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Review Article

Chemistry, Safety, and Challenges of the Use of Organic Acids and Their Derivative Salts in Meat Preservation

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Meat industries are constantly facing new waves of changes in the consumer's nutritional trends, food safety, and quality requirements and legislations leading to an increase in interest for meat biopreservation to respond to all of these modern socioeconomic demands. Hence, to replace synthetic and/or expensive additives, new technologies in preserving meat products from microbial contamination have been established. In this context, organic acids and their salts have been considered as the most popular examples of preservatives that offer several advantages to be applied in meat industry. Here, characteristics of organic acids/salts commonly used in meat preservation were described based on the published literature. Moreover, after outlining the challenges and advantages of their use in meat industry, their current applications as meat preservatives on various meat type matrices such as beef, pork, sheep, and poultry were quite exposed based on previous and recent research works. Then, different application types were highlighted. Besides, some potent synergistic approaches based on several combinations of organic acids/salts with different existing preservative techniques are reported with an emphasised discussion of their application as possible solution tools to mainly overcome some problems linked to organic acids/salts when used solely, thus contributing to ensure the overall safety and improve the quality of meats. Finally, despite their usefulness in meat preservation, organic acids/salts may possess detrimental traits. In this context, a detailed discussion on their limits of use in meat products was provided in the last section of this paper.

1. Introduction

Food preservation represents an important industrial challenge in terms of preserving nutritional and organoleptic qualities and food safety. In addition, consumer desires ranging from freshness, long-term storage, absence of chemical preservatives, and reasonable price of foods. To respond to all of these requirements, several preservation methods including drying, freezing, refrigeration, thermal processing, irradiation, modified atmosphere packaging (MAP), and addition of antimicrobials have been employed [1, 2]. However, despite the use of these various techniques, many issues are still encountered in terms of food spoilage, thus resulting in economic loss at industry level scale, and consumer health and, consequently, leading to diseases ranging from short-lived to severe complications and even death.

On the other hand, there is an increasing demand from consumers for more natural foods over the last decade that raises a great interest towards food biopreservation. This modern movement leaded to the search and development of new antimicrobials from various natural (animal, plant, and microbial) origins [3, 4]. Among the more widely researched antimicrobials as biopreservatives in food systems are organic acids and their derivative salts. Lactic, acetic, and citric acids and their corresponding salts have been of considerable interest since they occur naturally in foods. In addition, these preservatives exhibit antimicrobial activity by inhibiting the growth of several spoilage and pathogenic microorganisms, improve the sensory properties, and possess technological functions such as the stabilisation of colour, regulation of acidity, and development of characteristic flavour of several foods [5, 6]. Indeed, many organic acids are generally recognised as safe (GRAS) antimicrobials that could be used in food industry [6–8]. In this paper, we will focus on the most known ones commonly applied in meat biopreservation since these foods are assigned as very perishable due to their very short shelf-life because of microbial spoilage and lipid oxidation [5, 9]. In this line, we could notice that, in meat and meat products, the major challenges are the prevention of harmful microorganisms' growth and preservation of sensory properties (colour, flavour, odour, texture, etc.). Therefore, to successfully attain these objectives as well as responding to modern consumer trends and food legislation related to meat biopreservation, organic acids and their derivative salts seem to be very good examples of natural preservatives.

In this context, the present paper presents a general overview on organic acids and their salts in terms of their usefulness and practical importance as biopreservatives in meat. In fact, this review highlights their structures and aspects, antimicrobial action, roles in safety assurance, shelf-life prolongation, and organoleptic quality enhancement basing on the previous and recently published research and studies. Finally, some powerful approaches and promising strategies are exposed to potentially enhance the preservative effect of organic acids/salts in meat preservation and satisfy both meat industry's demand and consumer's desire for natural, safe, healthy, and low-cost meats (at production as well as at market purchase). Hence, the pros and cons of these natural tools are deeply discussed, and by this review, we hope to provide a valuable addition to mainly contribute to the enrichment of the scientific library and help any researcher working in this field.

