Organic Acids and Feeding

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Because the application of antibiotic growth promoters (AGP) causes accelerated adverse effects on the animal diet, the scientific community has taken progressive steps to enhance sustainable animal productivity without using AGP in animal nutrition. Organic acids (OAs) are non-antibiotic feed additives and a promising feeding strategy in the swine and broiler industry. Mechanistically, OAs improve productivity through multiple and diverse pathways in: (a) reduction of pathogenic bacteria in the gastro-intestinal tract (GIT) by reducing the gut pH; (b) boosting the digestibility of nutrients by facilitating digestive enzyme secretion and increasing feed retention time in the gut system; and (c) having a positive impact and preventing meat quality deterioration without leaving any chemical residues. Recent studies have reported the effectiveness of using encapsulated OAs and synergistic mechanisms of OAs combinations in swine and broiler productivity. On the other hand, the synergistic mechanisms of OAs and the optimal combination of OAs in the animal diet are not completely understood, and further intensive scientific explorations are needed.

organic acids feeding swine broilers digestibility meat quality

1. Introduction

The ultimate goal in the global livestock sector is to achieve enhanced quantitative and qualitative productive parameters. A few decades ago, enhanced production was gained by incorporating various antibiotic growth promoters (AGP), which resulted in improved feed efficacy, growth rate, and lower mortality and disease. On the other hand, the emergence of antimicrobial-resistant bacteria has led to a discussion regarding the global health problem. Consequently, the utilization of AGP was banned by the European Union. Thus, scientists and researchers have focused on sustainable potential antibiotic-free production systems in the poultry sector [1] and swine industry [2].

Researches have highlighted the effective utilization of organic acids (OAs), phytobiotics, probiotics, prebiotics, bacteriophages, and other numerous alternatives instead of antibiotics to establish appropriate health and production parameters of animals. As a group of chemicals, organic acids can be defined as carboxylic acids including fatty acids, which have the chemical structure of R-COOH with specific chemical characteristics. They can be categorized into three groups: (a) simple mono-carboxylic acids (acetic, formic, propionic, and butyric acids); (b) carboxylic acids containing hydroxyl group (malic, lactic, tartaric, and citric acids); and (c) carboxylic acids with double bonds (sorbic and fumaric acids) [3]. OAs produce effective responses owing to their antimicrobial properties, which can enhance the pH reduction rate in the GIT [4]. Consequently, the intestinal digestibility and mineral utilization were improved [5][6]. Acidifiers were incorporated into animal diets a few years earlier owing to the presence of preservatives and nutritional characteristics [7][8]. Despite controlling the desirable growth rate of molds, fungi, and bacteria in animal feed, several studies have reported the potential ability of improving nutrition digestion and retention, intestinal health, and ultimate growth development of non-ruminant animals, including feed sanitizing characteristics [9][10][11]. Effective production parameters and health-promoting evidence have been discovered for numerous OAs, such as citric, fumaric, and formic acids and their salts [12]. Enhanced meat quality characteristics and growth performances were observed in broilers fed a diet supplemented with OAs, including 30% lactic, 25.5% benzoic, 7% formic, 8% citric, and 6.5% acetic acid [13]. Partanen and Morz [7] reported that incorporating OAs into the pig diet modulates the beneficial gut microbiota and improves the growth performance. A reduced gastric pH and retarded enterotoxigenic *E. coli* proliferation in the gut system occurred due to the inclusion of lactic acid into the pig diet. Thus, developed gut health led to optimal feed intake and weight gain of the animal [14]. Furthermore, supplementation of OAs with feedstuff will increase the stimulation rate of the nutrient digestion process [15]. The application of OAs in the livestock sector has produced numerous benefits in both economic and quality product perspectives in the livestock sector (Figure 1).

