al*., 2023).

The dosage form also affects the distribution and release of organic acids in the digestive tract. The solid form is more stable in dry feed, while the liquid form can be released quickly in the early gastrointestinal system (Tugnoli *et al*., 2020). Microencapsulation techniques are gaining popularity because they protect the acid from degradation and allow for gradual release in the distal gut, thereby increasing overall antimicrobial effectiveness (Piva *et al*., 2007).

Combinations of several types of organic acids are often used to create a broader and synergistic spectrum of antibacterial activity (Gómez-García *et al*., 2019). Short-chain acids such as formic acid are effective in lowering pH in the early part of the intestine, while medium-chain acids such as butyrate provide a longer-lasting local effect and support mucosal integrity (Kumar *et al*., 2022). This combination strategy also helps reduce the risk of pathogen resistance and maintain beneficial microbiota populations (Chandrasekaran *et al*., 2024).

Furthermore, the environment of the digestive tract, which includes pH, the makeup of nutrients, and the presence of specific enzymes or microbiota, affects how well organic acids interact with harmful bacterial cells (Rowland *et al*., 2018). The effectiveness of pathogen suppression and the general digestive health of livestock will both be improved by conditions that promote acid stability and even distribution (Dittoe *et al*., 2018). Understanding these factors is essential for designing optimal, safe and sustainable feed formulations in modern livestock practices.

Application and implementation

The use of organic acids in animal husbandry can be applied through supplementation in feed or drinking water, combined with probiotics or prebiotics to strengthen digestive health, and as a strategy to reduce the use of conventional antibiotics.

Use in feed, drink, or direct mixture

Organic acids can be applied in livestock systems through various methods, including direct mixing into feed, addition to drinking water, or a combination of both, to maximize their effectiveness in improving digestive health and livestock performance (Waghmare *et al*., 2025). Through feed supplementation, nutrients can be directly absorbed and distributed uniformly throughout the day, reducing the pH of the rumen or gastrointestinal tract, preventing the formation of harmful bacteria, and promoting the development of beneficial microbiota (Rathnayake *et al*., 2021). Addition to drinking water offers flexibility in administration, particularly for pigs and poultry, and permits the early digestive tract to release organic acids quickly, successfully suppressing harmful bacteria like *Salmonella* spp. and *Escherichia coli* (De Busser *et al*., 2011).

The combination approach, which involves incorporating organic acids into drinking water and feed at the same time, can increase the range of antibacterial action, produce a synergistic effect, and guarantee efficient distribution throughout the digestive system (Szott *et al*., 2022). The selection of application method is adjusted to the characteristics of organic acids, optimal dosage, physical and chemical properties of feed or water, and the growth phase of livestock, to ensure consistent antimicrobial effects, maintenance of beneficial intestinal flora, as well as increasing the rate of weight gain and overall feed conversion efficiency (Mani-López *et al*., 2012). This approach is viable in contemporary animal production since it also encourages the decrease in the usage of traditional antibiotics.

Combination with probiotics or prebiotics

A synergistic approach that is being used more and more in livestock systems to enhance digestive health and performance is the combining of organic acids with probiotics or prebiotics (Markowiak and Śliżewska, 2018). Organic acids reduce the pH of the rumen or gastrointestinal tract and inhibit the growth of harmful bacteria, whereas probiotics like *Lactobacillus* and *Bifidobacterium* promote microbial balance, improve the fermentation of fiber, and generate bioactive metabolites that are good for the intestinal epithelium (Loo *et al*., 2025). Probiotic colonization and activity are increased by prebiotics, such as fermentable fibers or oligosaccharides, which act as substrates for good bacteria (You *et al*., 2022).

Applying this combination had a bigger impact than using probiotics, prebiotics, or organic acids by themselves. Probiotics and prebiotics help maintain microbiota homeostasis and increase the production of short-chain fatty acids (VFAs), which are important for immune system stimulation and intestinal mucosal integrity (Markowiak-Kopeć and Śliżewska, 2020). Organic acids cause the pH to drop, which makes the environment unfriendly to pathogens (Jiao *et al*., 2022). Additionally, this combination may improve feed conversion and weight gain rates, decrease the frequency of diarrhea, and boost the effectiveness of nutrient absorption (Shehata *et al*., 2022).

In addition, this strategy supports the reduction of conventional antibiotic use by selectively suppressing pathogens and maintaining beneficial gut flora, so that the risk of antimicrobial resistance can be minimized (Murugaiyan *et al*., 2022). The selection of organic acid types, probiotic strains, and prebiotic types and doses must be adjusted to livestock species, growth phases, and production objectives to achieve optimal, safe, and sustainable effects in modern livestock practices (Uyeno *et al*., 2015).

Strategy to reduce antibiotic use through organic acid supplementation

Supplementation of organic acids in livestock feed and drinking water has been identified as an effective strategy to reduce reliance on conventional antibiotics in livestock production (Abd El-Hack *et al*., 2022). The primary mechanisms behind this strategy's efficacy are a drop in the pH of the rumen or gastrointestinal tract, damage to the pathogenic bacteria's cell membrane integrity, and inhibition of the activity of metabolic enzymes crucial to the development and spread of harmful microorganisms (Yoon *et al*., 2024). The beneficial gut flora can stay stable by selectively lowering the number of pathogens including *Salmonella* spp., *Clostridium* spp., and *Escherichia coli* (Irkin *et al*., 2015). This promotes the formation of short-chain fatty acids, fiber fermentation, and the best possible absorption of nutrients.

Utilizing organic acids instead of antibiotics also lessens the selective pressure that typically results from using traditional antibiotics, lowering the possibility of long-term antimicrobial resistance (Muteeb *et al*., 2023). Higher and more sustainable animal productivity is a result of additional advantages such as enhanced growth performance, feed conversion efficiency, and more consistent digestive health (Sharifuzzaman *et al*., 2025).

This strategy can be implemented through various approaches, including mixing directly into feed, adding to drinking water, or using a combination with probiotics and prebiotics for a synergistic effect (Markowiak and Śliżewska, 2018). The kind of organic acid, dosage, and administration form (liquid, solid, or microencapsulated) must be chosen with the kind of livestock, growth stage, and production goals in mind (Partanen and Mroz, 1999). This strategy lessens dependency on traditional antibiotics without sacrificing cattle productivity or health while promoting safer, more sustainable, and ecologically friendly modern livestock operations.