2. General Characteristics of Organic Acids

2.1. Nature, Composition, and Production. Organic acids are chemical compounds widely present in nature as normal constituents of plants or animal tissues [10]. For instance, citric acid can be extracted from the juice of citrus and other acidic fruits such as limes, lemons, oranges, pineapples, and gooseberries [11–13], while benzoic acid exists naturally in cinnamon, cloudberries, cranberries, and lingonberries [3]. Ubiquitous microorganisms such as bacteria, fungi, and yeasts can also produce organic acids [10]. Nevertheless, lactic acid bacteria (LAB) are the most popular bacteria regarding the production of organic acids as their metabolic end-products of carbohydrate fermentation [3, 14]. Hence, these acids could occur naturally as ingredients of several food products or could later be added to them. Otherwise, organic acids possess the common characteristic of having carbon in their structure. Those having 10 carbons or less could thus be distinguished from fatty acids which have in their structure straight and even-number carbon chains of 4 to 24 [3]. In general, organic acids are weak acids and do not dissociate completely in water. Organic acids with low molecular mass such as lactic and formic acids are miscible in water; however, those with high molecular mass, such as benzoic acid, are insoluble in molecular form [6]. Furthermore, organic acids are mostly known to be very soluble in organic solvents [5]. On the other hand, it is important to note that organic acids exist in two basic forms: (i) pure organic acids (e.g., lactic, acetic, citric, and benzoic acids) and (ii) buffered organic acids such as the calcium and sodium salts of the already mentioned acids [3]. Organic acids differ in structure basing on the involvement of their constituent elements of carbon, hydrogen, and oxygen [10]. Chemical properties and physical characteristics of the most used organic acids and their salts that are commonly used in food industry are presented in Table 1.

2.2. Antimicrobial Activity and Mode of Action of Organic Acids and Their Salts

2.2.1. Antimicrobial Activity. Thanks to their potential antimicrobial activity widely reported in several studies, organic acids and their salts have gained a renewed interest to be applied as bioagents in meat industry. In fact, these acids and their salts have been demonstrated to exhibit a large spectrum of action against Gram-positive bacteria [5, 15–17], Gram-negative bacteria [15–19], and fungi and yeasts [20–22]. Some of the antimicrobial effects of common and most studied organic acids and their salts are summarised in Table 2.

2.2.2. Mode of Action. In general, the bioactive agents act as bacteriostatic or bactericidal molecules towards microorganisms suggesting several antimicrobial mechanisms of action [35–37]. The antimicrobial activity of organic acids such as lactic, acetic, and citric acids and/or their salts is based on lowering the pH level of a medium or foodstuff as a mechanism of action to inhibit the microbial growth [6, 38–40]. This pH decrease ability is dependent upon the chemical properties of organic acid compounds such as the acid constant (pK_a) and the dissociation constant (K_a) numbers (Table 1), the concentration of the undissociated forms as well as the organic acid concentration [6, 41]. In fact, the organic acids exist in a pH-dependent equilibrium between the dissociated and undissociated states [3]. The undissociated and uncharged organic acid molecules are first responsible for the antimicrobial activity since their concentration increases at low pH [3]. For this reason, it was mainly noticed that organic acids have optimal antimicrobial effects at low pH [3]. Here, it was believed that these undissociated molecules are lipophilic and therefore are able to easily cross the lipidic membrane of target microorganisms (bacteria, yeasts, and fungi) to enter into their cytoplasm, thus resulting in cell death [6, 42]. Indeed, once inside the cytoplasm of the bacterial or fungal cell, the organic acid molecules encounter a higher pH, provoking then their dissociation into charged anions and protons that could not recross the plasma membrane [3, 6, 42]. The accumulating H^+ ions will then decrease intracellular pH toward harsh physiological conditions inducing cellular damage and

Table 1: Characteristic of the most known organic acids and their salts.

