PREPRINT

PERTANIKA JOURNALS

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Physiological and Biochemical Effects of Citric Acid on Growth Performance, Gut Health and Environmental Sustainability of Broilers in Developing Countries

Muhammad Umair[1], Muhammad Mahboob Ali Hamid[1], Waseem Abbas[1], Asfa Fatima[1], Azhar Rafique[2], Riaz Mustafa[3], Umar Farooq[3], Muhammad Farooq Khalid[3], Abdul Basit[4], Abdur Rehman[1,5], Muhammad Farhan Ayaz Chishti[6], Munawar Hussain[7], and Muhammad Aziz ur Rahman[1]*

[1]*Institute of Animal and Dairy Sciences, University of Agriculture Faisalabad, 38000 Faisalabad, Pakistan*
[2]*Department of Zoology, Government College University, 38000 Faisalabad, Pakistan*
[3]*Constituent College Toba Tek Singh, University of Agriculture Faisalabad, 38000 Faisalabad, Pakistan*
[4]*Remount Veterinary and Farms Corps, 46000 Rawalpindi, Pakistan*
[5]*Department of Animal Sciences, Faculty of Agriculture, Sargodha University, 40100 Sargodha, Pakistan*
[6]*Department of Animal and Poultry Production, Gomal University, 32200 Dera Ismail Khan, Pakistan*
[7]*Sind Feed and Allied Products, 75600 Karachi, Pakistan*

ABSTRACT

Antibiotics is being used in the poultry sector as growth promoters (AGPs) to enhance productivity, and their extensive use in poultry feed contributes to antimicrobial resistance (AMR). Therefore, the use of AGPs has been restricted or banned in many countries, and alternatives are being sought and among the alternatives to AGPs, organic acids in general and citric acid (CA) in particular have emerged; CA is a naturally occurring compound generally recognised as safe and has been widely tested as a feed and water additive for broilers. This structured narrative review synthesises primary studies on the effects of CA on growth performance, nutrient utilisation, gastrointestinal pH, gut microbiota and morphology, and its potential role in AGP-free production, distinguishing evidence obtained with CA alone from that obtained with organic acid blends. The evidence reviewed shows that CA supplementation at about 0.5-1.0% of the diet improves weight gain,

ARTICLE INFO

Article history:
Received: 28 June 2026
Accepted: 13 November 2026
Published: 02 December 2026

DOI: https://doi.org/10.47836/pjtas.49.6.04

E-mail addresses:
mohammadumair372@gmail.com (Muhammad Umair)
dr.mmahboob@uaf.edu.pk (Muhammad Mahboob Ali Hamid)
waseem.abbas@uaf.edu.pk (Waseem Abbas)
asfa3396@gmail.com (Asfa Fatima)
azharrafique@gcuf.edu.pk (Azhar Rafique)
drriaz@uaf.edu.pk (Riaz Mustafa)
u.farooq@uaf.edu.pk (Umar Farooq)
farooq325@uaf.edu.pk (Muhammad Farooq Khalid)
abdulbasitcba@gmail.com (Abdul Basit)
abdur.rehman@uos.edu.pk (Abdur Rehman)
drfarhanayaz@gu.edu.pk (Muhammad Farhan Ayaz Chishti)
Munawar.Manais@gmail.com (Munawar Hussain)
drazizurrahman@uaf.edu.pk (Muhammad Aziz ur Rahman)
* Corresponding author

e-ISSN: 2231-8542

© Universiti Putra Malaysia Press

feed conversion and phosphorus utilisation, particularly in low-phosphorus diets and in combination with exogenous phytase enzymes. However, higher inclusion levels (around 6%) depress feed intake and growth. Environmental benefits of CA supplementation are mainly inferred from improved nutrient retention, and direct evidence on AMR outcomes in CA-fed broilers is lacking. The review also briefly describes the synergistic interactions of CA with other additives in broiler production and its economic feasibility in developing countries, and proposes practical recommendations and research priorities. Overall, this review concludes that CA is a promising nutritional tool whose efficacy depends on dose of CA, bird age, diet formulation, and husbandry practices.

Keywords: Antibiotic alternatives, broiler performance, citric acid, economic feasibility, gut pH, phytate phosphorus

INTRODUCTION

Genetic improvement and precision nutrition have increased poultry production, helping to meet the demand of a growing human population for affordable protein (Food and Agriculture Organization of the United Nations [FAO], 2025; Zampiga et al., 2021). Broilers are an efficient source of animal protein because of their rapid growth and high feed efficiency (Zampiga et al., 2021). Because feed represents the largest share of broiler production costs, improving feed conversion and nutrient retention is a major focus of broiler nutrition and directly affects economic sustainability (Choi, 2025; Akram et al., 2024). At the same time, concern about nitrogen and phosphorus excretion from nutrient-dense broiler diets has put pressure on producers to improve nutrient utilisation and reduce ecological impacts (Sporchia et al., 2023). Restrictions on antibiotic growth promoters (AGPs) in broiler feed have further increased this pressure, and nutritional strategies that sustain productivity without AGPs have become a major research area (Alsayeqh, 2025; Dimuccio et al., 2026; Iqbal & Iqbal, 2026).

Reducing nutrient excretion and using AGP alternatives effectively require an understanding of the gastrointestinal physiology of broilers. Gastrointestinal physiology is a central determinant of broiler productivity. Digestive enzyme activity, intestinal morphology, absorptive capacity and microbial balance collectively regulate nutrient utilisation, assimilation and muscle accretion (Miyakawa et al., 2024; Sharifuzzaman et al., 2024). Intensive production conditions affect gastrointestinal physiology, causing variability in digestive efficiency and microbial stability that can limit the expression of the genetic growth potential of broilers (Sharifuzzaman et al., 2024). Interest in nutritional interventions to improve nutrient bioavailability and metabolic efficiency has therefore increased because of AGP restrictions and environmental concerns (Acharya & Barsila, 2025).

Among the feed interventions used in broilers, probiotics, prebiotics, enzymes, phytogenic additives and organic acids (OA) are widely used to improve gut function

and performance (Alonzo et al., 2025; Berberoğlu et al., 2025; Gadde et al., 2017; Li et al., 2025; Yu et al., 2024). Dietary probiotics and phytogenic additives improve the growth and feed efficiency of broilers; however, their efficacy is often influenced by bird strain, environmental variability and storage stability, which may change the results under commercial conditions (Raza et al., 2024; Sharifuzzaman et al., 2024). Compared with probiotics, prebiotics, enzymes and phytogenic additives, OA are chemically defined, remain stable during feed manufacturing, can be stored without concerns about microbial viability, and exert relatively predictable physicochemical effects that promote digestive efficiency and bird performance (Abd El-Hack et al., 2025; Khan et al., 2022). However, responses to dietary OA vary and are affected by diet composition and dose (Dibner & Buttin, 2002). Recent research has investigated the capacity of OA to regulate luminal pH, nutrient solubility and microbial ecology in broilers (Khan et al., 2022; Awais et al., 2024), and these studies suggest that OA can enhance digestive kinetics, nutrient absorption and energy utilisation (Riaz et al., 2025; Sharifuzzaman et al., 2024).

Among OA, citric acid (CA) has emerged as a promising additive because of its biochemical structure and strong mineral-chelating properties (Abd El-Ghany, 2024; Chukwudi et al., 2025). Studies in broilers have shown that dietary CA lowers luminal pH, enhances proteolytic enzyme activity and improves protein digestion (Atapattu & Nelligaswatta, 2005; Abd El-Ghany, 2024). CA can form mineral-citrate complexes, increase calcium and phosphorus bioavailability and support skeletal integrity (Snow et al., 2004; Rafacz-Livingston et al., 2005; Sharifuzzaman et al., 2024). In addition, CA supplementation has been associated with modulation of microbial populations and improved villus morphology (Chukwudi et al., 2025; Rathnayake et al., 2021). Enhanced mineral bioavailability, modulation of microbial populations, and improved villus morphology have been linked to improved feed conversion ratio (FCR), greater nutrient retention and reduced nitrogen and phosphorus excretion (Attia et al., 2025; Fik et al., 2021; Hossain et al., 2025; Nguyen & Kim, 2020).

Although CA has beneficial effects on broiler production, findings among broiler studies are inconsistent (Hossain et al., 2025). Variation in CA inclusion level, diet composition, bird age and experimental design has produced heterogeneous dose-response relationships (Sharifuzzaman et al., 2024; Waghmare et al., 2025). Furthermore, performance improvements are frequently reported without mechanistic measurements, which limits the integration of biochemical, physiological and production data (Gerzilov & Hristakieva, 2025). Moreover, the environmental benefits of CA are often inferred from digestibility and nutrient retention data rather than quantified directly under commercial conditions, and comparative evaluations of CA against other established feed additives remain limited (Bist et al., 2024; Sharifuzzaman et al., 2024; Sporchia et al., 2023).

Although CA is widely available and biologically well characterised, its effects on digestion, mineral metabolism, microbial ecology and nutrient partitioning have not been examined within a single framework (Hossain et al., 2025). Previous studies have examined the individual effects of CA on growth performance, mineral digestibility or gut morphology rather than integrating them (Mamabolo et al., 2025). CA has a dual capacity for luminal acidification and mineral chelation, and both affect digestive and metabolic pathways that require further evaluation (Sharifuzzaman et al., 2024).

Several reviews have summarised the use of organic acids in poultry (Khan et al., 2022; Abd El-Ghany, 2024; Awais et al., 2024; Chukwudi et al., 2025; Gerzilov & Hristakieva, 2025), others have addressed CA specifically (Melaku et al., 2021; Makofane et al., 2022; Mamabolo et al., 2025), and a recent study evaluated the optimal CA dose and its environmental impact (Sharifuzzaman et al., 2024). However, these works generally treat CA alone and organic acid blends together, rarely distinguish demonstrated effects from proposed mechanisms, and give limited attention to the conditions that determine whether CA is effective. The present review therefore aims to provide a structured synthesis of primary broiler studies on CA, separating evidence obtained with CA alone from that obtained with blends and distinguishing directly measured outcomes from proposed or indirectly supported mechanisms. We further examine the synergistic and antagonistic interactions of CA with phytase, probiotics, enzymes and dietary components and evaluate the economic feasibility of CA under the feed-resource and price conditions of developing countries. Finally, we translate the evidence into practical recommendations for nutritionists and producers, together with the main knowledge gaps.