For a comprehensive overview, Figure 2 presents the implementation pathways of organic acids in livestock production, emphasizing their administration through feed and drinking water, their synergistic use with probiotics and prebiotics, and their role in reducing antibiotic dependency while enhancing digestive health and overall animal performance.

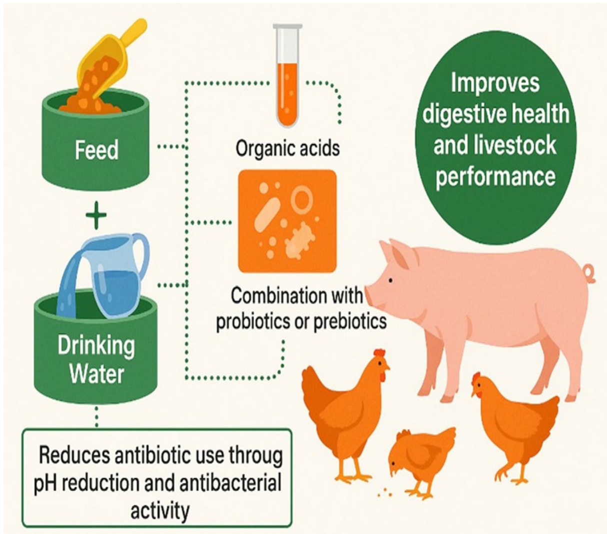

Figure 2. Implementation pathways of organic acids in modern livestock production.

Limitations and challenges

Limitations and challenges in the use of organic acids in livestock include variability in responses between species and environmental conditions, issues of compound stability in feed and the digestive tract, considerations of costs and production scale, and the need for further research to determine optimal doses, combinations, and formulations.

Variability of response between livestock and environmental conditions

The response of livestock to organic acid supplementation can differ significantly between species and is influenced by environmental conditions and husbandry management (Bhandari *et al*., 2021). Since ruminants like cattle, goats, and sheep have more complex digestive systems with rumen fermentation, the effects of supplementation may be slower but still significant on the production of short-chain fatty acids and the health of the rumen mucosa (Pokhrel and Jiang, 2024). In contrast, poultry, such as chickens and ducks, typically exhibit a rapid decrease in gastrointestinal pH and a relatively rapid growth response to organic acids (Fathima *et al*., 2022). The efficiency of organic acids is also influenced by environmental factors, including temperature, humidity, feed quality, cage density, and livestock stress levels, in addition to species considerations (Nguyen *et al*., 2018). This variation affects the capacity to suppress harmful bacteria, interactions with the local microbiota, and the distribution of chemicals in the digestive system. Therefore, supplementation strategies should be tailored to species characteristics, growth phases, and environmental conditions to ensure consistent effectiveness in improving digestive health, growth performance, and gut microbiota balance (Berding *et al*., 2021). A thorough understanding of this variability is essential to optimize the dosage, dosage form, and combination of organic acids in modern livestock practices.

Stability of organic acids in feed or digestive system

The potential of organic acids to inhibit harmful microorganisms and promote the digestive health of animals is significantly influenced by their stability (Atasoy *et al*., 2024). Degradation or chemical interactions between organic acids and feed ingredients like proteins, minerals, or fiber might lower the active concentration and lessen the antibacterial activity of the acid (Adewole *et al*., 2021). This stability is also influenced by the organic acid dosage form; for instance, liquid forms are more likely to degrade because of feed pH or water interaction, while solid and microencapsulated forms are more likely to remain stable and maintain effective concentrations until they reach the distal gastrointestinal tract (Adepu and Ramakrishna, 2021).

In the livestock digestive system, physiological conditions such as pH, the presence of digestive enzymes, and the activity of local microbiota also influence the stability and availability of organic acids (Xu *et al*., 2021). In the early gastrointestinal tract, short-chain acids like acetic and formic acid are effective because they dissociate more quickly in low pH environments. In contrast, medium-chain acids like propionic and butyric acid are more stable and tend to last into the rumen or distal intestine, where they support mucosal integrity and have a longer-lasting antimicrobial effect (Szczuko *et al*., 2024).

Understanding the factors that influence the stability of organic acids allows the design of optimal formulations, both in terms of the type of acid, dosage, and dosage form, so that the distribution and release of active compounds can be precisely controlled (Adepu and Ramakrishna, 2021). This approach is crucial for maintaining beneficial microbiota, guaranteeing consistent antimicrobial efficacy, and promoting sustainable animal growth performance.

Cost and scale of production

Important factors to take into account when implementing organic acid supplementation in the livestock business are cost and production scale (Kamal and Ragaa, 2014). Farmers must strike a balance between biological efficacy and economic efficiency because the cost of supplements is influenced by the active ingredient's price, the production process, and the dosage type (liquid, solid, or microencapsulated) (Rani *et al*., 2023). On a small scale, using pure organic acids or simple mixtures may be very cost-effective and efficient. However, on an industrial scale, using multi-acid combinations or microencapsulated formulations can result in significant cost increases even though they offer better distribution and gradual release in the gastrointestinal tract (Agriopoulou *et al*., 2023).

The best dosage and application method are also determined by the production scale. Proper homogenization machinery is necessary for large-scale farms to blend organic acids into feed evenly, ensuring uniform distribution and antibacterial efficacy (Sorathiya *et al*., 2025). However, use in drinking water can be more adaptable, but it still needs to be carefully dose-controlled to ensure that individual cattle consumption is still beneficial (Kurtz and Feeney, 2020). Cost-benefit analysis shows that although the initial investment for more stable dosage forms or microencapsulation is higher, the long-term benefits in terms of improved growth performance, reduced mortality, reduced disease incidence, and reduced dependence on conventional antibiotics can offset these additional costs (Singh *et al*., 2010).

Further research is needed to optimize dosage and combination

Even though organic acids have proven to be a successful substitute for antibiotics in the production of cattle, further investigation is required to identify the best dosages, combinations, and formulations for different species and stages of growth. The variety of livestock reactions to organic acids is controlled by physiological parameters, gastrointestinal microbiota, diet, and environmental conditions, so that doses that are helpful in one species or growth phase may not necessarily apply to other species or stages (Rowland *et al*., 2018). The types, doses, dosage forms, and possible synergies with probiotics or prebiotics must all be evaluated through systematic experimental investigations in order to optimize the antibacterial activity against infections and promote good gut flora.