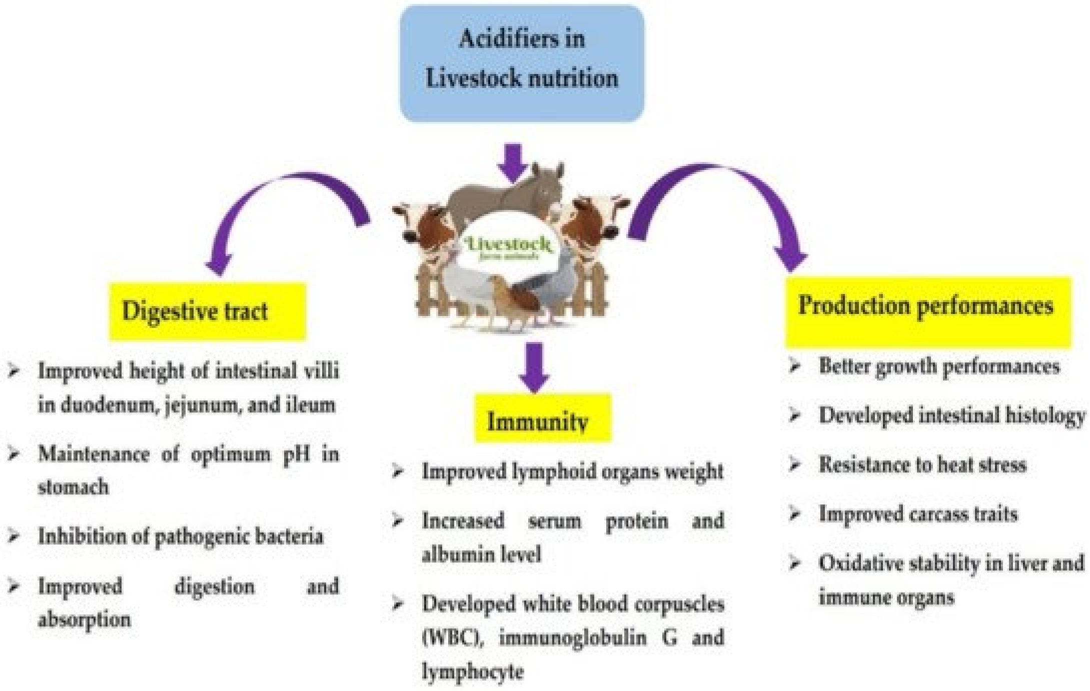

Figure 1. Various application and benefits of organic acids in the livestock sector [16].

Each organic acid has a distinguished range of pH, antimicrobial potential, pKa values, and membrane structure. Especially, a combination of OAs has various pKa values directly influencing the intestine pH due to the developed synergistic effect [17]. The most common OAs involved in animal nutrition are listed below (Table 1).

Table 1. Common organic acids involved in animal nutrition and their properties [16][18].

Acid	Chemical Name	Registration Number	Molecular Weight/GE (MJ/Kg)	Odor	pKa
Butyric	Butanoic Acid	-	88.12/24.8	rancid	4.82

Acid	Chemical Name	Registration Number	Molecular Weight/GE (MJ/Kg)	Odor	pKa
Citric	2-Hydroxy-1,2,3-Propanetricarboxylic Acid	E 330	192.1/10.2	odorless	3.13
Propionic	2-Propanoic Acid	1a297	74.08/20.6	pungent	4.88
Sorbic	2,4-Hexandienoic Acid	E 200	112.1/27.85	mildly acrid	4.76
Formic	Methanoic Acid	E 236	46.03/5.7	pungent	3.75
Acetic	Ethanoic Acid	E 260	60.05/14.6	pungent	4.76
Lactic	2-Hydroxypropanoic Acid	E 260	90.08/15.1	sour milk	3.83
Malic	Hydroxybutanedioic Acid	E 296	134.1/10.0	apple	3.40
Fumaric	2-Butenedioic Acid	2b08025	116.1/11.5	odorless	3.02
Benzoic	Benzenecarboxylic acid	-	-	-	4.20

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2. Potential Modes of Action of OAs

OAs have numerous benefits on the health and development of the gut system. Nevertheless, the mode of action is not completely understood. Their modes of action may be attributed partially to different factors, such as (A) mineral chelation and stimulation on intermediary metabolism; (B) inhibition of the development of pathogenic microbes; (C) facilitation of proper digestion due to lower gastric pH and enhanced pepsin secretion; and (D) reduction of gastric emptying rate and maintenance of endogenous enzymes secretion [4][19].

2.1. Effect of OAs on Mineral Utilization and Nutrient Digestibility

OA anions form complexes with Mg, P, Ca, and Zn, improving digestion and minimizing the excretion of beneficial minerals from the body. Phytate phosphorous utilization occurs through OAs administration by providing favorable pH conditions to convert phytase into hydrolyze phytate [20]. Bolling et al. [21] reported that citric acid facilitates the removal of attached minerals to phytate molecules, such as Ca, P, and Zn. Furthermore, it has been found that fumaric acid also can enhance the apparent absorption and retention of Ca, P, and Zn in the gastro-intestinal tract (GIT) [22].

The inclusion of OAs into the diet can improve energy utilization of certain feedstuffs. In soybean meal, for instance, the lower metabolizable energy (ME) in soybean meal occurs due to retarded digestibility in the carbohydrate portion. However, the presence of endogenous α-(1,6)-galactosidase enzyme in the intestines will facilitate the proper digestion of carbohydrate portion in the soybean meal. Ao [23] reported that the inclusion of 2% citric acid increased the digestion process by enhancing the activity of the α-galactosidase enzyme. Moreover, by reducing the dietary pH, OAs supplementation improved protein digestion owing to the microbial phytase activity and induced pepsin secretion [24]. A further protein digestion process improves through the secretion of a greater level of chymotrypsinogen A, chymotrypsinogen B, procarboxy peptidase A, procarboxy peptidase B, and trypsinogen enzymes [25]. OAs inclusion also increased the proper absorption rate of nutrients in the GIT by increasing the digesta retention time [26]. The increased ME and crude protein (CP) were observed due to the reduced microbial competition with the host, ammonia emission, and endogenous nitrogen elimination [27].