REVIEW METHODOLOGY

This article is a structured narrative review, and the literature was searched in Scopus, Web of Science, PubMed and Google Scholar for studies published between 2002 and 2026. We used combinations of terms such as 'citric acid', 'organic acid*' and 'acidifier*' with 'broiler*' or 'chicken*' and with 'performance', 'digestibility', 'phosphorus', 'phytase', 'gut pH', 'microbiota', 'intestinal morphology', 'immunity', 'excretion', 'ammonia' and 'economic*'. We also screened the reference lists of retrieved articles and recent reviews. Peer-reviewed articles in English were included if they reported original data on broilers fed CA in feed or drinking water, alone or in combination with defined additives, and stated the inclusion level and at least one outcome related to performance, nutrient or mineral utilisation, gastrointestinal physiology, microbiota, immunity, excretion or economics. Studies on organic acid blends were retained only to discuss mechanisms and are identified as such in the text and tables. Studies in laying hens, quails or other species, conference abstracts without full data and non-peer-reviewed sources were excluded from the evidence synthesis, although reviews and studies in other species are cited for background where

indicated. Titles and abstracts were screened by two authors, and disagreements were resolved by discussion. In total, 962 records were identified, 42 full texts were assessed, and 14 studies were included in the evidence synthesis (Table 2).

Because the studies differed widely in diet, bird age, CA form, route, dose and outcome definitions, no meta-analysis was attempted, and the synthesis is descriptive and critical rather than quantitative. The SANRA criteria for narrative reviews were followed in preparing this review (Baethge et al., 2019).

PHYSIOLOGICAL AND BIOCHEMICAL MECHANISMS OF CITRIC ACID ACTION IN BROILERS

CA is a promising feed additive for broiler production not only because it lowers gut pH but also because it affects nutrient digestibility, enzyme activity, microbial interactions and metabolic pathways related to growth and physiological homeostasis in broilers (Chukwudi et al., 2025). Supplementation of CA in feed or drinking water has improved the body weight gain and FCR of broilers in several studies (Islam et al., 2012; Hossain et al., 2025; Sharifuzzaman et al., 2024), although these improvements are not always consistent (Shahin et al., 2009). These improvements could be due to better digestion: after ingestion, CA dissociates and releases H+ ions, which lower gastrointestinal pH and create an acidic environment favorable for digestion. This acidified milieu enhances the conversion of zymogens such as pepsinogen to active proteolytic enzymes, which improves proteolysis (Gerzilov & Hristakieva, 2025). However, the reduction in pH is most consistently observed in the crop, proventriculus and gizzard, whereas pH in the small intestine and caeca is buffered by pancreatic bicarbonate and bile and often remains unchanged (Dibner & Buttin, 2002).

Together, increased proteolytic activity and digestive kinetics may improve feed efficiency by reducing the amount of undigested substrate reaching the distal gut, so that more energy is available for production (Abd El-Ghany, 2024). Luminal acidification by CA suppresses acid-sensitive pathogens such as E. coli and Salmonella spp. and favors acid-tolerant bacteria such as Lactobacillus spp. (Chukwudi et al., 2025). The lower pH also improves the solubility of dietary minerals, particularly divalent cations (Ca^{2+}, Mg^{2+}, Zn^{2+}, Fe^{2+}), and CA forms soluble citrate complexes that are more easily absorbed (Sharifuzzaman et al., 2024).

Experiments show that CA supplementation increases villus height (VH), which enlarges the absorptive surface area and may improve the transport of amino acids, glucose and minerals (Melaku et al., 2021). Changes in crypt depth (CD) are less consistent; a deeper crypt usually indicates higher epithelial turnover, so the VH: CD ratio is a better indicator of absorptive capacity in CA-supplemented broilers (Khosravinia et al., 2015). These changes may improve gut barrier integrity and reduce immune-related energy

expenditure, allowing more nutrients to be directed towards growth; however, this mechanism has been described mainly for AGPs (Miyakawa et al., 2024) and has not been examined directly in CA-fed broilers. Efficient nutrient absorption in CA-supplemented broilers therefore probably depends on both improved solubility and a larger absorptive surface. Figure 1 illustrates the proposed physiological and biochemical mechanisms of CA action in broilers.

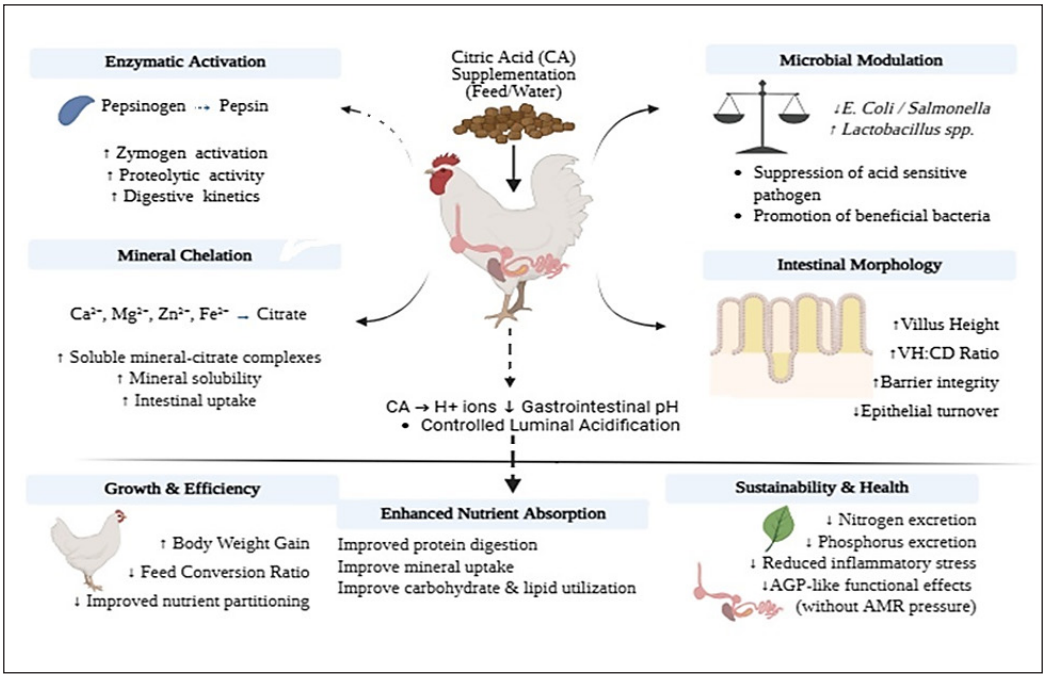


Figure 1. Proposed physiological and biochemical mechanisms of citric acid action in broilers. Solid arrows indicate effects reported in broiler studies with CA supplementation, whereas dashed arrows indicate proposed or indirectly supported mechanisms

Increased nutrient retention reduces nitrogen and phosphorus excretion in excreta, linking the digestive efficiency of broilers with environmental sustainability (Bist et al., 2024). Acid-mediated mineral chelation enhances mineral uptake and supports skeletal development in broilers (Rafacz-Livingston et al., 2005), potentially by cofactor-dependent pathways such as superoxide dismutase and catalase (Sharifuzzaman et al., 2024). Supplementation with CA alone or as part of OA blends has also been reported to shift microbial populations towards a more beneficial community, and this shift is characterised by reduced pathogen loads and increased beneficial bacteria in the digestive tract (Melaku et al., 2021); however, much of this microbiological evidence comes from blends rather than CA alone.

By stabilising the gut microbial ecosystem and reducing subclinical pathogenic stress, CA may reproduce some of the effects attributed to AGPs (Peng et al., 2024; Riaz et al., 2025). Because CA is not an antibiotic, its use may reduce reliance on antibiotics in feed or water and consequently the selection pressure for antibiotic resistance in broiler production. However, to the best of our knowledge, resistance genes or resistant bacterial populations have not been measured directly in CA-fed broilers. Controlled reductions in gastrointestinal pH with CA limit pathogen proliferation and enhance the competitive advantage of commensal bacteria that maintain intestinal stability (Vera-Álava et al., 2023).

EFFECTS ON PERFORMANCE AND NUTRIENT UTILISATION

CA supplementation in feed or water improves broiler performance through controlled acidification of the upper gastrointestinal tract, which supports efficient digestion and microbial balance (Chukwudi et al., 2025). Upon dissociation, the released H+ ions lower pH, which enhances the activation of digestive enzymes such as pepsin and improves nutrient digestibility (Gerzilov & Hristakieva, 2025; Makofane et al., 2022). This acidified milieu increases the solubility of nutrients, particularly proteins and minerals, facilitating their enzymatic breakdown and absorption (Sharifuzzaman et al., 2024). Improved digesta passage dynamics and mucosal contact time may further facilitate absorption (Rathnayake et al., 2021).

Beyond these physicochemical effects, CA modulates the gut microbiota by suppressing acid-sensitive pathogens and favoring acid-tolerant genera such as Lactobacillus spp., thereby reducing microbial competition for nutrients and the production of toxic metabolites; this in turn improves mucosal integrity and barrier function (Chukwudi et al., 2025; Riaz et al., 2025; Vera-Álava et al., 2023). Increased Lactobacillus and reduced Salmonella and E. coli counts have been reported in broilers fed CA (Chukwudi et al., 2025), whereas broader changes in microbial composition have been described mainly in general microbiome studies and with organic acid blends (Clavijo & Flórez, 2018; Peng et al., 2024). CA-mediated modulation of the gut microbiota may also reduce protein fermentation in the hindgut, limiting nitrogen losses (Hossain et al., 2025).

CA also affects individual nutrient fractions: CA supplementation enhances crude protein digestibility through acidification of the digestive tract, which suppresses proteolytic pathogens and enhances endogenous protease activity in the small intestine (Atapattu & Nelligaswatta, 2005; Nguyen & Kim, 2020). Less microbial competition for dietary nitrogen gives digestive enzymes greater access to protein substrates, favoring complete hydrolysis and absorption of amino acids (Attia et al., 2025). Furthermore, increased villus height enlarges the absorptive surface area, which facilitates amino acid uptake and supports lean tissue accretion (Khosravinia et al., 2015; Rathnayake et al., 2021). The effects of CA on performance and nutrient utilisation in broilers are shown in Figure 2.