Long-term research is also required to evaluate the cumulative effects on growth performance, feed efficiency, digestive health, and animal protein output, as well as the safety, tolerance, and potential microbial adaptation to repeated supplementation. Using a multidisciplinary approach that incorporates field performance testing, metabolomics, and microbiome investigation will yield more thorough data for creating precise supplementation programs. The findings of this study can be used to create useful recommendations for livestock farmers regarding the choice of acid type, dosage, combination, and application technique. This will make the use of organic acids in the contemporary livestock industry more efficient, safe, cost-effective, and sustainable.

To provide a clearer understanding of the limitations and challenges associated with the use of organic acids in modern livestock systems, Figure 3 presents a visual summary highlighting the variabilityy of responses across species, the stability of compounds in feed and the digestive tract, cost and production scale considerations, and the need for further research.

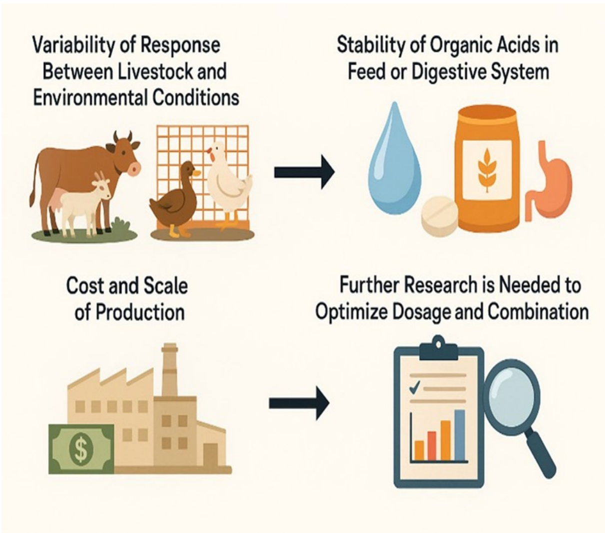

Figure 3. Limitations and challenges in the use of organic acids in livestock systems.

Conclusion

Organic acids exhibit multifaceted mechanisms in suppressing pathogenic bacteria, including lowering gastrointestinal pH, disrupting cell membranes, and inhibiting metabolic enzymes, while maintaining beneficial microbiota. Its effectiveness has been proven to improve digestive health, growth performance and feed efficiency in various livestock species, making it a safe and sustainable alternative to conventional antibiotics. The species and growth phase must be taken into consideration while adjusting the type, dosage, dosage form, and application technique for industrial use. It is advised that more study be done to determine the best combinations, interactions with probiotics or prebiotics, and long-term efficacy in order to optimize the use of organic acid supplements in contemporary livestock practices.

Acknowledgement

The authors would like to express their sincere gratitude to Universitas Airlangga and the National Research and Innovation Agency for their valuable support and contribution to this study.

Conflict of interest

The authors declare that there is no conflict of interest.

References

Abd El-Hack, M.E., El-Saadony, M.T., Salem, H.M., El-Tahan, A.M., Soliman, M.M., Youssef, G.B.A., Taha, A.E., Soliman, S.M., Ahmed, A.E., El-Kott, A.F., Al Syaad, K.M., Swelum, A.A., 2022. Alternatives to antibiotics for organic poultry production: types, modes of action and impacts on bird's health and production. Poult. Sci. 101, 101696. doi: 10.1016/j.psj.2022.101696.

Abd El-Hack, M.E., Ashour, E.A., Youssef, I.M., Elsherbeni, A.I., Tellez-Isaias, G., Aldhalmi, A.K., Swelum, A.A., Farag, S.A., 2024. Formic acid as an antibiotic alternative in broiler diets: effects on growth, carcass characteristics, blood chemistry, and intestinal microbial load. Poult. Sci. 103, 103973. doi: 10.1016/j.psj.2024.103973.

Ademosun, A.O., Ajeigbe, O.F., Ademosun, M.T., Ogunruku, O.O., Oboh, G., 2025. Improving gut microbiome through diet rich in dietary fibre and polyphenols: The case for orange peels. Hum. Nutr. Metab. 39, 200295. doi: 10.1016/j.hnm.2024.200295.

Adepu, S., Ramakrishna, S., 2021. Controlled Drug Delivery Systems: Current Status and Future Directions. Molecules 26, 5905. doi: 10.3390/molecules26195905.

Adewole, D.I., Oladokun, S., Santin, E., 2021. Effect of organic acids-essential oils blend and oat fiber combination on broiler chicken growth performance, blood parameters, and intestinal health. Anim. Nutr. 7, 1039–1051. doi: 10.1016/j.aninu.2021.02.001.

Adil, S., Banday, T., Bhat, G.A., Mir, M.S., Rehman, M., 2010. Effect of dietary supplementation of organic acids on performance, intestinal histomorphology, and serum biochemistry of broiler chicken. Vet. Med. Int. 2010, 479485. doi: 10.4061/2010/479485.

Agriopoulou, S., Tarapoulouzi, M., Varzakas, T., Jafari, S.M., 2023. Application of Encapsulation Strategies for Probiotics: From Individual Loading to Co-Encapsulation. Microorganisms 11, 2896. doi: 10.3390/microorganisms11122896.

Antone, U., Ciprovica, I., Zolovs, M., Scerbaka, R., Liepins, J., 2023. Propionic Acid Fermentation—Study of Substrates, Strains, and Antimicrobial Properties. Fermentation 9, 26. doi: 10.3390/fermentation9010026.

Anumudu, C.K., Miri, T., Onyeaka, H., 2024. Multifunctional Applications of Lactic Acid Bacteria: Enhancing Safety, Quality, and Nutritional Value in Foods and Fermented Beverages. Foods 13, 3714. doi: 10.3390/foods13233714.

Atasoy, M., Álvarez Ordóñez, A., Cenian, A., Djukić-Vuković, A., Lund, P.A., Ozogul, F., Trček, J., Ziv, C., De Biase, D., 2024. Exploitation of microbial activities at low pH to enhance planetary health. FEMS Microbiol. Rev. 48, fuad062. doi: 10.1093/femsre/fuad062.

Bagal, V.L., Khatta, V.K., Tewatia, B.S., Sangwan, S.K., Raut, S.S., 2016. Relative efficacy of organic acids and antibiotics as growth promoters in broiler chicken. Vet. World 9, 377–382. doi: 10.14202/vetworld.2016.377-382.