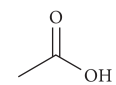
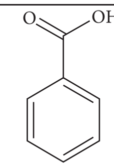
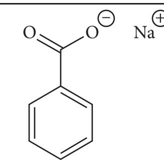
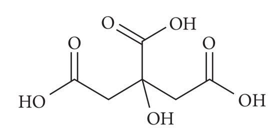
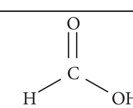
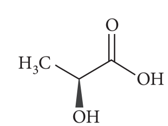
Organic acid/salt	Origin: Microbial producer	Origin: Plant	Origin: Animal	Molecular formula	Molecular weight (g/mol)	Structural formula	pK_a	K_a	Physical appearance	Solubility in water (g/L)
Acetic acid	*Acetobacter* spp., *Komagataeibacter europaeus*, *Dekkera bruxellensis*, *Brettanomyces* spp., *Saccharomyces cerevisiae*, *Fusarium oxysporum*, *Polyporus anceps*	—	—	$C_2H_4O_2$	60.05		4.76	1.73×10^{-5}	Liquid	Miscible
Benzoic acid	—	—	—	$C_7H_6O_2$	122.12		4.2	6.3×10^{-5}	Solid	2.9
Sodium benzoate	—	Cranberries, bilberries	—	$C_7H_5NaO_2$	144.10		4.2	6.3×10^{-5}	Solid	660
Citric acid	*Aspergillus*, *Acremonium*, *Ascochyta*, *Bacillus*, *Botrytis*, *Candida*, *Debaryomyces*, *Eupenicillium*, *Hansenula*, *Mucor*, *Penicillium*, *Pichia*, *Saccharomyces*, *Talaromyces*, *Torulopsis*, *Trichoderma*, *Yarrowia*, *Zygosaccharomyces*	All citrus fruits (lemons, limes, oranges), pineapples, gooseberries	—	$C_6H_8O_7$	192.12		3.13; 4.76; 6.4	7.4×10^{-4} 1.7×10^{-5} 3.9×10^{-7}	Solid	750
Formic acid	—	*Urtica dioica*	Ants, bees	CH_2O_2	46.025		3.745	1.8×10^{-4}	Liquid	Miscible
Lactic acid	*Aspergillus*, *Bacillus*, *Carnobacterium*, *Enterococcus* sp., *Escherichia*, *Lactobacillus plantarum*, *Lactococcus* sp., *Leuconostoc mesenteroides*, *Rhizopus*, *Saccharomyces*, *Candida*, *Pichia stipites*, *Torulaspora delbrueckii*	—	—	$C_3H_6O_3$	90.07		3.9	1.3×10^{-4}	Liquid	Miscible

Table 1: Continued.