2.2. Effect of OAs on Antimicrobial Activity and Pathogenic Bacteria

Both animals and plants have symbiotic relationships with various microbes to survive in the environment through an active defense system against pathogens and to regulate the metabolism associated with hormones. On the other hand, an excessive microflora content produces unnecessary competition between the host and nutrition. Hence, maintenance of the optimal microbial composition in the GIT should be investigated. Some OAs can alter the GIT by eliminating harmful pathogens, such as *Salmonella* and *E. coli* species [28]. Owing to pH reduction and their influence on the buffering capacity of the diet, OAs can improve gut health by providing the optimal environment to beneficial microbes while preventing the proliferation of pathogens [7][29][30]. OAs can be divided into two groups based on the microbial ameliorate capacity in the GIT (Figure 2).

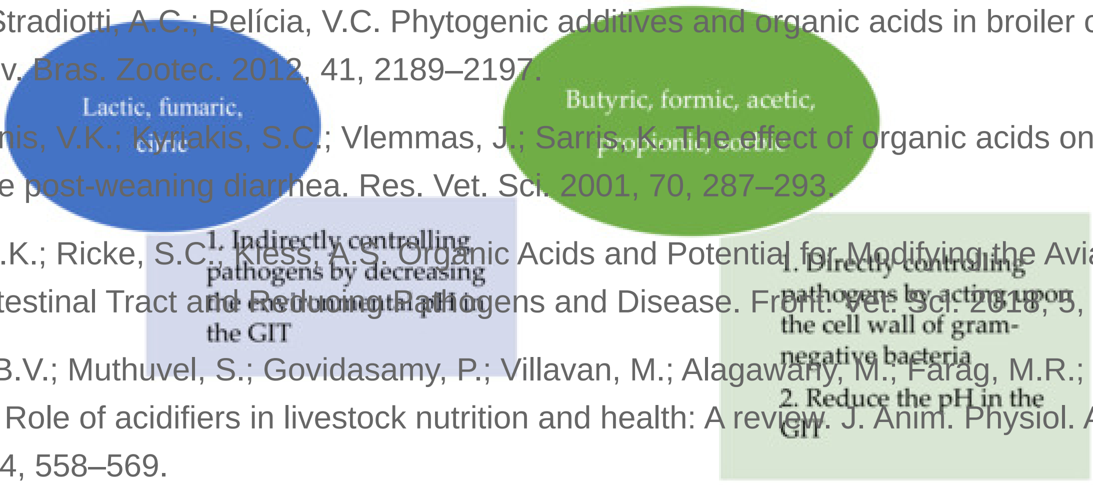

Figure 2. Two different mechanisms of organic acids on altering the pH of the GIT and their impact on pathogens [15].

Non-dissociated OAs enter the cytoplasm through the semipermeable membrane of the microorganism. Thereafter, OAs release their protons (H^+), and the cytoplasm pH decreases gradually. The enzymes involving reactions, such as nutrient transportation and glycolysis signal transductions of the microbes, are curtailed. Consequently, an energy deficiency occurs to maintain the normal pH [31]. Owing to the acidic conditions in the stomach, the efficacy of OAs is greater than in the neutral pH conditions, as in the intestines. On the other hand, most bacteria species endure their optimal environmental pH conditions and $pH < 4$ (extreme lower) conditions which adversely affect their survival. By releasing H^+ ions, OAs aid in the dysfunctions, retardation, or inhibition of the multiplication of pH-sensitive bacteria [32].

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Some bacteria in the GIT secrete various harmful compounds that reduce pig digestibility, stimulate rapid turnover of absorptive epithelial cells, stimulate mucus secretion, and induce an inflammatory responses due to the developed immune system. These factors help retard the growth performance, and approximately 6% net energy losses in pigs can be attributed to microflora [33]. OAs have the potential to eliminate specific species, such as *Coliforms*, while generating eubiosis. Thus, they can provide the optimal microbial atmosphere in the GIT that can benefit the host by accumulating lower toxic compounds, amines, and ammonia. While the gram-positive (G^+) bacteria are susceptible to long-chained OAs, the gram-negative (G^-) bacteria cannot resist OAs with fewer than eight carbons [34]. However, stronger effects of OAs affect G^+ bacteria due to cell structural differences. In contrast, the cytoplasmic membrane of bacteria is surrounded by a thick peptidoglycan layer. Generally, this peptidoglycan layer is thicker in G^+ bacteria than G^- bacteria. Nevertheless, G^- bacteria have an extra lipopolysaccharide layer that is more resistant to hydrophobic antibiotics and chemical compounds.