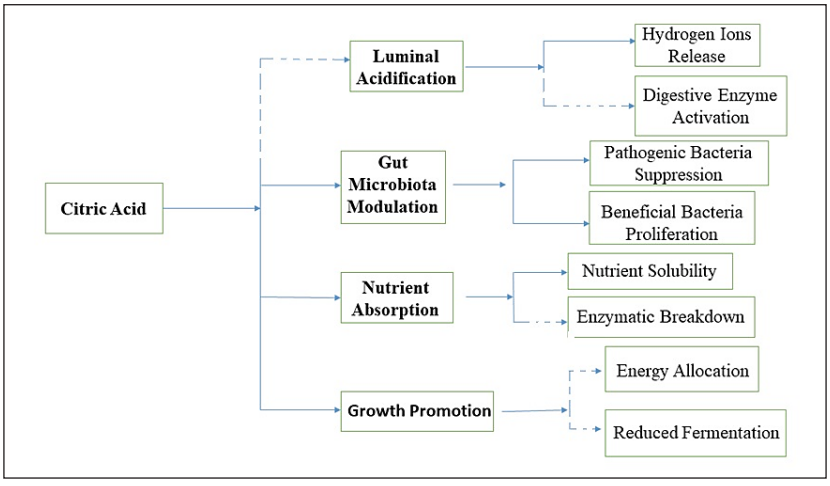


Figure 2. Effects of citric acid on performance and nutrient utilisation of broilers. Solid arrows indicate effects reported in broiler studies with citric acid, whereas dashed arrows indicate proposed or indirectly supported mechanisms

CA supplementation may also enhance the digestion and absorption of carbohydrates and lipids by favoring enzyme activity and nutrient solubilisation (Rathnayake et al., 2021). CA also modulates digesta passage rate, which may enhance metabolisable energy extraction and feed conversion efficiency (Attia et al., 2025). When combined with phytase, CA can further increase apparent metabolisable energy (AME) and phosphorus release by reducing the anti-nutritional effects of phytate (Woyengo et al., 2010). This effect is attributed to chelation of calcium by citrate, which reduces the formation of insoluble calcium-phytate complexes and makes phytate more accessible to phytase (Rafacz-Livingston et al., 2005; Snow et al., 2004).

CA enhances mineral utilisation through chelation of Ca, P, Mg, Zn and Fe, forming soluble complexes that increase intestinal absorption (Sharifuzzaman et al., 2024), and luminal acidification further enhances mineral solubility (Chukwudi et al., 2025). In low-phosphorus corn-soybean meal diets, 3% CA increased tibia ash by about 41% on average (Rafacz-Livingston et al., 2005), and CA, phytase and 1α-hydroxycholecalciferol had generally additive effects on phytate phosphorus utilisation (Snow et al., 2004). When combined with phytase, CA enhances phosphorus release from phytate and supports phosphorus retention (Attia et al., 2025; Ebrahimnezhad et al., 2008).

In parallel, suppression of microbial overgrowth may reduce energy losses associated with fermentation and inflammatory stress, allowing more dietary energy to be directed towards growth rather than maintenance (Riaz et al., 2025), although energy partitioning has not been measured directly in CA studies. The growth-promoting effect of CA has been attributed to improved digestive efficiency and nutrient availability (Chukwudi et al., 2025).

Dietary CA at 0.25-0.75% increased final body weight by about 2-5% compared with an unsupplemented diet (Islam et al., 2012), and similar improvements have been reported in Japanese quail (Fikry et al., 2021). Supplementation of CA through drinking water (2.5 g/L) improved overall FCR from 1.74 to 1.66 (Hossain et al., 2025), likely because of improved digestive efficiency and gut health. Responses in carcass traits are less consistent: CA increased carcass weight and yield in some studies (Fik et al., 2021), whereas carcass yield was not affected in others (Hossain et al., 2025; Mamabolo et al., 2025). Figure 3 illustrates the proposed integrated effects of CA in broiler nutrition.

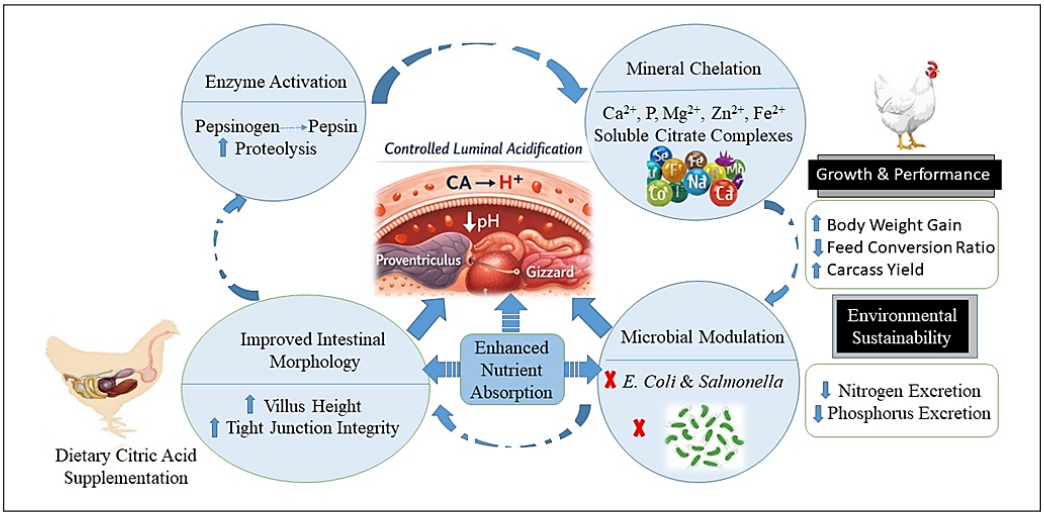


Figure 3. Integrated mechanistic effects of citric acid in broiler nutrition. Solid arrows indicate effects reported in broiler studies with citric acid, whereas dashed arrows indicate proposed or indirectly supported mechanisms

GUT HEALTH AND PH

Gut health in broilers is determined by the interaction between luminal pH, epithelial integrity, microbial populations and functional metabolites, which together influence nutrient absorption, immune responses and disease resistance (Melaku et al., 2021). CA acts as a weak OA that lowers luminal pH through H+ release, creating an environment unfavorable for harmful microbes and favorable for digestive enzyme activity (Abd El-Ghany, 2024). Abou-Ashour et al. (2021) observed that dietary CA reduced gastrointestinal pH in broilers, and a similar effect was reported for lemon juice, a natural source of CA (Ndelekwute et al., 2019). The acidified environment suppresses pathogens such as Salmonella and Escherichia coli by disrupting their intracellular pH homeostasis, while favoring acid-tolerant genera such as Lactobacillus (Wang et al., 2025). This pH-mediated selection shifts the community towards beneficial microbes that compete with pathogens for substrates and maintain intestinal homeostasis (Saleem et al., 2020).

Increased Lactobacillus counts and reduced caecal total viable bacteria, Salmonella and E. coli have been reported in broilers fed CA monohydrate, indicating a shift towards a healthier microbiota (Chukwudi et al., 2025). Together, pH reduction and microbial modulation directly inhibit acid-sensitive pathogens and indirectly favor acid-tolerant beneficial bacteria. CA supplementation lowered Salmonella prevalence in both the crop and caeca of broilers (Wang et al., 2025). Increased expression of tight-junction genes and higher short-chain fatty acid (SCFA) concentrations have been reported mainly for organic acid blends (Waghmare et al., 2025), and data for CA alone in broilers are still limited; these effects should therefore be regarded as plausible rather than demonstrated for CA.

Beneficial microbes produce SCFAs such as acetate and butyrate, which serve as energy sources for enterocytes and stimulate mucin secretion (Pangga et al., 2025). Acidified conditions and microbial balance may stimulate epithelial proliferation, increasing VH and the VH: CD ratio (Melaku et al., 2021). Together, reduced pathogen load, beneficial microbes, SCFA production and improved morphology may enhance intestinal health and resilience to enteric challenges, as reported for coated essential oil and organic acid mixtures (Hu et al., 2023). Although not a direct gut effect, the antimicrobial action of CA in feed may also improve feed hygiene by lowering the microbial load before ingestion (Waghmare et al., 2025).

ENVIRONMENTAL SUSTAINABILITY OF CITRIC ACID USE IN BROILER NUTRITION

Dietary strategies that improve nutrient utilisation and reduce waste outputs are central to the environmental sustainability of intensive broiler production, because poultry systems contribute to nutrient excretion, gaseous emissions and waste management challenges that affect air, soil and water quality (Gržinić et al., 2023). The evidence for CA can be grouped into three levels: effects directly measured in CA studies, plausible downstream consequences, and outcomes that have not yet been validated.

Effects directly measured. CA improved phosphorus and protein utilisation in broilers (Atapattu & Nelligaswatta, 2005; Rafacz-Livingston et al., 2005), and in diets with reduced mineral density it improved nutrient digestibility and mineral retention (Katoch et al., 2023). When combined with phytase, CA enhanced phosphorus digestibility and protein utilisation (Reihani et al., 2025). Lower nitrogen and phosphorus excretion and reduced ammonia emission have been measured mainly with protected organic acid blends (Nguyen & Kim, 2020), and few studies with CA alone have quantified excreta nitrogen, phosphorus or ammonia directly.

Plausible downstream consequences. Higher retention of nitrogen and phosphorus is expected to reduce their excretion in manure and thus the risk of ammonia volatilisation and eutrophication (Azizi et al., 2024; Nguyen & Kim, 2020). Improved nutrient utilisation

may also reduce litter moisture and pH, which favor the microbial processes that generate ammonia and odorous gases (Huanhong et al., 2023); however, this evidence comes from litter treatments and other feed additives rather than from CA (de Toledo et al., 2020; Jacquier et al., 2022). Replacing antibiotics with non-antibiotic additives such as CA may also reduce selection pressure for resistant bacteria in the gut and in excreta (Acharya & Barsila, 2025). Outcomes not yet validated. Better feed efficiency could reduce feed use per kilogram of meat, and thus the land use and greenhouse gas emissions associated with feed production (Sporchia et al., 2023), but no emission measurements or life-cycle assessments of CA use in broilers are available. Collectively, the current evidence suggests that CA can contribute to more sustainable broiler production mainly through improved nutrient utilisation (Du et al., 2024), whereas its effects on emissions and environmental contamination remain to be confirmed.