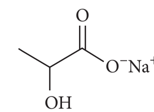
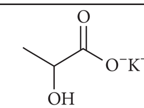
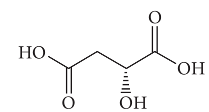
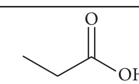
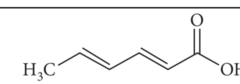
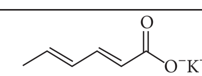
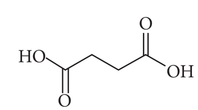
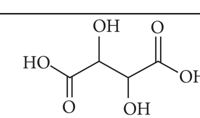
Organic acid/salt	Origin: Microbial producer	Origin: Plant	Origin: Animal	Molecular formula	Molecular weight (g/mol)	Structural formula	pK_a	K_a	Physical appearance	Solubility in water (g/L)
Sodium lactate	—	—	—	$C_3H_5NaO_3$	112.06		3.9	1.3×10^{-4}	Liquid (colourless or slightly yellowish)	Miscible
Potassium lactate	—	—	—		128.17		3.9	1.3×10^{-4}	Liquid (colourless, clear)	Viscous
Malic acid	*Aspergillus* spp., *Escherichia*, *Saccharomyces*, *Zygosaccharomyces*	Blackberries, blueberries cherries, apricots, peaches, mango, plums, apples, pears, quinces, mirabelles	—	$C_4H_6O_5$	134.08		3.46; 5.10	—	Solid	558
Propionic acid	*Lactobacillus* spp., *Clostridium propionicum*, *Propionibacterium* spp.	Apples, grains, strawberries	—	$C_3H_6O_2$	74		4.87	1.3×10^{-5}	Liquid	370
Sorbic acid	—	Berries of rowan tree (*Sorbus aucuparia*)	—	$C_6H_8O_2$	112.13		4.76	1.73×10^{-5}	Solid	1.6
Potassium sorbate	—	—	—	$C_6H_7KO_2$	150.21		4.76	1.73×10^{-5}	Solid	1400
Succinic acid	*Anaerobiospirillum succiniciproducens*, *Mannheimia succiniciproducens*, *Actinobacillus succinogenes*, *Bacillus fragilis*, *Fusarium* spp., *Aspergillus* spp., *Candida* spp., *Yarrowia lipolytica*, *Saccharomyces cerevisiae*	—	—	$C_4H_6O_4$	118.088		4.2 5.6	6.21×10^{-5} 2.31×10^{-6}	Solid	58
Tartaric acid	*Gluconobacter* spp.	Grapes, bananas, tamarinds, citrus	-	$C_4H_6O_6$	150.08		2.89 4.40	6.8×10^{-4} 1.2×10^{-5}	Solid	1330

Table 2: Spectrum of action of frequently encountered organic acids and their salts.

Organic acid/salt	Activity spectrum	Reference
Lactic acid	*L. monocytogenes*, *S. aureus*, *E. faecalis*, *B. cereus*, *Salmonella* sp., *E. coli*, *P. aeruginosa*, *Proteus* sp., *C. albicans*, *S. cerevisiae*, *Penicillium nordicum*, *Penicillium purpurogenum*, *Aspergillus flavus*, *Rhizopus nigricans*, *Rhodotorula* sp.	[5, 17–21, 23–25]
Sodium lactate	Psychrotrophic bacteria, faecal streptococci, *L. monocytogenes*, *Enterobacteriaceae*, *E. coli*, *Salmonella* sp.	[26]
Potassium lactate	*L. monocytogenes*, *E. coli*, *Salmonella* sp.	[26]
Citric acid	*L. monocytogenes*, *Salmonella typhimurium*, *E. coli* O157:H7, *Aspergillus flavus*, *Penicillium purpurogenum*, *Rhizopus nigricans*, *Fusarium oxysporum*, *Saccharomyces cerevisiae*, *Zygosaccharomyces bailii*	[5, 18, 19, 21, 24, 27, 28]
Sodium citrate	*Fusarium* sp.	[21]
Acetic acid	*L. monocytogenes*, *E. coli* O157:H7, *Salmonella typhimurium*, *Enterobacteriaceae*, *Penicillium nordicum*, *Penicillium purpurogenum*, *Aspergillus flavus*, *Rhizopus nigricans*, *Fusarium* sp.	[5, 18–21, 23–25]
Propionic acid	*L. monocytogenes*, *E. coli*, *Salmonella* spp., *Clostridium perfringens*, *Aspergillus flavus*, *Fusarium* sp., *Penicillium* sp., *Rhizopus nigricans*,	[16, 19, 21, 23, 24]
Tartaric acid	*Salmonella typhimurium*, *Aspergillus flavus*, *Fusarium* sp., *Penicillium* sp., *Rhizopus nigricans*	[16, 18, 21]
Formic acid	*E. coli*, *Salmonella* spp., *Clostridium perfringens*, *Aspergillus flavus*, *Fusarium* sp., *Penicillium* sp., *Rhizopus nigricans*	[16, 21]
Sodium formate	*Streptococcus* sp., *Clostridium perfringens*, *E. coli*, *Salmonella enterica* typhimurium, *Campylobacter jejuni*	[15]
Benzoic acid	*E. coli*, *L. monocytogenes*	[29]
Sodium benzoate	*Fusarium sambucinum*, *L. monocytogenes*	[21, 30–32]
Succinic acid	*Salmonella typhimurium*, *E. coli*, *B. subtilis*, *S. suis*	[19]
Sorbic acid	*Fusarium* sp., *L. monocytogenes*, *E. coli*	[21, 29, 33]
Potassium sorbate	*Fusarium* sp., *L. monocytogenes*, *Salmonella* spp.	[21, 30, 31, 34]