Because OAs have both bactericidal and bacteriostatic properties, Luckstadt and Mellor [35] sketched out the mode of action of OAs on G^- bacteria as follows: (1) Lipophilic undissociated OAs penetrate the G^- bacteria cytoplasm (*Salmonella*). (2) OAs release H^+ ions, which reduces the cellular pH, and the enzyme-based microbial metabolism tends to decrease. (3) To restore the normal cytoplasmic pH, the cell is forced to discard H^+ ions through the cell membrane via the H^+-ATPase pump. (4) Ultimately, G^- bacteria proliferation is gradually impeded when exposed to OAs for some time (Figure 3).

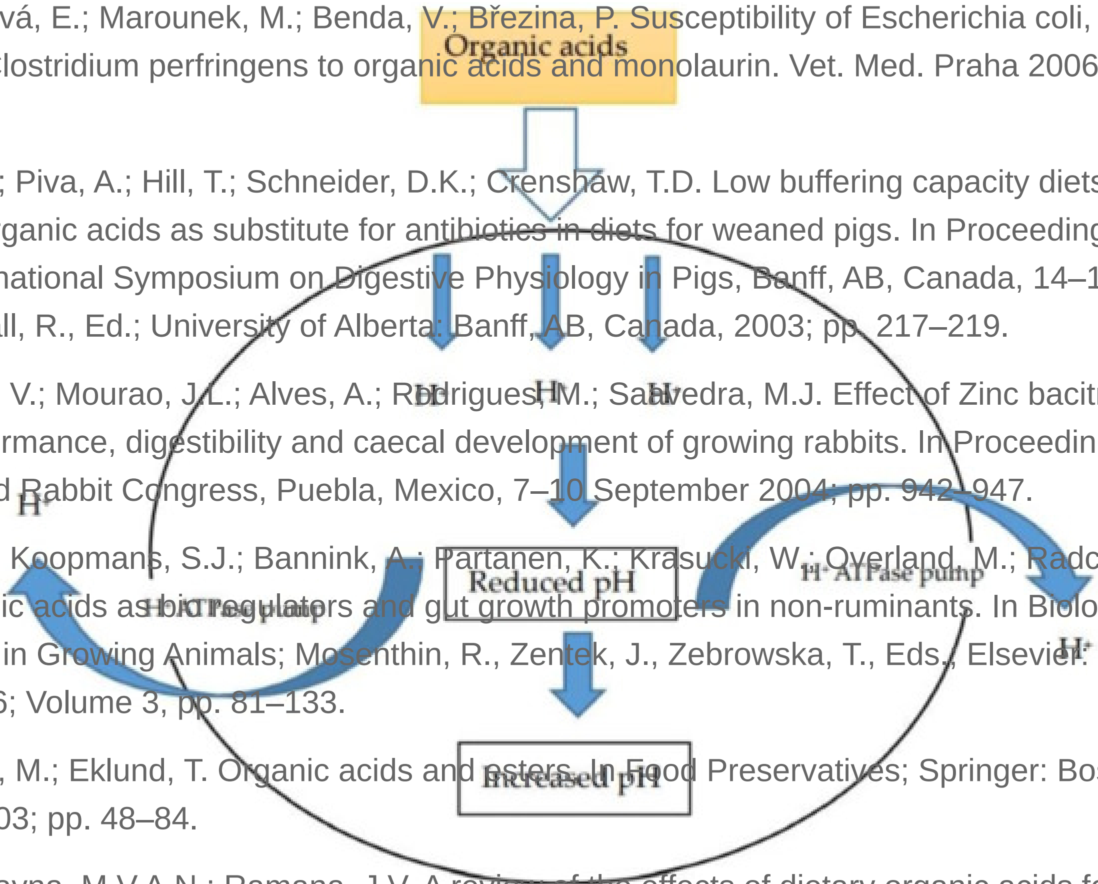

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Figure 3. Mode of action of organic acids on gram-negative bacteria (*Clostridia, Salmonella, Coliforms, Listeria* spp.) [36].

This anion model of OAs can vary upon two factors: (1) the lipophilic nature of the OAs, which can transmit through the microbes cell wall; and (2) various anion complexes involved with different inhibitory actions within the cell [37][38].