CITRIC ACID AS AN ALTERNATIVE TO ANTIBIOTIC GROWTH PROMOTERS

AGPs were widely used in broiler production to enhance growth and balance intestinal flora, but increasing AMR and regulatory bans have necessitated non-antibiotic strategies (Alahmadi, 2025; Khan et al., 2022; Iqbal & Iqbal, 2026). As a weak OA, CA lowers gut pH and disrupts bacterial metabolism, thereby mimicking some antimicrobial functions of antibiotics (Gerzilov & Hristakieva, 2025). CA has bactericidal and bacteriostatic properties: the undissociated form penetrates bacterial cell walls and, upon dissociation, acidifies the cytoplasm, inhibiting acid-sensitive pathogens such as Salmonella and coliforms (Chukwudi et al., 2025; Hajati, 2018). CA also fosters competitive exclusion by promoting beneficial microbiota and reducing niches for pathogens, which stabilises the gut ecosystem and reduces colonisation pressure (Chukwudi et al., 2025; Peng et al., 2024). In broilers, CA alone and in combination with Spirulina platensis has been evaluated directly as an AGP alternative (Ismita et al., 2022). However, CA should not be assumed to carry no resistance risk. Bacteria can develop an adaptive acid tolerance response after exposure to mild acid (Foster & Hall, 1990; Ricke, 2003); in vitro, CA conferred broad antibiotic tolerance by altering bacterial metabolism and oxidative stress (Li et al., 2023), and acid-adapted Salmonella showed reduced susceptibility to some antibiotics (Ghoshal et al., 2023). Thus, the main AMR-related benefit of CA is that it may reduce the need for antibiotics, rather than a demonstrated reduction in resistance, and resistance genes and resistant bacterial populations should be monitored in future CA studies.

Dietary organic acids have been reported to enhance immunocompetence by increasing serum immunoglobulins (Ig) and antioxidant enzyme activities (Ma et al., 2021, using mixed organic acids), whereas CA-specific evidence on immune responses in broilers is more limited. Compared with AGPs, CA may improve intestinal health, reduce pathogen load and support performance without leaving antibiotic residues (Abd El-Ghany, 2024).

When combined with complementary additives such as probiotics or coated OA blends, CA may enhance intestinal health and pathogen control (Waghmare et al., 2025); these interactions are discussed in a separate section below. The differences between AGPs and CA are summarised in Table 1.

Table 1
Comparison of antibiotic growth promoters and citric acid nutrition regarding mechanism, resistance risk, gut health and food safety

Parameter	AGPs	Citric Acid
Mode of action	Antimicrobial activity against gut bacteria at sub-therapeutic doses (Miyakawa et al., 2024)	Lowers pH mainly in the upper gut; undissociated acid penetrates bacterial cells; mineral chelation (Chukwudi et al., 2025; Dibner & Buttin, 2002)
Antibiotic-resistance selection	Documented; contributes to AMR (Iqbal & Iqbal, 2026)	No known direct antibiotic-resistance selection comparable with AGPs; acid tolerance and in vitro antibiotic tolerance reported (Foster & Hall, 1990; Li et al., 2023)
Gut microbiota	Broad changes in microbial composition (Peng et al., 2024)	Selective effects on acid-sensitive and acid-tolerant bacteria; evidence partly from blends (Chukwudi et al., 2025)
Immune effects	Reduced immune stimulation and inflammation (Miyakawa et al., 2024)	Increased Ig and antioxidant enzymes reported mainly with organic acid blends (Ma et al., 2021)
Residues	Antibiotic residues possible if withdrawal periods are not respected	No antibiotic residues; CA is a natural metabolite
Regulatory status and conditions of use	Banned or restricted as growth promoters in many countries (Dimuccio et al., 2026)	Permitted feed additive, generally recognied as safe when used as directed; high levels reduce intake and growth (Nourmohammadi & Khosravinia, 2015)

DRAWBACKS AND MITIGATION STRATEGIES

The response to CA is strongly dose-dependent. In the studies summarised in Table 2, improvements in growth and feed efficiency were most frequently reported at about 0.5-1.0% of the diet (Islam et al., 2012; Sharifuzzaman et al., 2024), whereas bone mineralisation continued to increase up to 3-4% CA in low-phosphorus diets (Rafacz-Livingston et al., 2005) and growth was depressed at 6% (Nourmohammadi & Khosravinia, 2015). These differences do not indicate a single optimal level. They reflect differences in dietary phosphorus and calcium, the use of phytase, the acid-binding capacity of the diet (largely determined by limestone), bird age, CA form, route of administration and the outcome measured (Attia et al., 2025; Dibner & Buttin, 2002). For example, 2% CA did not consistently improve growth or nutrient retention of broilers fed rice bran-based diets (Wickramasinghe et al., 2014).

In contrast, very high inclusion levels have reduced feed intake and growth because of the metabolic acid load and disruption of luminal homeostasis (Nourmohammadi & Khosravinia, 2015; Rathnayake et al., 2021). In drinking water, moderate CA concentrations provide acidification that can improve FCR and microbial control. However, over-acidification of water can suppress intake and disturb electrolyte balance, highlighting the importance of precise dosing regardless of the delivery route (Chukwudi et al., 2025).

The transition from beneficial to detrimental inclusion levels highlights the importance of precise application (Abd El-Ghany, 2024). High inclusion levels can over-acidify the gastrointestinal tract, disrupting luminal pH homeostasis and epithelial function and increasing maintenance energy demands (Nourmohammadi & Khosravinia, 2015). Figure 4 shows the inclusion levels of CA in broiler feed and the corresponding responses reported in the studies summarised in Table 2.

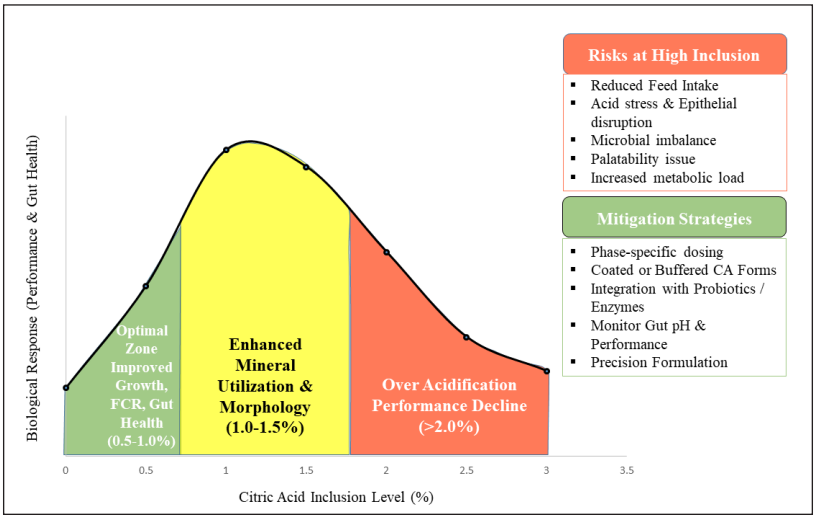


Figure 4. Inclusion level (%) of Citric acid in broiler feed and its biological response. Figure prepared from the studies summarised in Table 2; the dose zones are indicative and are not derived from a meta-analysis

High inclusion levels cause prolonged acidification, which suppresses non-acid-tolerant commensal bacteria and may reduce microbial diversity and destabilise the gut microbial ecosystem (Attia et al., 2025). Such disruption can cause physiological and metabolic stress, including altered nutrient partitioning and inflammatory signalling, that counteracts growth-promoting effects under suboptimal management conditions (Waghmare et al., 2025).

A high dietary acid load can reduce palatability, because excessive sourness may reduce feed or water intake, particularly in young broilers or under heat stress (Rathnayake et al., 2021). CA may also interact with other additives and diet components; antagonistic effects can occur with buffering agents or mineral sources, whereas synergistic responses

depend on formulation and the ingredient matrix (Nguyen & Kim, 2020), as discussed in the following section.

Inconsistent inclusion levels of CA and formulation costs across production systems can complicate cost-benefit optimisation for commercial broiler producers (Sharifuzzaman et al., 2024). These limitations can largely be mitigated through phase-specific dosing, the use of coated or buffered CA forms, careful integration with enzymes or probiotics, and monitoring of gut pH and performance indicators (Khan et al., 2022). Studies evaluating different CA inclusion levels in broiler diets are summarised in Table 2.