modification of the functionality of enzymes, structural proteins, and DNA [43, 44]. Furthermore, the generated anions were demonstrated to be toxic leading to inhibit metabolic reaction and cause cell death [3, 44]. On the other hand, the release of these anions increases the osmotic pressure in the cytoplasm that is deleterious to cytosolic enzymes [44]. This mechanism of action is generally attributed as "weak organic acid theory" [43]. In this line, it was previously reported that weak organic acids such as sorbic and benzoic acids could act in their undissociated forms with penetrating microbial cells and inactivating them by lowering their internal pH level or by interfering with metabolic reactions [7]. Therefore, the organic acids were assigned to exhibit stronger antimicrobial effects than the highly dissociating inorganic acids at the same pH level due to their amount of undissociated molecules and their cell penetration capacity, suggesting their application in food biopreservation.

Other modes of action were suggested for the microbial growth inhibition by weak organic acids including induced stress response on intracellular pH homeostasis and cell membrane disruptions related to proton motive force and membrane transport resulting in energy depletion and inhibition of essential metabolic reactions [3, 42, 45]. Effectively, target affected by organic acids attempts to counter the unsuitable cellular acidification by restoring homeostasis using an integral membrane protein known as Hsp30 to actively export the excess proton out of the cytoplasm. This stress response leads to a rapid starvation, thus reducing the cellular energy required for growth and several metabolic functions that were already consumed for protein activity in maintaining homeostasis [6, 46]. Moreover, the cell electrochemical potential dropped, and nutritional substance uptake was inhibited [6]. These mechanisms were observed for lactic, malic, citric, acetic, and propionic acids although the classical "weak organic acid theory" as mode of action has previously been attributed to them [6, 42, 47, 48]. For instance, lactic acid was shown to destabilise the membrane of Gram-negative bacteria by the reduction of membrane-associated molecular interactions resulting in the formation of pores which causes rapid cell death [49]. Furthermore, lactic and acetic acids were found to disturb the trans-membrane proton motive force, denature acid-sensitive proteins and DNA, and overall interfere with both metabolic and anabolic processes [42]. Regarding citric and malic acids, they were able to destabilise the cellular outer membrane by intercalation or chelation of essential ions, thus inhibiting their access for the cell, and then, metabolic pathways that depend upon certain ion conditions will be arrested [6, 28, 44]. Concerning sorbic acid, it may not only act as a classic weak organic acid but also could inhibit the membrane-associated protein H^+-ATPase that is implicated in the microbial respiration chain crucial for cellular energy generation [43]. On the other hand, according to previous results of York and Vaughn [50], another mode of action of sorbic acid, involving the inhibition of intracellular enzymes (e.g., cysteine) by interactions with their thiol groups, was proposed.

Therefore, it is worth mentioning that weak organic acids do not display one basic mechanism of action as already mentioned, and deep investigations of these modes of action remain to be continued to clearly explain the outcomes in this regard in terms of target sites, action on bacteria, moulds and/or yeasts, and interactions with the surrounding environment.

2.3. Other Technological Functions of Organic Acids. Many organic acids and their salts are GRAS and approved to be applied in meat industry for different matrices thanks to their various and useful effects [6]. In addition to their potential antimicrobial activity towards several spoilage and pathogenic microorganisms, organic acids and their salts display further functionalities helpful for their application as biotechnological agents such as antioxidant activity [51–53], enhancement of physicochemical properties, and improvement of sensory attributes of meat and meat products [54–57]. In this context, these acids and their salts were accordingly listed in the European legislation as preservatives (P), acidifiers (A), acidity regulators (AR), antioxidants (AO), stabilisers (S), colour stabilisers (C), flavour enhancers (FE), and flavour treatment agents (F) [8]. Table 3 highlights approved technological functions of some organic acids and their salts commonly used in food industry with a close link to meat biopreservation purpose.