3. Effect of OAs in Swine and Broiler

3.1. Supplementation of OAs on the Growth Performance of Swine and Broilers

Studies have found that the optimal dosage of OAs can enhance the productivity of pigs compared to AGPs. Increased growth performance, gain to feed (G: F) and feed intake (FI) was observed in piglets supplemented with an OAs mixture (benzoic, fumaric, lactic, propionic, and citric) [39]. Because benzoic acid in the diet can increase the butyric acid concentration in the GIT, the gut microflora ameliorating process occurs by acting as an energy source agent in gut epithelial cells [40]. The feed conversion ratio (FCR) was increased by 10%, and the average daily gain (ADG) was increased by 3% when pigs were administered fumaric and citric acids at four weeks of age [41]. Kuang et al. [42] reported that the inclusion of an OAs blend (calcium formate, calcium lactate, and citric acid) and medium-chain fatty acids (MCFAs—lauric, capric, and myristic) enhanced the FI, ADG, and FCR in weaning pigs compared to pigs fed with dietary zinc oxide inclusion. Feeding weaning pigs with 0.8% fumaric acids reduced the *E. coli* and *Coliforms* population in the cecum [43]. On the other hand, Risley et al. [44] reported that 1.5 % fumaric acid addition did not affect the microflora composition in the GIT. According to the study conducted by Htto et al. [45], the ADG, FCR, and body weight (BW) during 0–14 days (piglets) were not significantly different from those fed OAs. In the same study, however, the ADG and FCR were enhanced during 15–35 days and, overall, 35 days of periods due to salts of organic acid (potassium diformate and potassium formate) supplementation. Furthermore, a trend of developed growth performance in response to the inclusion of OAs combined with salts combination was more reliable in growing-finishing pigs than in weaning pigs [6]. Canibe et al. [46] and Partanen et al. [47] reported increased ADG and G: F ratios in pigs fed a diet containing formic acid, ammonium formate, and formic acids. A combination of phytogenic feed additives with organic acids (10% citric, 10% sorbic, 6.5% malic, and 13.5% fumaric acid) also improved the BW and ADG of weaning pigs. Moreover, Yang et al. [48] reported that a high abundance of *Limosilactobacillus mucosae* also occurred compared to the control treatment. Nevertheless, 1.8% formic acid inclusion did not have a positive response on the ADG and average daily feed intake (ADFI) of weaning pigs, but it enhanced the G: F [46]. The above dissimilarities among the different studies might be related to the inclusion dosage, diet formulation, supplementation, and animals' health conditions (Table 2). Therefore, further studies will be needed to identify the best OAs concentration for different growth stages.

In the broiler growth performance, the utilization of OAs has not gained as much attention as in the swine industry. The rapid metabolization process in crops to the gizzard (foregut) causes a deficiency of OAs availability and retards the growth performance [33]. However, Fascina et al. [13] reported that the administration of OAs combination (30% lactic, 25.5% benzoic, 7% formic, 8% citric, and 6.5% acetic acid) improved the BW, weight gain

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(WG) and FCR compared to the control group at 42 days of broilers. Broilers fed OAs supplemented diets showed a significant ($p < 0.05$) improvement in the FCR due to better utilization of nutrients [49]. Hassan et al. [50] reported that microencapsulated blend OAs mixture (fumaric acid, calcium formate, calcium propionate, potassium sorbate, and hydrogenated vegetable oil) enhanced the WG by 16% compared to the control groups. Kamal and Ragaa [51] also indicated that in 42 days old broilers, the BWG and FCR were enhanced in those fed 3% organic acids (butyric, fumaric, and lactic acid). Hence, the higher BWG was achieved through direct antimicrobial effect, reducing the digesta pH level in the GIT while acting as a barrier to pathogens and buffering reactivity in conjunction with the enhanced nutrient digestibility [52]. Interestingly, the synergistic effects of combined 0.3 g/kg essential oils (thymol, vanillin, and eugenol) with encapsulated OAs (fumaric, sorbic, malic, and citric) increased the FCR significantly while minimizing the *E. coli* population through a lower gut pH value [53].

Table 2. Effect of organic acids mixture on growth performances and other parameters of swine and broilers.

Dosage and Organic Acid/Acids	Growth Phase	Growth Performances			Intestinal/Fecal Microbial Counts (CFU)	Other Parameters	References
		BWG/FBW	ADFI	G:F			
Swine							
0.1% and 0.2% fumaric, citric, malic, MCFA (capric and caprylic)	Weaning	S	NS	S	*E. coli*; S *Lactobacilli*; S *Clostridium*; S *Salmonella*; S	• Reduced diarrhea score, fecal ammonia, and acetic acid emission	Yang et al., 2018 [54]
0.1% and 0.2% fumaric, citric, malic, MCFA (capric and acrylic)	Growing	S	NS	S	*Lactobacilli*; S *E. coli*; NS	-	Upadhya et al., 2016 [55]
0.15% benzoic, fumaric, calcium formate	Weaning	S	NS	NS	*E. coli*; NS *Lactobacilli*; NS	• Increased villus height in duodenum and jejunum • Increased butyric acid level in the cecum and valeric acid level in the colon	Xu et al., 2017 [56]
1.1% acetic, propionic, phosphoric, citric acid	Weaning	NS	NS	NS	*Lactobacilli*; NS *E. coli*; NS *Coliforms*; NS	• Reduced pH level in colon • Retardation of *Coliforms* proliferation	Namkung et al., 2004 [57]