Table 2
Summary of broiler studies evaluating dietary citric acid at different inclusion levels

Study	Birds, Age and Diet	CA Form, Route and Level	Main Outcomes	Limitations/Notes
Snow et al. (2004)	Male crossbred chicks, 8-21 d; P-deficient corn-soybean meal diet	CA in feed with or without phytase and 1α-(OH)D3; 3% CA	↑ weight gain and tibia ash; effects of CA, phytase and 1α-(OH) D3 generally additive; 3% CA released about 0.03% P	Short chick assay; crossbred chicks
Rafacz-Livingston et al. (2005)	Crossbred and Ross chicks; corn-soybean meal diets with low non-phytate P	CA in feed; 0-4%	↑ weight gain and tibia ash; tibia ash increased linearly up to 4%; 3% CA increased bone ash by about 41%	Short chick assays; low-P diets
Ebrahimnezhad et al. (2008)	Broilers, 0-49 d; available P 0.2% below control	CA (0, 2.5, 5%) × phytase (0, 500 IU/kg) in feed	↑ weight gain and ↓ feed: gain in low-P diets; CA × phytase interaction ($P < 0.01$); no effect on intake or tibia ash	High CA levels
Atapattu and Nelligaswatta (2005)	Broilers; 20-40 d; Ca 1%, available P 0.5%	CA in feed; 0, 1 and 2%	Gut pH 5.1 (control),4.8 (1% CA) and 4.0 (2% CA); effects on P and crude protein utilisation	Rice bran-based diet and CA supplementation after 21 days of age
Islam et al. (2012)	Broilers; 0-37 d; Isonitrogenous and isocaloric starter without coccidiostat	CA in feed; 0, 0.25, 0.75 and 1.25%	BW 1,986 g (control) vs 2,030-2,086 g (+2.2-5.0%); feed efficiency 565 vs 582-595 g gain/kg feed (FCR about 1.77 vs 1.68-1.72)	Feed efficiency, not FCR, reported in original
Sharifuzzaman et al. (2024)	Broilers; CA supplementation in feed and drinking water	CA in feed; 0.5-1.0% (higher range modelled)	↑ BWG, ↓ FCR, gut pH 4.5-5.0, ↑ VH and VH: CD, ↑ digestibility; environmental outcomes assessed	Range of 1.65-2.65% was suggested by modelling, not tested directly

Study	Birds, Age and Diet	CA Form, Route and Level	Main Outcomes	Limitations/Notes
Shahin et al. (2009)	Broilers; Corn-soybean based starter diet	CA in feed; 0.2, 0.4, 0.6, 0.8, and 1.0%	BW +4.9%; performance -4.4%	CA is not efficient in commercial diet; could be beneficial with homemade rations
Ghazalah et al. (2011)	Arbor-Acres broiler chicks; 0-42 d;	Organic acids incl. CA in feed 1,2, and 3%	↑ BWG ($P < 0.05$); FCR not significant; ↓ gut pH ($P < 0.01$); ↑ VH ($P < 0.01$)	CA blend with Formic, Fumaric, and AC blends
Abdel-Fattah et al. (2008)	Hubbard Broilers; 0-42 d; basal diet	Organic acids incl. CA, AC and lactic acid in feed; 1.5-3.0%	↑ BWG ($P < 0.01$); ↓ FCR ($P < 0.01$); gut pH not significant decreased	Organic acid blend (not CA alone)
Waghmare et al. (2025)	Broilers; 0-42 d; Basal feed supplemented with Acidapure powder + Acidapure Liquid	Organic acid blend (not CA alone); 1.0%	↑ BWG, ↓ FCR, gut pH 4.8, ↑ VH, ↑ tight-junction gene expression	Blend; effect of CA cannot be isolated
Hossain et al. (2025)	Broilers; drinking water	CA 2.5 g/L water (vs synbiotic and probiotic)	↑ BWG (week 5); FCR 1.74 vs 1.66; carcass yield not affected; ↓ cholesterol and LDL	Water route; probiotic most effective
Wickramasinghe et al. (2014)	Broilers, 21-42 d; 20 or 30% rice bran; 0.25 or 0.35% non-phytate P	CA in feed; 0 and 2%	No effect on intake, gain, FCR or N and P retention; ↑ tibia ash with 2% CA and 0.35% non-phytate P	Non-Phytate Phosphorus and Rice bran-based diets
Khosravinia et al. (2015)	Broilers; 7-42 d; dietary citric acid	CA in feed; up to 3% (30 g/kg) and 6% (60 g/kg)	↑ BWG ($P < 0.001$); ↑ villus length	Diet: CA in feed, 0, 10, 20, 30 and 60 g/kg
Nourmohammadi & Khosravinia (2015)	Broilers; 7-42 d; Ca in feed	CA in feed; 0, 3 and 6% (0, 30 and 60 g of CA per kilogram of diet)	↓ BWG ($P < 0.001$) and ↓ feed intake at 6%	Acid stress at high inclusion

Note. BW = body weight; BWG = body weight gain; FCR = feed conversion ratio; VH = villus height; VH:CD = villus height to crypt depth ratio; P = phosphorus; 1α-(OH) D3 = 1α-hydroxycholecalciferol; AC = Acetic acid; ↑ increase; ↓ decrease; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

SYNERGISTIC AND ANTAGONISTIC INTERACTIONS OF CITRIC ACID WITH OTHER ADDITIVES AND DIET COMPONENTS

The response to CA depends not only on its inclusion level in feed and water but also on the dietary context in which it is used. Several synergies have been documented, but the

strongest primary evidence for synergy concerns microbial phytase. In low-phosphorus corn-soybean meal diets, CA, phytase and 1α-hydroxycholecalciferol improved the weight gain and tibia ash of broiler chicks; their effects were generally additive, and about 0.03% phosphorus was released from 3% CA and 0.02% from 300 units/kg phytase (Snow et al., 2004). Similarly, in broilers fed diets containing 0.2% less available phosphorus than the control, CA (2.5 and 5%) and phytase (500 IU/kg) both improved weight gain and FCR, with a significant CA × phytase interaction (Ebrahimnezhad et al., 2008). Moreover, phytase has also been evaluated alone or in combination with CA and multicarbohydrase (Woyengo et al., 2010), with phytase superdosing and different feed forms (Reihani et al., 2025) and at different CA concentrations (Attia et al., 2025), and phytase superdosing alone can replace part of the added inorganic phosphorus (Ali et al., 2025). Because citrate binds calcium, CA is expected to be most useful when dietary calcium and phytate are high relative to available phosphorus, as in diets containing cereal by-products such as rice bran. However, 2% CA did not consistently improve the performance of broilers fed rice bran-based diets (Wickramasinghe et al., 2014), indicating that this expectation needs further experimental evaluation.

CA has also been compared directly with probiotics and synbiotics. In drinking water, CA (2.5 g/L), a synbiotic and a probiotic each improved growth and FCR compared with an unsupplemented control; the probiotic was the most effective, but the combination of CA with probiotics was not tested (Hossain et al., 2025). Acidification of the upper gut may favor lactic acid bacteria, suggesting a potential complementary effect with *Lactobacillus-based probiotics* (Chukwudi et al., 2025); however, factorial studies testing CA together with probiotics in broilers are scarce. Organic acid blends containing CA, sometimes combined with essential oils, have improved gut morphology, barrier function and performance (Hu et al., 2023; Waghmare et al., 2025), but the specific contribution of CA in these products was not examined. Exogenous enzymes improve nutrient digestibility, particularly in low-energy diets (Hussain & Sharif, 2026), and the acidic environment created by CA may favor the activity of enzymes with acidic pH optima, such as most commercial phytases; this interaction deserves direct testing. Organic acids have also been delivered on carriers such as corn cob biochar in finisher diets (Rana et al., 2024), and CA has been combined with Spirulina platensis as an AGP alternative (Ismita et al., 2022).

Antagonistic interactions are equally important. Limestone and other buffering minerals increase the acid-binding capacity of the diet and can neutralise part of the added acid, reducing the pH response (Dibner & Buttin, 2002). High dietary calcium also reduces phytate phosphorus availability and can therefore offset part of the benefit of CA and phytase (Snow et al., 2004; Woyengo et al., 2010). The main interactions reported or expected are summarised in Table 3.

Table 3
Reported and expected interactions of citric acid with other additives and diet components in broilers

Combination	Type of Evidence	Main Reported or Expected Effect	Key references
CA + microbial phytase	Primary broiler studies	Additive or synergistic improvement in phytate-P utilisation, weight gain and tibia ash, especially in low-P diets	Snow et al. (2004); Ebrahimnezhad et al. (2008); Woyengo et al. (2010)
CA + 1α-hydroxycholecalciferol	Primary chick study	Additive improvement in phytate-P utilisation	Snow et al. (2004)
CA + phytase superdosing or different feed forms	Primary broiler studies	Improved phosphorus digestibility and protein utilisation	Reihani et al. (2025); Attia et al. (2025)
CA vs probiotics and synbiotics (drinking water)	Parallel comparison	Each improved growth and FCR; combination not tested	Hossain et al. (2025)
CA within organic acid blends, with or without essential oils	Blend studies	Improved morphology, barrier function and pathogen control; contribution of CA not isolated	Hu et al. (2023); Waghmare et al. (2025)
CA + exogenous enzymes (carbohydrases)	Primary study with phytase; indirect for other enzymes	Possible complementary effect on digestibility; requires direct testing	Woyengo et al. (2010); Hussain & Sharif (2026)
CA + Spirulina platensis	Primary broiler study	Combination evaluated as an AGP alternative	Ismita et al. (2022)
CA + high limestone or buffering minerals	Mechanistic	Antagonistic: higher acid-binding capacity reduces the pH response; high Ca reduces phytate-P availability	Dibner & Buttin (2002); Snow et al. (2004)

ECONOMIC FEASIBILITY AND APPLICATION IN DEVELOPING COUNTRIES

In most developing countries, feed accounts for the largest share of broiler production costs, AGP use is being restricted at different rates, and diets often contain locally available cereal by-products, such as rice bran or wheat bran, that are rich in phytate (Choi, 2025; Iqbal & Iqbal, 2026). Under these conditions, the economic value of CA depends on its price relative to the value of the improvement in feed conversion and on whether it allows a reduction in inorganic phosphorus. Only a few studies have reported economic indicators. In Egypt, CA at 5 g/kg feed gave the best FCR (1.61) and a higher net profit, benefit-cost ratio and relative economic efficiency than spirulina or cinnamon oil, partly because of

its low price (El-Sharnobey et al., 2023). The economic appraisal of feeding strategies is equally important for local broiler production systems (Akram et al., 2024).

An illustrative calculation shows the margin involved. Bulk food-grade CA is currently quoted at about USD 0.90-1.25 per kg FOB (Seth, 2026); allowing for import and distribution costs, a local price of about USD 1.2-1.5 per kg may be assumed. At an inclusion of 0.5% (5 kg/t), CA would therefore add about USD 6.0-7.5 per tonne of feed, or about 1.5-2% of the cost of a broiler feed priced at about USD 350-400 per tonne. To break even on feed cost per kilogram of gain, FCR would need to improve by a similar proportion, for example from 1.70 to about 1.67. The improvements reported in several studies, such as a reduction in FCR from 1.74 to 1.66 (about 4.6%; Hossain et al., 2025) or body weight gains of 2-5% (Islam et al., 2012), exceed this threshold. At 1% inclusion, however, the cost rises to about 3-4% of the feed cost, and the margin becomes small unless CA also allows a reduction in inorganic phosphorus or improves flock health. This calculation is indicative only and should be repeated with local prices.