2.4. Regulatory Use of Organic Acids and Their Salts as Food Preservatives. Regarding the regulation for use of organic acids and their salts as food preservatives in meat, it is evident that each compound must technologically be applied in different meat matrices at specified concentrations. This latter must be respected to a legislative values determined from the Acceptable Daily Intake (ADI), in which the maximum, corresponding to a hundredth of the No Observable Adverse Effect Level (NOAEL), must not be exceeded [6]. The ADI values for the most common organic acids and their salts used as preservatives in meat are shown in Table 4. Generally, the maximum applicable amounts of the majority of organic acids and their salts in foodstuffs range between 0.1 and 0.4% [6]. Specifically, in accordance with European food legislation, lactic, citric, and acetic acids should be applied with *quantum satis* principle (no maximum level is specified, but the applied amount shall be used at a level not higher that is necessary to achieve the intended technological purpose) [8]. Regarding sorbic and benzoic acids, the allowed amounts normally range between 1000 and 2000 mg/kg of food [8]. Details related to toxicological data, ADI values, and application limits of some organic acids and their salts are given in Table 4.

3. Application of Organic Acids and Their Salts in Meat Preservation

The use of synthetic preservatives in meats such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) remains a major issue since these chemical additives have been involved in several health problems [58]. Therefore, as a challenge, meat industries and scientific researchers have increased their attention on investigating natural antimicrobials efficient in preserving meats in terms of preventing their microbial, physicochemical, and sensory deteriorations during processing, storage, and transport and extending their shelf-life in accordance with food legislation. In this line, the application of organic acids and their salts gained a great attention as food preservatives in meat and meat products since they are food ingredients and often naturally produced by several microorganisms. But, despite the wide numbers of useful and well characterised organic acids and their salts for their efficiency as preservatives, until now there are likely still relatively few ones coming onto natural agents approved for such application in meat industries. Effectively, strict *in vitro* and *in vivo* assessments must be performed before concluding about their effectiveness in preserving different meat systems to finally obtain approval from the international regulation agencies. These evaluations could thus take many years because of their complexity in terms of ADI and NOAEL determination to avoid allergenic and toxicological problems when consumed, high antimicrobial and preservative activities when incorporated into diverse meat matrices, absence of effects on the meat sensory properties, and absence of interactions with meat components.

The worldwide policy in the agrofood field is the implementation of improved meat quality and safety with an emphasised focus on the most perishable foodstuffs such as meats and derivative products. Although organic acids have been previously used for such purposes, there is a glaring need to evaluate and improve their continued efficiency and sustainability.

3.1. Advantages of Organic Acids and Their Derivative Salts Application in Meat and Meat Products. Recently, it was demonstrated that organic acids and their salts have been of considerable value as natural preservatives of meat and meat products and their application represent a promising biotechnological approach. In fact, their use is quite advantageous as they have GRAS status since they are natural food ingredients and several microorganisms (e.g., LAB, yeasts, and fungi) naturally produce most of them [6]. Hence, due to this great and natural distribution, their extraction seems to be much easier and simple comparing to other rare antimicrobials. Another advantage of the use of organic acids and their salts in meat and meat products is the fact that they did not affect the organoleptic quality when applied in respect to amounts allowed by the food legislation. Moreover, most of them are not limited in the ADI for humans such as lactic, citric, and acetic acids [8, 19].

Furthermore, according to the published literature, many of the characterised organic acids and their salts have shown potent antimicrobial activity with large spectrum of action against spoilage and pathogenic microorganisms (Table 2) with significant improvement of the physicochemical (delay of lipid and protein oxidation) and sensory properties (stabilisation of red colour, inhibition of off-odour, and enhancement of characteristic flavour or taste or tenderness or juiciness) of treated meats, suggesting that

Table 3: Technological functionality of commonly used organic acids and their salts in food industry.