Bakshi, S., Paswan, V.K., Yadav, S.P., Bhinchhar, B.K., Kharkwal, S., Rose, H., Kanetkar, P., Kumar, V., Al-Zamani, Z.A.S., Bunkar, D.S., 2023. A comprehensive review on infant formula: nutritional and functional constituents, recent trends in processing and its impact on infants' gut microbiota. Front. Nutr. 10, 1194679. doi: 10.3389/fnut.2023.1194679.

Batista-Silva, W., Nascimento, V.L., Medeiros, D.B., Nunes-Nesi, A., Ribeiro, D.M., Zsögön, A., Araújo, W.L., 2018. Modifications in Organic Acid Profiles During Fruit Development and Ripening: Correlation or Causation? Front. Plant Sci. 9, 1689. doi: 10.3389/fpls.2018.01689.

Berding, K., Vlckova, K., Marx, W., Schellekens, H., Stanton, C., Clarke, G., Jacka, F., Dinan, T.G., Cryan, J.F., 2021. Diet and the Microbiota-Gut-Brain Axis: Sowing the Seeds of Good Mental Health. Adv. Nutr. 12, 1239–1285. doi: 10.1093/advances/nmaa181.

Bhandari, R., Dhungana, R., Neupane, P., 2021. Effect of organic acid as a feed supplement on growth performance of broiler. Sustain. Food Agric. 2, 57–60. doi: 10.26480/sfna.02.2021.57.60.

Bozkurt, M., Küçükyılmaz, K., Çatlı, A.U., Çınar, M., 2009. The effect of single or combined dietary supplementation of prebiotics, organic acid and probiotics on performance and slaughter characteristics of broilers. S. Afr. J. Anim. Sci. 39, 197–205. doi: 10.4314/sajas.v39i3.49152.

Broom, L.J., 2015. Organic acids for improving intestinal health of poultry. World's Poult. Sci. J. 71, 630–642. doi: 10.1017/S0043933915002391.

Bücher, C., Burtscher, J., Domig, K.J., 2021. Propionic acid bacteria in the food industry: An update on essential traits and detection methods. Compr. Rev. Food Sci. Food Saf. 20, 4299–4323. doi: 10.1111/1541-4337.12804.

Carpenter, C.E., Broadbent, J.R., 2009. External concentration of organic acid anions and pH: key independent variables for studying how organic acids inhibit growth of bacteria in mildly acidic foods. J. Food Sci. 74, R12-R15. doi: 10.1111/j.1750-3841.2008.00994.x.

Castillo, C., Benedito, J.L., Méndez, J., Pereira, V., López-Alonso, M., Miranda, M., Hernández, J., 2004. Organic acids as a substitute for monensin in diets for beef cattle. Anim. Feed Sci. Technol. 115, 101–116. doi: 10.1016/j.anifeedsci.2004.02.001.

Chandrasekaran, P., Weiskirchen, S., Weiskirchen, R., 2024. Effects of Probiotics on Gut Microbiota: An Overview. Int. J. Mol. Sci. 25, 6022. doi: 10.3390/ijms25116022.

Chen, W., Ma, Q., Li, Y., Wei, L., Zhang, Z., Khan, A., Khan, M.Z., Wang, C., 2025. Butyrate Supplementation Improves Intestinal Health and Growth Performance in Livestock: A Review. Biomolecules 15, 85. doi: 10.3390/biom15010085.

Chukwudi, P., Umeugokwe, P.I., Ikeh, N.E., Amaefule, B.C., 2025. The effects of organic acids on broiler chicken nutrition: A review. Anim. Res. One Health 3, 43–53. doi: 10.1002/aro2.85.

De Busser, E.V., Dewulf, J., Zutter, L.D., Haesebrouck, F., Callens, J., Meyns, T., Maes, W., Maes, D., 2011. Effect of administration of organic acids in drinking water on faecal shedding of *E. coli*, performance parameters and health in nursery pigs. Vet. J. 188, 184–188. doi: 10.1016/j.tvjl.2010.04.006.

Dempsey, E., Corr, S.C., 2022. *Lactobacillus* spp. for Gastrointestinal Health: Current and Future Perspectives. Front. Immunol. 13, 840245. doi: 10.3389/fimmu.2022.840245.

Dibner, J.J., Buttin, P., 2002. Use of Organic Acids as a Model to Study the Impact of Gut Microflora on Nutrition and Metabolism. J. Appl. Poult. Res. 11, 453–463. doi: 10.1093/japr/11.4.453.

Dittoe, D.K., Ricke, S.C., Kiess, A.S., 2018. Organic Acids and Potential for Modifying the Avian Gastrointestinal Tract and Reducing Pathogens and Disease. Front. Vet. Sci. 5, 216. doi: 10.3389/fvets.2018.00216.

Du, K., Foote, M.S., Mousavi, S., Buczkowski, A., Schmidt, S., Peh, E., Kittler, S., Bereswill, S., Heimesaat, M.M., 2023. Combination of organic acids benzoate, butyrate, caprylate, and sorbate provides a novel antibiotics-independent treatment option in the combat of acute campylobacteriosis. Front. Microbiol. 14, 1128500. doi: 10.3389/fmicb.2023.1128500.

Duan, H., Wang, L., Huangfu, M., Li, H., 2023. The impact of microbiota-derived short-chain fatty acids on macrophage activities in disease: Mechanisms and therapeutic potentials. Biomed. Pharmacother. 165, 115276. doi: 10.1016/j.biopha.2023.115276.

Ebeid, T.A., Al-Homidan, I.H., 2021. Organic acids and their potential role for modulating the gastrointestinal tract, antioxidative status, immune response, and performance in poultry. World's Poult. Sci. J. 78, 83–101. doi: 10.1080/00439339.2022.1988803.

El-Garhi, H.E.M., Abd-Elghany, A.A., Ibrahim, A.M.A., El-Aidie, S.A.M., Castro-Muñoz, R., 2025. Effect of Organic Acids on Pathogenic and Lactic Acid Bacteria in Directly Raw Milk Cheddar Cheese. Probiotics Antimicrob. Proteins. doi: 10.1007/s12602-025-10622-2.

Fathima, S., Shanmugasundaram, R., Adams, D., Selvaraj, R.K., 2022. Gastrointestinal Microbiota and Their Manipulation for Improved Growth and Performance in Chickens. Foods 11, 1401. doi: 10.3390/foods11101401.

Ferraz, M.P., 2024. Antimicrobial Resistance: The Impact from and on Society According to One Health Approach. Societies 14, 187. doi: 10.3390/soc14090187.