Other practical constraints in developing countries include fluctuations in the price of imported CA, variable product quality, corrosion of equipment and the handling of concentrated acid, and the need to adjust drinking-water dosing to water hardness and alkalinity. Locally produced CA or citrus by-products could reduce costs, but their consistency and efficacy have rarely been tested in broilers. Heat stress, which is common in tropical regions, reduces feed and water intake and may make birds more sensitive to the palatability of acidified feed or water (Rathnayake et al., 2021). Practical recommendations derived from the evidence reviewed are summarised in Table 4.

Table 4
Practical recommendations for the use of citric acid in broiler production based on the evidence reviewed

Aspect	Recommendation
Inclusion level	Start at about 0.5-1.0% of the diet; levels above 2-3% are rarely cost-effective for growth, and around 6% can depress intake and growth
Diet type	Expect the largest responses in low-phosphorus or phytate-rich diets; reduce inorganic phosphorus only after on-farm validation
Combination with phytase	Use CA together with phytase in low-phosphorus diets and avoid excess limestone, which buffers the added acid
Route of administration	Feed is suitable for continuous use; drinking water (e.g., about 2.5 g/L) can be used for shorter periods, with dosing adjusted to water alkalinity to avoid over-acidification
Young chicks and heat stress	Monitor feed and water intake closely when introducing CA
Economic check	Calculate the cost per tonne of feed at local prices; CA is justified when the expected FCR improvement exceeds the relative increase in feed cost
Monitoring	Record FCR, mortality and litter quality and, where possible, crop or gizzard pH
Antibiotic stewardship	Use CA as part of an AGP-free programme that includes biosecurity and vaccination, not as a stand-alone replacement for antibiotics

CONCLUSION AND FUTURE RESEARCH AVENUES

This review presents CA as a multifunctional nutritional modulator in broilers that lowers pH in the upper gastrointestinal tract, enhances digestive enzyme activity and nutrient solubility and digestibility, and favors beneficial microbiota over enteric pathogens, ultimately improving growth and feed efficiency. The most consistent effect of CA is improved phytate phosphorus and mineral utilisation, particularly in low-phosphorus diets and in combination with phytase, whereas effects on SCFA production, barrier function and immunity are supported mainly by studies on organic acid blends.

CA can replicate some effects of AGPs by suppressing pathogens and supporting competitive exclusion, and its use may reduce reliance on antibiotics; however, direct evidence that CA reduces AMR in broiler production is lacking. Its effects are strongly dose-dependent, because high inclusion levels can cause over-acidification that reduces palatability and impairs performance. Environmental benefits are currently inferred mainly from improved nutrient retention rather than from measured emissions. Overall, CA is a promising nutritional tool whose efficacy depends on dose, diet composition, bird age, formulation and production conditions. In practical terms, an inclusion of about 0.5-1.0% in feed, combined with phytase in low-phosphorus diets and with attention to dietary calcium, is the most frequently supported starting point, and its cost-effectiveness should be checked at local prices (Table 4).

Future studies should optimise the dose, timing and delivery method of CA in diets typical of developing countries, including rice bran and other phytate-rich by-products, and under heat stress, to establish application strategies that consistently improve performance while maintaining gut homeostasis.

Microbiome-centered approaches such as metagenomics, metabolomics and functional ecology analyses are needed to move beyond describing shifts and to clarify how CA influences microbial functions, metabolic outputs and ecosystem stability. A better understanding of host-microbe-acid interactions is needed to explain how pH modulation affects epithelial signalling, immune regulation and nutrient sensing. Future studies should also measure resistance genes and resistant bacterial populations in CA-fed flocks.

Strategies combining CA with probiotics, enzymes, phytogenic additives or encapsulation should be evaluated systematically in factorial designs to improve robustness and reduce variability under commercial conditions. Environmental assessments should combine nutrient balance with measurements of ammonia emission and life-cycle assessment of carbon footprint. Economic evaluations, including feed cost per kilogram of gain and comparisons with other AGP alternatives at equal cost, should accompany performance trials. Large-scale, multi-location field trials are needed to validate laboratory findings and to establish the role of CA as a scientifically supported tool in antibiotic-free broiler nutrition.

ACKNOWLEDGEMENT

The authors acknowledge the postgraduate laboratory of Animal Sciences for bench work and support during the preparation of this draft.

REFERENCES

Abd El-Ghany, W. A. (2024). Applications of organic acids in poultry production: an updated and comprehensive review. *Agriculture*, *14*(10), Article 1756. https://doi.org/10.3390/agriculture14101756

Abd El-Hack, M. E., Aldhalmi, A. K., Abu-Hiamed, H. A., Almarkhan, W. D., Alharbi, N. A., Alhassani, W. E., Alkholy, S. O., Kamal, M., Youssef, I. M., Khalifa, N. E., Taha, A. E., & Swelum, A.A. (2025). Antibiotic alternatives to produce organic poultry meat as a safe food source and the impact of its consumption on human health – A Review. *Annals of Animal Science*, *25*(3), 815-828. https://doi.org/10.2478/aoas-2024-0090

Abdel-Fattah, S., El-Sanhoury, M., El-Mednay, N., & Abdel-Azeem, F. (2008). Thyroid activity, some blood constituents, organs morphology and performance of broiler chicks fed supplemental organic acids. *International Journal of Poultry Science*, *7*(3), 215-222. https://doi.org/10.3923/ijps.2008.215.222

Abou-Ashour, A. M. H., Manal, K., El-Naga, A., Eman, M. A., Hussein, & El-Bana, . M. A. (2021). Effect of dietary citric, acetic acids or their mixture on broiler chicks performance, carcass characteristics and some intestinal histomorphological parameters. *Egyptian Journal of Nutrition and Feeds*, *24*(1), 119-138. https://doi.org/10.21608/ejnf.2021.170317

Acharya, A., & Barsila, S. R. (2025). Exploring alternatives to antibiotics in poultry production: a comprehensive review of emerging strategies and their implications for avian health. *World's Poultry Science Journal*, *81*(4), 1427-1460. https://doi.org/10.1080/00439339.2025.2522139

Akram, A., Mehmood, S., Manzoor, S., Bölükbaş, B., & Qaisrani, S. N. (2024). Comparative efficacy and economic appraisal of different feeds in sexed broilers. *Applied Animal Science Bulletin*, *1*(1), 23-28. https://doi.org/10.22194/AASB/24.1003

Alahmadi, B. A. (2025). The potential of *Spirulina platensis* to substitute antibiotics in broiler chickens diets: Influences on growth performance, serum biochemical profiles, meat quality, and gut microbiota. *Kafkas Üniversitesi Veteriner Fakültesi Dergisi*, *31*(4), 527-538. https://doi.org/10.9775/kvfd.2025.34198

Ali, B., Irfan, M., Ramzan, F., Abbas, B., Ashraf, M., Mehmood, M., Khan, O. A., Ishtiaq, I., & Abbas, W. (2025). Super dosing of IP6 phytase in phosphorus-deficit diets to replace added phosphorus and evaluate growth performance, nutrient digestibility and bone mineralization of broiler chickens. *Journal of Global Innovations in Agricultural Sciences*, *13*(1), 219-226. https://doi.org/10.22194/JGIAS/25.1580

Alonzo, N. A. N., Badua, A. T., Martin, E. A., San Andres, J. V., & Santiago, K. G. (2026). Combined use of alpha monolaurin and probiotics an alternative to antibiotic growth promoter in broilers. *Journal of Global Innovations in Agricultural Sciences*, *14*(1), 11-16. https://doi.org/10.22194/JGIAS/26.1855

Alsayeqh, A. F. (2025). Antibiotic resistance and emerging alternatives for controlling foodborne pathogens. *Pakistan Veterinary Journal*, *45*(2), 499-514. https://doi.org/10.29261/pakvetj/2025.185

Atapattu, N., & Nelligaswatta, C. (2005). Effects of citric acid on the performance and the utilisation of phosphorous and crude protein in broiler chickens fed on rice by-products based diets. *International Journal of Poultry Science*, *4*(12), 990-993. https://doi.org/10.3923/ijps.2005.990.993

Attia, Y. A., Addeo, N., Bovera, F., Qota, E. S. M., Alhotan, R. A., Albanoby, M., & Mahmoud, M. A. (2025). Assessment of bacterial phytase and citric acid concentrations on economic traits, nutrients' digestibility and protein metabolites of broiler chickens fed diets containing marginal level of nutrients. *Italian Journal of Animal Science*, *24*(1), 109-122. https://doi.org/10.1080/1828051X.2024.2442032

Awais, A., Iqbal, W., & Rasool, A. (2024). Organic acids and exogenous enzymes in poultry nutrition: A comprehensive review. *Applied Animal Science Bulletin*, *1*(1), 11-22. https://doi.org/10.22194/AASB/24.1002

Azizi, M. N., Zahir, A., Mahaq, O., & Aminullah, N. (2024). The alternatives of antibiotics in poultry production for reducing antimicrobial resistance. *World's Veterinary Journal*, *14*(2), 270-283. https://doi.org/10.54203/scil.2024.wvj34

Baethge, C., Goldbeck-Wood, S., & Mertens, S. (2019). SANRA - a scale for the quality assessment of narrative review articles. *Research Integrity and Peer Review*, *4*, Article 5. https://doi.org/10.1186/s41073-019-0064-8

Berberoğlu, T. M., Riaz, R., Gezer, A., Yilmaz, B., Karadağ Sarı, E., Karadağoğlu, Ö., & Şahin, T. (2025). Effects of probiotics (*Bacillus subtilis*), prebiotics (MOS+ β-glucans) and their combination on growth performance, duodenal histomorphology and meat quality in broiler chickens. *Kafkas Üniversitesi Veteriner Fakültesi Dergisi*, *31*(6), 731-73. https://doi.org/10.9775/kvfd.2025.34619