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Dosage and Organic Acid/Acids	Growth Phase	Growth Performances			Intestinal/Fecal Microbial Counts (CFU)	Other Parameters	References
		BWG/FBW	ADFI	G:F			
0.4% and 0.2% fumaric, lactate, citric, propionic, benzoic acid	Weaning	NS	NS	NS	*E. coli*; NS	-	Walsh et al., 2007 [39]
0.5% benzoic acid	Weaning	S	S	S	*Lactobacilli*; S	-	Wei et al., 2021 [58]
0.5, 1% benzoic acid	Weaning	S	NS	NS	NE	• Reduced the number of aerobic, total anaerobic, lactic acid-forming, and gram-negative bacteria in the stomach • Reduced gram-negative bacteria and acetic acid in the duodenum • Reduced gram-negative bacteria in ileum	Kluge et al., 2005 [59]
0.5% butanoic, fumaric, benzoic acid	Piglets	S	NS	S	*Lactobacilli*; NS *E. coli*; NS	• Decreased ileal *E. coli* bacteria level • Did not exert negative impacts on GIT pH level and immunity	Li et al., 2008 [60]
0.1% fumaric, citric, malic, MCFA (capric and caprylic)	Finishing	S	NS	S	*Lactobacilli*; NS *E. coli*; NS	• Reduced feces H_2S gas emission	Upadhya et al., 2014 [61]
0.85% formic, benzoic, sorbic, Ca-butyrate	Growing male pigs	NS	NS	NS	*E. coli*; S *Lactobacilli*; S	• Lower level of *Coliforms*, *Enterococci*, and lactic acid bacteria in jejunum and colon descendens	Øverland et al., 2007 [62]

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Dosage and Organic Acid/Acids	Growth Phase	Growth Performances BWG/FBW	ADFI	G:F	Intestinal/Fecal Microbial Counts (CFU)	Other Parameters	References
0.5% benzoic acid	Weaning	S	S	S	*E. coli*; NS *Lactobacilli*; NS	• Reduced diarrhea in weaning pigs	Papatsiros et al., 2011 [63]
0.14% and 0.64% formic acid	Weaning	S	S	NS	*Lactobacilli*; S	• Higher microbiota diversity in 0.64% dosage	Luise et al., 2017 [9]
Broilers							
0.3% and 0.4% calcium formate, calcium propionate 0.3, 0.4% ammonium formate, ammonium propionate	Finishing	S	NS	S	NE	• Reduced the ileal total bacterial count • Improved villi length	Saleem et al., 2020 [64]
1% formic, lactic, propionic, citric acid	Finishing	S	NS	NS	NE	• Enhanced V: C in GIT • Increased water consumption during 15–22 days	Ali et al., 2020 [65]
0.5% citric, sorbic, synthetic essential oil	Finishing	NS	NS	NS	*E. coli*; NS *Enterococci*; S *Clostridium*; NS *Enterobacteriaceae*; NS	• Increased villi height, crypt depth, number of villi, mucosa thickness, and villi area	Stamilla et al., 2020 [66]
0.15% formic, lactic, citric, malic, tartaric, phosphoric acids	Finishing	S	S	S	*Lactobacilli*; S *E. coli*; S	• Enhanced inhibitory action owing to organic acid	Goh et al., 2020 [67]

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Dosage and Organic Acid/Acids	Growth Phase	Growth Performances			Intestinal/Fecal Microbial Counts (CFU)	Other Parameters	References
		BWG/FBW	ADFI	G:F			
0.3% formic, acetic, propionic, ammonium formate	Finishing	S	NS	NS	NE	• Increased SCFAs level in the cecum • Increased jejunal goblet cell density and ileal villus height	Dai et al., 2021 [68]
0.1% lactic, citric, acetic, formic, propionic, phosphoric, and sodium butyrate	Finishing	S	NS	S	*Lactobacilli*; S *Coliforms*; NS	• Increased jejunum villus height • Enhanced humoral immune response	Sabour et al., 2018 [69]
0.3, 0.5% formic, propionic acid	Finishing	S	NS	S	*Lactobacilli*; S *E. coli*; S	• Lower duodenal pH • High immune response against Newcastle disease, infectious bronchitis	Fathi et al., 2016 [70]
0.06% fumaric, calcium format, calcium propionate, potassium sorbate, hydrogenated vegetable oil	Finishing	S	S	S	*Lactobacilli*; S *Salmonella*; S	• Increased dressing percentage and bursa weight	Hassan et al., 2010 [50]
0.2, 0.4, and 0.6% butyric acid	Finishing	S	NS	S	*E. coli*; S	• pH reduction of upper GIT • Increased villus length and crypt depth in the duodenum	Panda et al., 2009 [71]