Feye, K.M., Swaggerty, C.L., Kogut, M.H., Ricke, S.C., Piva, A., Grilli, E., 2020. The biological effects of microencapsulated organic acids and botanicals induces tissue-specific and dose-dependent changes to the Gallus gallus microbiota. BMC Microbiol. 20, 332. doi: 10.1186/s12866-020-02001-4.

Fitsum, S., Gebreyohannes, G., Sbhatu, D.B., 2025. Bioactive compounds in fermented foods: Health benefits, safety, and future perspectives. Appl. Food Res. 5, 101097. doi: 10.1016/j.afres.2025.101097.

Fontoura, A.B.P., de la Maza-Escolà, V.S., Richards, A.T., Tate, B.N., Van Amburgh, M.E., Grilli, E., McFadden, J.W., 2023. Effects of dietary organic acid and pure botanical supplementation on growth performance and circulating measures of metabolic health in Holstein calves challenged by heat stress. J. Dairy Sci. 106, 2904–2918. doi: 10.3168/jds.2021-21724.

Garcia-Gutierrez, E., Mayer, M.J., Cotter, P.D., Narbad, A., 2019. Gut microbiota as a source of novel antimicrobials. Gut Microbes 10, 1–21. doi: 10.1080/19490976.2018.1455790.

Gauba, A., Rahman, K.M., 2023. Evaluation of Antibiotic Resistance Mechanisms in Gram-Negative Bacteria. Antibiotics 12, 1590. doi: 10.3390/antibiotics12111590.

Gómez-García, M., Sol, C., de Nova, P.J.G., Puyalto, M., Mesas, L., Puente, H., Mencía Ares, Ó., Miranda, R., Argüello, H., Rubio, P., Carvajal, A., 2019. Antimicrobial activity of a selection of organic acids, their salts and essential oils against swine enteropathogenic bacteria. Porcine Health Manag. 5, 32. doi: 10.1186/s40813-019-0139-4.

Guan, Z.W., Yu, E.Z., Feng, Q., 2021. Soluble Dietary Fiber, One of the Most Important Nutrients for the Gut Microbiota. Molecules 26, 6802. doi: 10.3390/molecules26226802.

Huang, C.B., Alimova, Y., Myers, T.M., Ebersole, J.L., 2011. Short- and medium-chain fatty acids exhibit antimicrobial activity for oral microorganisms. Arch. Oral Biol. 56, 650–654. doi: 10.1016/j.archoralbio.2011.01.011.

Huang, Y.Y., Qin, S.M., Nguyen, M.T., Chen, W., Si, X.M., Huang, Y.Q., Zhang, H.Y., 2025. The protective effects of dietary resistant starch against post-antibiotic bone loss in meat ducks associated with the recovery of caecal microbiota dysbiosis. Poult. Sci. 104, 105238. doi: 10.1016/j.psj.2025.105238.

Irkin, R., Değirmencioğlu, N., Güldaş, M., 2015. Effects of organic acids to prolong the shelf-life and improve the microbial quality of fresh-cut broccoli florets. Qual. Assur. Saf. Crops Foods 7, 737–745. doi: 10.3920/QAS2014.0489.

Jandhyala, S.M., Talukdar, R., Subramanyam, C., Vuyyuru, H., Sasikala, M., Reddy, D.N., 2015. Role of the normal gut microbiota. World J. Gastroenterol. 21, 8787–8803. doi: 10.3748/wjg.v21.i29.8787.

Ji, Q.Y., Wang, W., Yan, H., Qu, H., Liu, Y., Qian, Y., Gu, R., 2023. The Effect of Different Organic Acids and Their Combination on the Cell Barrier and Biofilm of *Escherichia coli*. Foods 12, 3011. doi: 10.3390/foods12163011.

Jiao, W., Liu, X., Li, Y., Li, B., Du, Y., Zhang, Z., Chen, Q., Fu, M., 2022. Organic acid, a virulence factor for pathogenic fungi, causing postharvest decay in fruits. Mol. Plant Pathol. 23, 304–312. doi: 10.1111/mpp.13159.

Kalkan, A.E., BinMowyna, M.N., Raposo, A., Ahmad, M.F., Ahmed, F., Otayf, A.Y., Carrascosa, C., Saraiva, A., Karav, S., 2025. Beyond the Gut: Unveiling Butyrate's Global Health Impact Through Gut Health and Dysbiosis-Related Conditions: A Narrative Review. Nutrients 17, 1305. doi: 10.3390/nu17081305.

Kamal, A.M., Ragaa, N.M., 2014. Effect of Dietary Supplementation of Organic Acids on Performance and Serum Biochemistry of Broiler Chicken. Nat. Sci. 12, 38–45.

Kasimanickam, V., Kasimanickam, M., Kasimanickam, R., 2021. Antibiotics Use in Food Animal Production: Escalation of Antimicrobial Resistance: Where Are We Now in Combating AMR? Med. Sci. 9, 14. doi: 10.3390/medsci9010014.

Khan, R.U., Naz, S., Raziq, F., Qudratullah, Q., Khan, N.A., Laudadio, V., Tufarelli, V., Ragni, M., 2022. Prospects of organic acids as safe alternative to antibiotics in broiler chickens diet. Environ. Sci. Pollut. Res. Int. 29, 32594–32604. doi: 10.1007/s11356-022-19241-8.

Khan, S., Moore, R.J., Stanley, D., Chousalkar, K.K., 2020. The Gut Microbiota of Laying Hens and Its Manipulation with Prebiotics and Probiotics To Enhance Gut Health and Food Safety. Appl. Environ. Microbiol. 86, e00600-20. doi: 10.1128/AEM.00600-20.

Ko, H., Goo, D., Lee, J., Gyawali, I., Katha, H.R., Lee, K.Y., Kim, W.K., 2025. Effect of coated organic acids on growth performance, *Clostridium* perfringens colonization, gut integrity and immune response in broilers challenged with subclinical necrotic enteritis. Poult. Sci. 104, 105504. doi: 10.1016/j.psj.2025.105504.

Kumar, A., Toghyani, M., Kheravii, S.K., Pineda, L., Han, Y., Swick, R.A., Wu, S.B., 2021. Potential of blended organic acids to improve performance and health of broilers infected with necrotic enteritis. Anim. Nutr. 7, 440–449. doi: 10.1016/j.aninu.2020.11.006.