Bist, R. B., Bist, K., Poudel, S., Subedi, D., Yang, X., Paneru, B., Mani, S., Wang, D., & Chai, L. (2024). Sustainable poultry farming practices: a critical review of current strategies and future prospects. *Poultry Science*, *103*(12), Article 104295. https://doi.org/10.1016/j.psj.2024.104295

Choi, J. (2025). Challenges in poultry production systems and nutritional interventions. *Animals*, *15*(4), Article 530. https://doi.org/10.3390/ani15040530

Chukwudi, P., Umeugokwe, P. I., Ikeh, N. E., & Amaefule, B. C. (2025). The effects of organic acids on broiler chicken nutrition: A review. *Animal Research and One Health*, *3*(1), 43-53. https://doi.org/10.1002/aro2.85

Clavijo, V., & Flórez, M. J. V. (2018). The gastrointestinal microbiome and its association with the control of pathogens in broiler chicken production: A review. *Poultry Science*, *97*(3), 1006-1021. https://doi.org/10.3382/ps/pex359

de Toledo, T. d. S., Roll, A. A. P., Rutz, F., Dallmann, H. M., Dai Prá, M. A., Leite, F. P. L., & Roll, V. F. B. (2020). An assessment of the impacts of litter treatments on the litter quality and broiler performance: A systematic review and meta-analysis. *PLOS One*, *15*(5), Article e0232853. https://doi.org/10.1371/journal.pone.0232853

Dibner, J. J., & Buttin, P. (2002). Use of organic acids as a model to study the impact of gut microflora on nutrition and metabolism. *Journal of Applied Poultry Research*, *11*(4), 453-463. https://doi.org/10.1093/japr/11.4.453

Dimuccio, M. M., Conforti, V., Celentano, F. E., Circella, E., Salvaggiulo, A., Bozzo, G., & Corrente, M. (2026). Regulation of antibiotic use in livestock: european and international strategies to prevent and control antimicrobial resistance and ensure animal welfare. *Antibiotics*, *15*(1), Article 67. https://doi.org/10.3390/antibiotics15010067

Du, H., Sarwar, I., Ahmad, S., Suheryani, I., Anjum, S., Andlib, S., Kakar, M. U., & Arain, M. A. (2024). Organic acids in poultry industry: a review of nutritional advancements and health benefits. *World's Poultry Science Journal*, *80*(1), 133-153. https://doi.org/10.1080/00439339.2023.2262435

Ebrahimnezhad, Y., Shivazad, M., Taherkhani, R., & Nazeradl, K. (2008). Effects of citric acid and microbial phytase supplementation on performance and phytate phosphorus utilisation in broiler chicks. *The Journal of Poultry Science*, *45*(1), 20-24. https://doi.org/10.2141/jpsa.45.20

El-Sharnobey, R. R., Atallah, S. T., Saad, A. H., & El-Ktany, E. (2023). Comparative appraisal of relative economic efficiency of spirulina, cinnamon oil and citric acid dietary supplementations and their effect on growth performance and carcass traits in broiler chicken. *Journal of Advanced Veterinary Research*, *13*(8), 1523-1529. https://advetresearch.com/index.php/AVR/article/view/1443

Fik, M., Hrnčár, C., Hejniš, D., Hanusová, E., Arpášová, H., & Bujko, J. (2021). The effect of citric acid on performance and carcass characteristics of broiler chickens. *Scientific Papers Animal Science and Biotechnologies*, *54*(1), 187-192. https://www.cabidigitallibrary.org/doi/pdf/10.5555/20210260288

Fikry, A. M., Attia, A. I., Ismail, I. E., Alagawany, M., & Reda, F. M. (2021). Dietary citric acid enhances growth performance, nutrient digestibility, intestinal microbiota, antioxidant status, and immunity of Japanese quails. *Poultry Science*, *100*(9), Article 101326. https://doi.org/10.1016/j.psj.2021.101326

Food and Agriculture Organization of the United Nations (FAO). (2025). *FAOSTAT: Livestock primary (Global, National – Annual)* [Data set]. https://data.fao.org/catalog/iso/55375b1e-51d0-47db-ac9b-536ac8a1c738

Foster, J. W., & Hall, H. K. (1990). Adaptive acidification tolerance response of Salmonella typhimurium. *Journal of Bacteriology*, *172*(2), 771-778. https://doi.org/10.1128/jb.172.2.771-778.1990

Gadde, U., Kim, W., Oh, S. T., & Lillehoj, H. S. (2017). Alternatives to antibiotics for maximizing growth performance and feed efficiency in poultry: a review. *Animal Health Research Reviews*, *18*(1), 26-45. https://doi.org/10.1017/S1466252316000207

Gerzilov, V., & Hristakieva, P. (2025). Organic acids supplementation in poultry nutrition: A review. *Open Veterinary Journal*, *15*(8), 3448-3458. https://doi.org/10.5455/OVJ.2025.v15.i8.8

Ghazalah, A., Atta, A., Elkloub, K., Moustafa, M., & Shata, R. F. (2011). Effect of dietary supplementation of organic acids on performance, nutrients digestibility and health of broiler chicks. *International Journal of Poultry Science*, *10*(3), 176-184. https://doi.org/10.3923/ijps.2011.176.184

Ghoshal, M., Bechtel, T. D., Gibbons, J. G., & McLandsborough, L. (2023). Adaptive laboratory evolution of Salmonella enterica in acid stress. *Frontiers in Microbiology*, *14*, Article 1285421. https://doi.org/10.3389/fmicb.2023.1285421

Gržinić, G., Piotrowicz-Cieślak, A., Klimkowicz-Pawlas, A., Górny, R. L., Ławniczek-Wałczyk, A., Piechowicz, L., Olkowska, E., Potrykus, M., Tankiewicz, M., Krupka, M., Siebielec G., & Wolska, L. (2023). Intensive poultry farming: A review of the impact on the environment and human health. *Science of the Total Environment*, *858*(Part 3), Article 160014. https://doi.org/10.1016/j.scitotenv.2022.160014

Hajati, H. (2018). Application of organic acids in poultry nutrition. *International Journal of Avian Wildlife & Biology*, *3*(4), 324-329. https://doi.org/10.15406/ijawb.2018.03.00114

Hossain, S., Biswas, B. K., Das, S., Pory, F. S., Raut, R., Yeasmin, F., Khan, S. U., Dipta, P. M., Shuvo, S. A., & Yeasmin, T. (2025). Effects of citric acid, synbiotic, and probiotic supplementation through drinking water on growth performance, carcass yield, and blood biochemistry of broiler chickens. *Animals*, *15*(8), Article 1168. https://doi.org/10.3390/ani15081168

Hu, Z., Liu, L., Guo, F., Huang, J., Qiao, J., Bi, R., Huang, J., Zhang, K., Guo, Y., & Wang, Z. (2023). Dietary supplemental coated essential oils and organic acids mixture improves growth performance and gut health along with reduces Salmonella load of broiler chickens infected with Salmonella Enteritidis. *Journal of Animal Science and Biotechnology*, *14*(1), Article 95. https://doi.org/10.1186/s40104-023-00889-2

Huanhong, K., Thomya, S., Teerakitchotikan, P., Lumsangkul, C., Tangpao, T., Prasad, S. K., Prasad, K. S., & Sommano, S. R. (2023). Volatile organic compound emissions in free-range chicken production: Impacts on environment, welfare and sustainability. *AIMS Agriculture and Food*, *8*(4), 1071-1091. https://doi.org/10.3934/agrfood.2023058

Hussain, S., & Sharif, M. (2026). Impact of exogenous enzyme supplementation on growth performance, nutrient digestibility, and carcass characteristics in broilers fed normal and low energy diets during the finisher phase. *Applied Animal Science Bulletin*, *3*(1), 63-70.

Iqbal, L., & Iqbal, N. (2026). Livestock production and antimicrobial resistance in developing countries: Drivers, risks, and sustainable control strategies. *Applied Animal Science Bulletin*, *3*(1), 35-45. https://share.google/Bylots6IOgfCrMYq4

Islam, K. M. S., Schaeublin, H., Wenk, C., Wanner, M., & Liesegang, A. (2012). Effect of dietary citric acid on the performance and mineral metabolism of broiler. *Journal of Animal Physiology and Animal Nutrition*, *96*(5), 808-817. https://doi.org/10.1111/j.1439-0396.2011.01225.x

Ismita, J., Islam, K. M. S., Al-Mamun, M., & Debi, M. R. (2022). Comparative efficacy of citric acid, Spirulina platensis, and their combination as alternatives to an antibiotic growth promoter on the performances of broilers. *Journal of Advanced Veterinary and Animal Research*, *9*(1), 1-7. https://doi.org/10.5455/javar.2022.i562

Jacquier, V., Walsh, M. C., Schyns, G., Claypool, J., Blokker, B., Bortoluzzi, C., & Geremia, J. (2022). Evaluation of a precision biotic on the growth performance, welfare indicators, ammonia output, and litter quality of broiler chickens. *Animals*, *12*(3), Article 231. https://doi.org/10.3390/ani12030231

Katoch, S., Sharma, S., Sankhyan, V., Wadhwa, D., Sharma, A., & Kumar, S. (2023). Growth studies in commercial broiler birds offered citric acid in formulated feed with low mineral density. *Tropical Animal Health and Production*, *55*, Article 33. https://doi.org/10.1007/s11250-022-03443-w

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. *Environmental Science and Pollution Research*, *29*, 32594-32604. https://doi.org/10.1007/s11356-022-19241-8

Khosravinia, H., Nourmohammadi, R., & Afzali, N. (2015). Productive performance, gut morphometry, and nutrient digestibility of broiler chicken in response to low and high dietary levels of citric acid. *Journal of Applied Poultry Research*, *24*(4), 470-480. https://doi.org/10.3382/japr/pfv050

Li, X. -S., Xue, J. -Z., Qi, Y., Muhammad, I., Wang, H., Li, X. -Y., Luo, Y. -J., Zhu, D. -M., Gao, Y.-H., Kong, L.-C., & Ma, H.-X. (2023). Citric acid confers broad antibiotic tolerance through alteration of bacterial metabolism and oxidative stress. *International Journal of Molecular Sciences*, *24*(10), Article 9089. https://doi.org/10.3390/ijms24109089