including 10% malic, 13% citric, and 17% fumaric acids, enhanced the digestion of nitrogen (N), dry matter (DM), and energy in finishing pigs and lactating sows [61][75][76] and significantly increased DM, crude protein (CP), fat, and energy digestibility in growing pigs [77]. The supplementation of 1.5% citric acid increased the coefficient of the total tract digestibility (CTTAD) of crude protein (CP), calcium (Ca), and phosphorous (P) of sows during the late gestation and lactation period [78]. Moreover, Yang et al. [54] stated that protected OAs incorporation has positive effects on the apparent total tract digestibility (ATTD) of (DM) in weaning pigs. The inclusion of benzoic acid

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Dosage and Organic Acid/Acids	Growth Phase	Growth Performances			Intestinal/Fecal Microbial Counts (CFU)	Other Parameters	References
		BWG/FBW	ADFI	G:F			
0.5, 1, 1.5, and 2% citric, lactic, phosphoric acid	Finishing	S	NS	S	*E. coli*; S *Salmonella*; S	• 2% OAs blend enhanced the carcass yield • 1.5%, 2% OAs blend increased the liver weight	Sultan et al., 2015 [72]
0.6% formic acid	Finishing	S	NS	S	*E. coli*; S (in crop)	• Higher digestibility of crude protein, higher dressed yield, and lower fat content in carcass	Panda et al., 2009 [73]
2% butyric, fumaric, lactic, and 3% butyric, fumaric, lactic acid	Finishing	S	NS	S	NE	• Increased villus height in the small intestines • Enhanced serum calcium and phosphorus concentrations	Adil et al., 2010 [25]
0.2% propionic, 0.3% butyric acid	Finishing	S	NE	S	NE	• Increased tibia weight, tibia length	Lakshmi and Sunder., 2015 [74]

BWG, body weight gain; FBW, final body weight; ADFI, average daily feed intake; G: F, gain to feed ratio; S,

from the citric acid with microbial phytase. The non-significant impact on the AID of CP and amino acids (AA) might be associated with the formation of complexes among citric acids with Ca and the subsequent decrease in binding ability with phytate allowing easy hydrolyzation by the enzymes.

Table 3. Effect of organic acids combination on nutrient digestibility of swine and broilers.

Dosage and Organic Acid/Acids	Growth Phase	Digestibility				Reference
		DM	N	E	CP	
Swine						
0.2% fumaric, citric, malic, capric, and caprylic acid	Growing	S	S	S	S	Hossain et al., 2011 [77]
0.05% citric, sorbic acid	Growing	S	NS	S	NC	Cho et al., 2014 [91]
2% benzoic acid	Lactating sows	S (OM)	NE	NE	S	Kluge et al., 2010 [82]
0.1% and 0.2% fumaric, citric, MCFA	Finishing	S	S	S	NE	Upadhaya et al., 2014 [75]

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condition in chicken meat used for commercial meat processing and its effect on roasted chicken breast. J. Anim. Sci. Technol. 2016, 58, 27.

Dosage and Organic Acid/Acids	Growth Phase	Digestibility				Reference
		DM	N	E	CP	
0.5% phenyllactic acid	Weaning	S	S	NE	NE	Wang et al., 2009 [92]
0.3% formic, acetic, propionic, MCFA	Weaning	S (DM) NS (OM)	NS	NS	NS	Long et al., 2018 [93]
0.5% formic, propionic, lactic, citric, sorbic acid	Post-weaning	NS	NS	NS	NS	Gerritsen et al., 2010 [94]
300 mEq acid/kg formic, n-butyric acid	Growing	S	S	S	S	Mroz et al., 2000 [95]
0.15% citric acid	Lactating sows	NE	NE	NE	S	Liu et al., 2014a [78]
0.2% fumaric, citric, malic, capric, caprylic acid	Lactating sows	S	S	S	NE	Devi et al., 2016 [96]
Broilers						
0.2% formic, propionic acid	Finishing	NS	NE	NE	S	Emami et al., 2013 [87]
0.5% formic acid	Finishing	NS	NE	NE	NS	Hernández et al., 2006 [84]
0.25, 0.5, and 0.75% formic acid	Finishing	NS	NE	NE	S	Ndelekwute et al., 2015 [97]
5000ppm and 10,000ppm formic acid	Finishing	S	NE	NE	S	Garcia et al., 2007 [84]
0.25% acetic, butyric, citric, formic acid	Finishing	S	NE	NS	S	Ndelekwute et al., 2019 [98]
1, 2, and 3% citric acid	Finishing	NE	NE	S	S	Ghazalah et al., 2011 [52]
0.5, 1, and 1.5% fumaric acid	Finishing	NE	NE	S	S	Ghazalah et al., 2011 [52]
0.25, 0.5% formic acid	Finishing	NE	NE	NS	S	Ghazalah et al., 2011 [52]
0.25, 0.5, and 0.75% acetic acid	Finishing	NE	NE	S	NS	Ghazalah et al., 2011 [52]

N, nitrogen, E, energy, CP, crude protein, S, significant, NS, non-significant, NE, not-evaluated, OM, organic matter, DM, dry matter.