Kumar, A., Toghyani, M., Kheravii, S.K., Pineda, L., Han, Y., Swick, R.A., Wu, S.B., 2022. Organic acid blends improve intestinal integrity, modulate short-chain fatty acids profiles and alter microbiota of broilers under necrotic enteritis challenge. Anim. Nutr. 8, 82–90. doi: 10.1016/j.aninu.2021.04.003.

Kurtz, D.M., Feeney, W.P., 2020. The Influence of Feed and Drinking Water on Terrestrial Animal Research and Study Replicability. ILAR J. 60, 175–196. doi: 10.1093/ilar/ilaa012.

Li, Z., Li, C., Lin, F., Yan, L., Wu, H., Zhou, H., Guo, Q., Lin, B., Xie, B., Xu, Y., Lin, Z., Liu, W., Huang, Y., 2024. Duck compound probiotics fermented di*et al*ters the growth performance by shaping the gut morphology, microbiota and metabolism. Poult. Sci. 103, 103647. doi: 10.1016/j.psj.2024.103647.

Lin, L., Chi, J., Yan, Y., Luo, R., Feng, X., Zheng, Y., Xian, D., Li, X., Quan, G., Liu, D., Wu, C., Lu, C., Pan, X., 2021. Membrane-disruptive peptides/peptidomimetics-based therapeutics: Promising systems to combat bacteria and cancer in the drug-resistant era. Acta Pharm. Sin. B 11, 2609–2644. doi: 10.1016/j.apsb.2021.07.014.

Liu, L., Li, Q., Yang, Y., Guo, A., 2021. Biological Function of Short-Chain Fatty Acids and Its Regulation on Intestinal Health of Poultry. Front. Vet. Sci. 8, 736739. doi: 10.3389/fvets.2021.736739.

Loo, J.S., Oslan, S.N.H., Mokshin, N.A.S., Othman, R., Amin, Z., Dejtisakdi, W., Prihanto, A.A., Tan, J.S., 2025. Comprehensive Review of Strategies for Lactic Acid Bacteria Production and Metabolite Enhancement in Probiotic Cultures: Multifunctional Applications in Functional Foods. Fermentation 11, 241. doi: 10.3390/fermentation11050241.

Luise, D., Correa, F., Bosi, P., Trevisi, P., 2020. A Review of the Effect of Formic Acid and Its Salts on the Gastrointestinal Microbiota and Performance of Pigs. Animals 10, 887. doi: 10.3390/ani10050887.

Ma, J., Piao, X., Shang, Q., Long, S., Liu, S., Mahfuz, S., 2021. Mixed organic acids as an alternative to antibiotics improve serum biochemical parameters and intestinal health of weaned piglets. Anim. Nutr. 7, 737–749. doi: 10.1016/j.aninu.2020.11.018.

Mani-López, E., García, H.S., López-Malo, A., 2012. Organic acids as antimicrobials to control *Salmonella* in meat and poultry products. Food Res. Int. 45, 713–721. doi: 10.1016/j.foodres.2011.04.043.

Manyi-Loh, C., Mamphweli, S., Meyer, E., Okoh, A., 2018. Antibiotic Use in Agriculture and Its Consequential Resistance in Environmental Sources: Potential Public Health Implications. Molecules 23, 795. doi: 10.3390/molecules23040795.

Markowiak, P., Śliżewska, K., 2018. The role of probiotics, prebiotics and synbiotics in animal nutrition. Gut Pathog. 10, 21. doi: 10.1186/s13099-018-0250-0.

Markowiak-Kopeć, P., Śliżewska, K., 2020. The Effect of Probiotics on the Production of Short-Chain Fatty Acids by Human Intestinal Microbiome. Nutrients 12, 1107. doi: 10.3390/nu12041107.

Murugaiyan, J., Kumar, P.A., Rao, G.S., Iskandar, K., Hawser, S., Hays, J.P., Mohsen, Y., Adukkadukkam, S., Awuah, W.A., Jose, R.A.M., Sylvia, N., Nansubuga, E.P., Tilocca, B., Roncada, P., Roson-Calero, N., Moreno-Morales, J., Amin, R., Kumar, B.K., Kumar, A.,

Mustafa, A., Bai, S., Zeng, Q., Ding, X., Wang, J., Xuan, Y., Su, Z., Zhang, K., 2021. Effect of organic acids on growth performance, intestinal morphology, and immunity of broiler chickens with and without coccidial challenge. AMB Express 11, 140. doi: 10.1186/s13568-021-01299-1.

Muteeb, G., Rehman, M.T., Shahwan, M., Aatif, M., 2023. Origin of Antibiotics and Antibiotic Resistance, and Their Impacts on Drug Development: A Narrative Review. Pharmaceuticals 16, 1615. doi: 10.3390/ph16111615.

Nguyen, D.H., Seok, W.J., Kim, I.H., 2020. Organic Acids Mixture as a Dietary Additive for Pigs-A Review. Animals 10, 952. doi: 10.3390/ani10060952.

Nguyen, D.H., Lee, K.Y., Mohammadigheisar, M., Kim, I.H., 2018. Evaluation of the blend of organic acids and medium-chain fatty acids in matrix coating as antibiotic growth promoter alternative on growth performance, nutrient digestibility, blood profiles, excreta microflora, and carcass quality in broilers. Poult. Sci. 97, 4351–4358. doi: 10.3382/ps/pey339.

Nhara, R.B., Marume, U., Nantapo, C.W.T., 2024. Potential of Organic Acids, Essential Oils and Their Blends in Pig Diets as Alternatives to Antibiotic Growth Promoters. Animals 14, 762. doi: 10.3390/ani14050762.

Pandey, S., Doo, H., Keum, G.B., Kwak, J., Ryu, S., Choi, Y., Kang, J., Kim, S., Lee, N.R., Oh, K.K., Lee, J.H., Kim, H.B., 2024. Antibiotic resistance in livestock, environment and humans: One Health perspective. J. Anim. Sci. Technol. 66, 266–278. doi: 10.5187/jast.2023.e129.

Partanen, K.H., Mroz, Z., 1999. Organic acids for performance enhancement in pig diets. Nutr. Res. Rev. 12, 117–145. doi: 10.1079/095442299108728884.

Paul, S.K., Halder, G., Mondal, M.K., Samanta, G., 2007. Effect of Organic Acid Salt on the Performance and Gut Health of Broiler Chicken. J. Poult. Sci. 44, 389–395. doi: 10.2141/jpsa.44.389.