Li, Z., Rafique, M. S., Li, A., & Yuan, H. (2025). Effects of probiotics on carcass, gut microbiota and immunity of broilers. *Pakistan Veterinary Journal*, *45*(4), 1514-1523. https://doi.org/10.29261/pakvetj/2025.326

Ma, J., Mahfuz, S., Wang, J., & Piao, X. (2021). Effect of dietary supplementation with mixed organic acids on immune function, antioxidative characteristics, digestive enzymes activity, and intestinal health in broiler chickens. *Frontiers in Nutrition*, *8*, Article 673316. https://doi.org/10.3389/fnut.2021.673316

Makofane, V., Ng'ambi, J. W., & Gunya, B. (2022). The effect of citric acid supplementation on growth performance, digestibility and linear body measurement of Ross 308 broiler chickens: A Review. *Indian Journal of Animal Research*, *56*(4), 387-391. https://doi.org/10.18805/IJAR.BF-1433

Mamabolo, M. V., Ng'ambi, J. W., & Gunya, B. (2025). Effect of citric acid on carcass characteristics and physico chemical attributes of broiler chickens: A Review. *Indian Journal of Animal Research*, *59*(4), 541-547. https://doi.org/10.18805/IJAR.BF-1633

Melaku, M., Zhong, R., Han, H., Wan, F., Yi, B., & Zhang, H. (2021). Butyric and citric acids and their salts in poultry nutrition: Effects on gut health and intestinal microbiota. *International Journal of Molecular Sciences*, *22*(19), Article 10392. https://doi.org/10.3390/ijms221910392

Miyakawa, M. E. F., Casanova, N. A., & Kogut, M. H. (2024). How did antibiotic growth promoters increase growth and feed efficiency in poultry? *Poultry Science*, *103*(2), Article 103278. https://doi.org/10.1016/j.psj.2023.103278

Ndelekwute, E. K., Assam, E. D., Unah, U. L., Assam, E. M., & Okonkwo, A. C. (2019). Antibacterial action and dietary effect of lemon juice on nutrient digestibility and growth performance of broiler chickens. *Nigerian Journal of Animal Production*, *46*(2), 102-110. https://doi.org/10.51791/njap.v46i2.17

Nguyen, D. H., & Kim, I. H. (2020). Protected organic acids improved growth performance, nutrient digestibility, and decreased gas emission in broilers. *Animals*, *10*(3), Article 416. https://doi.org/10.3390/ani10030416

Nourmohammadi, R., & Khosravinia, H. (2015). Acidic stress caused by dietary administration of citric acid in broiler chickens. *Archives Animal Breeding*, *58*(2), 309-315. https://doi.org/10.5194/aab-58-309-2015

Pangga, G. M., Star-Shirko, B., Psifidi, A., Xia, D., Corcionivoschi, N., Kelly, C., Hughes, C., Lavery, U., Richmond, A., Ijaz, U. Z., & Gundogdu, O. (2025). Impact of commercial gut health interventions on caecal metagenome and broiler performance. *Microbiome*, *13*, Article 30. https://doi.org/10.1186/s40168-024-02012-7

Peng, C., Ghanbari, M., May, A., & Abeel, T. (2024). Effects of antibiotic growth promoter and its natural alternative on poultry cecum ecosystem: an integrated analysis of gut microbiota and host expression. *Frontiers in Microbiology*, *15*, Article 1492270. https://doi.org/10.3389/fmicb.2024.1492270

Rafacz-Livingston, K. A., Martinez-Amezcua, C., Parsons, C. M., Baker, D. H., & Snow, J. (2005). Citric acid improves phytate phosphorus utilisation in crossbred and commercial broiler chicks. *Poultry Science*, *84*(9), 1370-1375. https://doi.org/10.1093/ps/84.9.1370

Rana, A. A., Ali, A., & Chishti, M. F. A. (2024). Performance and carcass characteristics of broiler chickens supplemented with organic acids-enriched corn cob biochar in the finisher diets. *Applied Animal Science Bulletin*, *1*(1), 35-42. https://doi.org/10.22194/AASB/24.1005

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*(6), Article 476. https://doi.org/10.3390/life11060476

Raza, A., Abbas, R. Z., Karadağoğlu, Ö., Raheem, A., Khan, A. M. A., Khalil, M. Z., Maheen, N., Quddus, A., Hussain, A., & Kanchev, K. P. (2024). Role of probiotics in increasing meat and egg production in poultry. *Kafkas Universitesi Veteriner Fakultesi Dergisi*, *30*(6), 753-760. https://doi.org/10.9775/kvfd.2024.32861

Reihani, M., Mousavi, S., Froudi, F., & Karimi, K. (2025). Efeito da forma física da ração, da superdosagem de fitase e/ou do ácido cítrico sobre o desempenho de crescimento, a digestibilidade do fósforo e a população microbiana intestinal microbiana intestinal de frangos de corte [Effect of physical feed form, phytase super dosing, and/or citric acid on growth performance, phosphorus digestibility, and intestinal microbial population of broiler chickens]. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia*, *77*(1), Article e13255. https://doi.org/10.1590/1678-4162-13255

Riaz, R., Ahmed, I., Raza, A., Khan, Y., Ahsan, U., & Ellakwa, D. E.-S. (2025). Response of different infection models in broiler chickens against supplemental Organic acid-A review. *Microbial Pathogenesis*, *204*, Article 107527. https://doi.org/10.1016/j.micpath.2025.107527

Ricke, S. C. (2003). Perspectives on the use of organic acids and short chain fatty acids as antimicrobials. *Poultry Science*, *82*(4), 632-639. https://doi.org/10.1093/ps/82.4.632

Saleem, K., Saima, Rahman, A., Pasha, T. N., Mahmud, A., & Hayat, Z. (2020). Effects of dietary organic acids on performance, cecal microbiota, and gut morphology in broilers. *Tropical Animal Health and Production*, *52*, 3589-3596. https://doi.org/10.1007/s11250-020-02396-2

Seth, H. (2026, July 9). *Bulk price of citric acid in 2026: Cost per kg, MOQ & how to source (buyer's guide).* Elchemy. https://elchemy.com/blogs/chemical-market/bulk-price-citric-acid-2026-cost-per-kg-moq-guide

Shahin, M. S. A., Islam, K. M. S., Akbar, M. A., Haque, M. N., Chowdhury, R., & Islam, K. N. (2009). Effect of citric acid supplementation on the performance of broilers. *Indian Journal of Animal Nutrition, 26*(2), 181-185. https://indianjournals.com/article/ijan-26-2-018

Sharifuzzaman, M. D., Mun, H.-S., Ampode, K. M. B., Lagua, E. B., Park, H.-R., Kim, Y.-H., Hasan, M. K., & Yang, C.-J. (2024). Optimizing broiler growth, health, and meat quality with citric acid-assessing the optimal dose and environmental impact: Citric acid in Broiler Health and Production. *Poultry Science*, *104*(2), Article 104668. https://doi.org/10.1016/j.psj.2024.104668

Snow, J. L., Baker, D. H., & Parsons, C. M. (2004). Phytase, citric acid, and 1α-hydroxycholecalciferol improve phytate phosphorus utilisation in chicks fed a corn-soybean meal diet. *Poultry Science*, *83*(7), 1187-1192. https://doi.org/10.1093/ps/83.7.1187

Sporchia, F., Galli, A., Kastner, T., Pulselli, F. M., & Caro, D. (2023). The environmental footprints of the feeds used by the EU chicken meat industry. *Science of the Total Environment*, *886*, Article 163960. https://doi.org/10.1016/j.scitotenv.2023.163960

Vera-Álava, J. O., Arteaga Solórzano, J. G., & Reyna Gallegos, S. L. (2023). Organic acids, microbiota, gut health and productive response in broilers chickens: Organic acids in broilers chickens. *Revista Colombiana de Ciencia Animal–RECIA, 15*(2), Article e1019. https://revistas.unisucre.edu.co/index.php/recia/article/view/1019/1091

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 the growth performance, intestinal morphology, microbiota, and serum lipid parameters of broiler chickens. *Poultry Science*, *104*(1), Article 104546. https://doi.org/10.1016/j.psj.2024.104546

Wang, J., Mallavarapu, B., Subedi, D., Patil, P. S., Bhumanapalli, S., Vaddu, S., Singh, A. K., Kim, W. K., Kumar, S., Poudel, S., Bourassa, D. V., Manjankattil, S., Naeem, M., Adhikari, Y., & Thippareddi, H. (2025). A systematic review and meta-analysis of the efficacy of organic acids in reducing Salmonella colonization in the crop and ceca of broilers. *Poultry Science*, Article 106075. https://doi.org/10.1016/j.psj.2025.106075

Wickramasinghe, K. P., Atapattu, N. S. B. M., & Seresinhe, R. T. (2014). Effects of citric acid on growth performance and nutrient retention of broiler chickens fed diets containing two levels of non-phytate phosphorus and rice bran. *Iranian Journal of Applied Animal Science*, *4*(4), 809-815. https://www.cabidigitallibrary.org/doi/epdf/10.5555/20143414411

Woyengo, T. A., Slominski, B. A., & Jones, R. O. (2010). Growth performance and nutrient utilisation of broiler chickens fed diets supplemented with phytase alone or in combination with citric acid and multicarbohydrase. *Poultry Science*, *89*(10), 2221-2229. https://doi.org/10.3382/ps.2010-00832

Yu, H., Rahman, A., Sadique, M. A., Batool, T., Imtiaz, B., Zaman, M. A., Riaz, T., Anwar, M. Z., & Waqas, M. (2024). Impact of bacillus subtilis probiotic on growth performance, bone health, intestinal morphology, and cecal microbiota in cobb broiler chicks. *Pakistan Veterinary Journal*, *44*(4), 1243-1248. https://doi.org/10.29261/pakvetj/2024.254

Zampiga, M., Calini, F., & Sirri, F. (2021). Importance of feed efficiency for sustainable intensification of chicken meat production: implications and role for amino acids, feed enzymes and organic trace minerals. *World's Poultry Science Journal*, *77*(3), 639-659. https://doi.org/10.1080/00439339.2021.1959277