...mal diets. ...mption of quality meat has gained an important place in the food industry. Upadhya et al. [75] reported that supplementation of an OAs blend (consisting of fumaric, citric, malic, and MCFA) did not have adverse effects or improvements in the meat color, pH, cooking loss, drip loss, and water holding capacity (WHC). Similarly, Cho et al. [91] reported that the administration of a microencapsulated OAs combination, including citric and sorbic acids, did not significantly affect the meat color, pH, sensory attributes (color, firmness, marbling), cooking loss, and WHC. In contrast, the inclusion of 0.05 and 0.1% fumaric, citric, malic, and MCFAs resulted in lower drip loss in pork (22.05%) except for any differences in meat color, sensory evaluation, cooking loss, pH, and WHC [99]. Jansons et al. [100] reported a higher protein content (21.94%) in *longissimus lumborum* muscle tissues and lower cholesterol content (51.1 mg/kg^{-1}) in pork after the addition of formic, acetic, citric, phosphoric acid along with phytogenic feed additives to the diet. This might be attributed to the synergistic effect and the presence of antioxidant compounds in the feed. However, further investigations will be needed to determine the possible mode of actions associated with the meat quality characteristics by introducing OAs to the animal diet.

Brzóska et al. [101] reported that the supplementation of OAs to a broiler diet resulted in no significant influence on breast muscle content and leg muscle weight. The chemical constitutes of the leg meat, including DM, protein, and fat content, also did not vary due to OAs application. Nevertheless, Jha et al. [102] reported that the inclusion of OAs (formic + propionic acid, formic + citric acid, formic + sorbic, and formic+ lactic acid) enhanced the meat thigh weight (29.03%), back weight (53.4%), wings weight (31.27%), and breast weight (34.57%) compared to the control group. On the other hand, they did not evaluate any other meat quality parameters regarding OAs inclusion. Supplementation at the recommended dosage of an acetic, butyric, formic, phosphoric, lactic acid blend did not have significantly favorable results on carcass pH, shear force, WHC, cooking loss, and meat color values, but the TBARS value was increased significantly in birds fed with an OAs mixed diet (2.01 nmol MDA/mg) as compared with control group (1.10 nomol MDA/mg). This suggests that a higher fat content facilitated a higher lipid oxidation process in meat [103]. Meat pH has a significant influence on WHC, meat color, juiciness, tenderness, and shelf-life. The changes of meat pH result from post-mortem metabolism and the conversion of glycogen into lactic acid [104]. In contrast, at a lower pH range (pH < 5.8), broiler meat exhibited a pale, soft, and exudative (PSE) condition, which is considered a degraded meat quality parameter compared to meat exposed to higher pH levels (pH > 5.8) [105]. Sugiharto et al. [106] found that a higher meat pH (6.7%) in broilers occurred in a diet administered with 0.1% formic and 0.3% butyric acid compared to the control group. El-Senousey et al. [107] presented a possible reason for the OAs and higher meat pH occurrence: the decline in post-mortem muscle glycolysis inhibited the decrease in muscle pH after slaughter. Furthermore, lower drip loss and a lightness value were reported in the diet combined with both formic and butyric acid but decreased due to the single administration of butyric acid. This might be due to the distinctive characteristics of each OA and the metabolic activities of each associated with specific pKa. Menconi et al. [108] reported less drip loss (65.85%) in broiler meat with feeding blends of lactic, tannic, caprylic, propionic, acetic acids, and butyric acid. Nevertheless, inconsistent results were obtained by Attia et al. [109], who reported a decrease in WHC (26.45%) in broiler meat owing to the supplementation of citric and fumaric acids. These results were attributed to differences in the OAs type, dosage, and experimental environment.

Nutritional quality of meat can also be influenced by the feeding strategies. Akbar et al. [110] observed a significantly higher PUFA content and lower SFA proportion of the birds fed a diet supplemented with organic acid salts (1% calcium propionate), which is beneficial, from the human nutrition point of view, as lower saturated fatty acid (SFA) and higher (PUFA) may positively influence human health. Furthermore, a lower cholesterol content was also reported in the diet containing dietary OAs.