Pickard, J.M., Zeng, M.Y., Caruso, R., Núñez, G., 2017. Gut microbiota: Role in pathogen colonization, immune responses, and inflammatory disease. Immunol. Rev. 279, 70–89. doi: 10.1111/imr.12567.

Piva, A., Pizzamiglio, V., Morlacchini, M., Tedeschi, M., Piva, G., 2007. Lipid microencapsulation allows slow release of organic acids and natural identical flavors along the swine intestine. J. Anim. Sci. 85, 486–493. doi: 10.2527/jas.2006-323.

Pokhrel, B., Jiang, H., 2024. Postnatal Growth and Development of the Rumen: Integrating Physiological and Molecular Insights. Biology 13, 269. doi: 10.3390/biology13040269.

Qui, N.H., 2023. Recent advances of using organic acids and essential oils as in-feed antibiotic alternative in poultry feeds. Czech J. Anim. Sci. 68, 141–160. doi: 10.17221/99/2022-CJAS.

Raftari, M., Jalilian, F.A., Abdulamir, A.S., Son, R., Sekawi, Z., Fatimah, A.B., 2009. Effect of organic acids on *Escherichia coli* O157:H7 and Staphylococcus aureus contaminated meat. Open Microbiol. J. 3, 121–127. doi: 10.2174/1874285800903010121.

Rahman, A., Baharlouei, P., Koh, E.H.Y., Pirvu, D.G., Rehmani, R., Arcos, M., Puri, S., 2024. A Comprehensive Analysis of Organic Food: Evaluating Nutritional Value and Impact on Human Health. Foods 13, 208. doi: 10.3390/foods13020208.

Rahman, M.R.T., Fliss, I., Biron, E., 2022. Insights in the Development and Uses of Alternatives to Antibiotic Growth Promoters in Poultry and Swine Production. Antibiotics 11, 766. doi: 10.3390/antibiotics11060766.

Rani, M., Kaushik, P., Bhayana, S., Kapoor, S., 2023. Impact of organic farming on soil health and nutritional quality of crops. J. Saudi Soc. Agric. Sci. 22, 560–569. doi: 10.1016/j.jssas.2023.07.002.

Rathert-Williams, A.R., McConnell, H.L., Salisbury, C.M., Lindholm-Perry, A.K., Lalman, D.L., Pezeshki, A., Foote, A.P., 2023. Effects of adding ruminal propionate on dry matter intake and glucose metabolism in steers fed a finishing ration. J. Anim. Sci. 101, skad072. doi: 10.1093/jas/skad072.

Rathnayake, D., Mun, H.S., Dilawar, M.A., Baek, K.S., Yang, C.J., 2021. Time for a Paradigm Shift in Animal Nutrition Metabolic Pathway: Dietary Inclusion of Organic Acids on the Production Parameters, Nutrient Digestibility, and Meat Quality Traits of Swine and Broilers. Life 11, 476. doi: 10.3390/life11060476.

Rowland, I., Gibson, G., Heinken, A., Scott, K., Swann, J., Thiele, I., Tuohy, K., 2018. Gut microbiota functions: metabolism of nutrients and other food components. Eur. J. Nutr. 57(1), 1–24. doi: 10.1007/s00394-017-1445-8.

Ryssel, H., Kloeters, O., Germann, G., Schäfer, T., Wiedemann, G., Oehlbauer, M., 2009. The antimicrobial effect of acetic acid--an alternative to common local antiseptics? Burns 35, 695–700. doi: 10.1016/j.burns.2008.11.009.

Salam, M.A., Al-Amin, M.Y., Salam, M.T., Pawar, J.S., Akhter, N., Rabaan, A.A., Alqumber, M.A.A., 2023. Antimicrobial Resistance: A Growing Serious Threat for Global Public Health. Healthcare 11, 1946. doi: 10.3390/healthcare11131946.

Sharifuzzaman, M., Mun, H.-S., Ampode, K.M.B., Lagua, E.B., Park, H.-R., Kim, Y.-H., Hasan, M.K., Yang, C.-J., 2025. Optimizing broiler growth, health, and meat quality with citric acid- assessing the optimal dose and environmental impact: Citric acid in Broiler Health and Production. Poult. Sci. 104, 104668. doi: 10.1016/j.psj.2024.104668.

Shehata, A.A., Yalçın, S., Latorre, J.D., Basiouni, S., Attia, Y.A., Abd El-Wahab, A., Visscher, C., El-Seedi, H.R., Huber, C., Hafez, H.M., Eisenreich, W., Tellez-Isaias, G., 2022. Probiotics, Prebiotics, and Phytogenic Substances for Optimizing Gut Health in Poultry. Microorganisms 10, 395. doi: 10.3390/microorganisms10020395.

Siddiqui, S.A., Erol, Z., Rugji, J., Taşçı, F., Kahraman, H.A., Toppi, V., Musa, L., Di Giacinto, G., Bahmid, N.A., Mehdizadeh, M., Castro-Muñoz, R., 2023. An overview of fermentation in the food industry - looking back from a new perspective. Bioresour. Bioprocess. 10, 85. doi: 10.1186/s40643-023-00702-y.

Singh, M.N., Hemant, K.S., Ram, M., Shivakumar, H.G., 2010. Microencapsulation: A promising technique for controlled drug delivery. Res. Pharm. Sci. 5, 65–77.

Slonczewski, J.L., Fujisawa, M., Dopson, M., Krulwich, T.A., 2009. Cytoplasmic pH measurement and homeostasis in bacteria and archaea. Adv. Microb. Physiol. 55, 1–79. doi: 10.1016/s0065-2911(09)05501-5.

Soares-Silva, I., Ribas, D., Sousa-Silva, M., Azevedo-Silva, J., Rendulić, T., Casal, M., 2020. Membrane transporters in the bioproduction of organic acids: state of the art and future perspectives for industrial applications. FEMS Microbiol. Lett. 367, fnaa118. doi: 10.1093/femsle/fnaa118.

Song, B., Li, H., Wu, Y., Zhen, W., Wang, Z., Xia, Z., Guo, Y., 2017. Effect of microencapsulated sodium butyrate dietary supplementation on growth performance and intestinal barrier function of broiler chickens infected with necrotic enteritis. Anim. Feed Sci. Technol. 232, 6–15. doi: 10.1016/j.anifeedsci.2017.07.009.

Sorathiya, K.B., Melo, A., Hogg, M.C., Pintado, M., 2025. Organic Acids in Food Preservation: Exploring Synergies, Molecular Insights, and Sustainable Applications. Sustainability 17, 3434. doi: 10.3390/su17083434.

Sujani, S., Gleason, C.B., Dos Reis, B.R., White, R.R., 2024. Rumen fermentation of meal-fed sheep in response to diets formulated to vary in fiber and protein degradability. J. Anim. Sci. 102, skad406. doi: 10.109

Sutton, J.D., Dhanoa, M.S., Morant, S.V., France, J., Napper, D.J., Schuller, E., 2003. Rates of production of acetate, propionate, and butyrate in the rumen of lactating dairy cows given normal and low-roughage diets. J. Dairy Sci. 86, 3620–3633. doi: 10.3168/jds.S0022-0302(03)73968-X.

Szczuko, M., Duliban, G., Drozd, A., Sochaczewska, D., Pokorska-Niewiada, K., Ziętek, M., 2024. Association of short-chain fatty acids with the occurrence of gastrointestinal symptoms in infants. Int. J. Mol. Sci. 25, 12487. doi: 10.3390/ijms252312487.

Szott, V., Peh, E., Friese, A., Roesler, U., Kehrenberg, C., Ploetz, M., Kittler, S., 2022. Antimicrobial effect of a drinking water additive comprising four organic acids on Campylobacter load in broilers and monitoring of bacterial susceptibility. Poult. Sci. 101, 102209. doi: 10.1016/j.psj.2022.102209.

Takiishi, T., Fenero, C.I.M., Câmara, N.O.S., 2017. Intestinal barrier and gut microbiota: shaping our immune responses throughout life. Tissue Barriers 5, e1373208. doi: 10.1080/21688370.2017.1373208.

Teshome, E., Forsido, S.F., Rupasinghe, H.P.V., Keyata, E.O., 2022. Potentials of natural preservatives to enhance food safety and shelf life: a review. Sci. World J. 2022, 9901018. doi: 10.1155/2022/9901018.

Tian, Z., Zhuang, X., Luo, M., Yin, W., Xiong, L., 2020. Propionic acid and butyric acid in serum but not in feces are increased in patients with diarrhea-predominant irritable bowel syndrome. BMC Gastroenterol. 20, 73. doi: 10.1186/s12876-020-01212-3.

Tugnoli, B., Giovagnoni, G., Piva, A., Grilli, E., 2020. From acidifiers to intestinal health enhancers: how organic acids can improve growth efficiency of pigs. Animals 10, 134. doi: 10.3390/ani10010134.

Uyeno, Y., Shigemori, S., Shimosato, T., 2015. Effect of probiotics/prebiotics on cattle health and productivity. Microbes Environ. 30, 126–132. doi: 10.1264/jsme2.ME14176.

Van Immerseel, F., Russell, J.B., Flythe, M.D., Gantois, I., Timbermont, L., Pasmans, F., Haesebrouck, F., Ducatelle, R., 2006. Use of organic acids to combat *Salmonella* in poultry: a mechanistic explanation of the efficacy. Avian Pathol. 35, 182–188. doi: 10.1080/03079450600711045.

Vinayamohan, P., Joseph, D., Viju, L.S., Baskaran, S.A., Venkitanarayanan, K., 2024. Efficacy of probiotics in reducing pathogenic potential of infectious agents. Fermentation 10, 599. doi: 10.3390/fermentation10120599.

Waghmare, S., Gupta, M., Bahiram, K.B., Korde, J.P., Bhat, R., Datar, Y., Rajora, P., Kadam, M.M., Kaore, M., Kurkure, N.V., 2025. Effects of organic acid blends on growth performance, intestinal morphology, microbiota, and serum lipid parameters of broiler chickens. Poult. Sci. 104, 104546. doi: 10.1016/j.psj.2024.104546.

Warnecke, T., Gill, R.T., 2005. Organic acid toxicity, tolerance, and production in *Escherichia coli* biorefining applications. Microb. Cell Fact. 4, 25. doi: 10.1186/1475-2859-4-25.

Wu, Y., Xia, M., Zhang, X., Li, X., Zhang, R., Yan, Y., Lang, F., Zheng, Y., Wang, M., 2021. Unraveling the metabolic network of organic acids in solid-state fermentation of Chinese cereal vinegar. Food Sci. Nutr. 9, 4375–4384. doi: 10.1002/fsn3.2409.

Xu, Q., Qiao, Q., Gao, Y., Hou, J., Hu, M., Du, Y., Zhao, K., Li, X., 2021. Gut microbiota and their role in health and metabolic disease of dairy cow. Front. Nutr. 8, 701511. doi: 10.3389/fnut.2021.701511.

Yoon, J.H., Oh, M.S., Lee, S.Y., 2024. Effectiveness of organic acids for inactivating pathogenic bacteria inoculated in laboratory media and foods: an updated minireview. Food Sci. Biotechnol. 33, 2715–2728. doi: 10.1007/s10068-024-01618-9.

You, S., Ma, Y., Yan, B., Pei, W., Wu, Q., Ding, C., Huang, C., 2022. Promotion mechanism of prebiotics for probiotics: a review. Front. Nutr. 9, 1000517. doi: 10.3389/fnut.2022.1000517.

Zhang, F., Cheng, W., 2022. Mechanism of bacterial resistance and potential bacteriostatic strategies. Antibiotics 11, 1215. doi: 10.3390/antibiotics11091215.

Zhang, Q.Y., Yan, Z.B., Meng, Y.M., Hong, X.Y., Shao, G., Ma, J.J., Cheng, X.R., Liu, J., Kang, J., Fu, C.Y., 2021. Antimicrobial peptides: mechanism of action, activity and clinical potential. Mil. Med. Res. 8, 48. doi: 10.1186/s40779-021-00343-2.

Zhou, H., Sun, J., Ge, L., Liu, Z., Chen, H., Yu, B., Chen, D., 2020. Exogenous infusion of short-chain fatty acids can improve intestinal functions independently of the gut microbiota. J. Anim. Sci. 98, skaa371. doi: 10.1093/jas/skaa371.

Zhuang, Y., Abdelsattar, M.M., Fu, Y., Zhang, N., Chai, J., 2024. Butyrate metabolism in rumen epithelium affected by host and diet regime through regulating microbiota in a goat model. Anim. Nutr. 19, 41–55. doi: 10.1016/j.aninu.2024.04.027.