E. no	Organic acid/salt	Functionality						
		Preservative	Acidifier	Acidifier regulator	Antioxidant	Stabiliser	Colour stabiliser	Flavour enhancer
E200	Sorbic acid	×						
E202	Potassium sorbate	×						
E210	Benzoic acid	×						
E211	Sodium benzoate	×						
E212	Potassium benzoate	×						
E260	Acetic acid	×	×	×				
E261	Potassium acetate	×		×				
E262	Sodium acetate	×		×				
E270	Lactic acid	×	×				×	
E280	Propionic acid	×						
E296	Malic acid		×				×	
E300	Ascorbic acid		×		×		×	
E301	Sodium ascorbate		×		×		×	
E325	Sodium lactate			×		×		
E326	Potassium lactate			×		×		
E330	Citric acid		×				×	
E334	Tartaric acid		×				×	
E355	Adipic acid		×					×
E363	Succinic acid		×	×				

Table 4: Lethal dose by rat oral ingestion (LD_{50} rat), Acceptable Daily Intake (ADI), and application limits in meat of commonly used organic acids/salts.

Organic acid/salt	LD_{50} rat, oral (mg/kg_{BW})	ADI (mg/kg_{BW})	Application limits in meat
Acetic acid	3310	Undefined	*Quantum satis*
Sodium acetate	3530	Undefined	Good manufacturing practice
Benzoic acid	1700	5	1000 ppm
Sodium benzoate	4070	5	1000 ppm
Citric acid	3000	Undefined	*Quantum satis*
Lactic acid	3540	Undefined	*Quantum satis*
Potassium lactate	>2000	Undefined	Good manufacturing practice
Propionic acid	370	Undefined	2500 ppm
Tartaric acid	7500	30	Good manufacturing practice
Sorbic acid	7360	25	1000 ppm
Potassium sorbate	2600	25	1000 ppm

LD_{50} rat: lethal dose 50% for rat, dose required to kill 50% of tested rats; oral: oral ingestion; BW : body weight.

these bioagents could have important functions as natural meat preservatives.

Finally, it is important to denote that the application of organic acids and their salts in meat preservation become nowadays common because acid treatment procedures are cheap, simple, and fast to apply [19].

Therefore, taken into account all of these potential aspects and merits played by organic acids and their salts, it could be admitted that they are attracting considerable interest which favour their use as innovative natural food preservatives to ensure safety, improve quality, and prolong the shelf-life of meats.

3.2. Current Applications of Organic Acids and Their Salts in Meat Preservation

3.2.1. Beef Meat. Added to vacuum-packaged raw ground beef at 30 g/kg, sodium lactate showed an interesting result on the microbiological and chemical qualities [59]. In fact, its addition significantly delayed the proliferation of aerobic plate counts, psychrotrophic counts, LAB, and Enterobacteriaceae and clearly extended the shelf-life of the treated beef up to 15 days *versus* 8 days only for control. In addition, over the storage experiment (21 days at 2°C), this organic salt (sodium lactate) maintained the ground beef at almost constant pH and lipid oxidation was not affected.

Furthermore, it has been reported by Quilo et al. [60] that the use of potassium lactate at 3% on beef trimmings before grinding could improve the sensory (odour and taste) attributes and technological (cooking yield) characteristics and maintain the physicochemical (pH and TBARS) parameters.

Another study of the effect of sodium and potassium lactates at 2% on the cook yield and tenderness of bovine chuck muscles highlighted a significant ($P < 0.05$) decrease of the WBSF (Warner–Bratzler shear force) and a remarkable improvement of sensory attributes (tenderness and cook yield rating) compared to noninjected controls [61].

On the other hand, lactic and acetic acids at 2% displayed strong ($P < 0.05$) antimicrobial activity on the decontamination of *E. coli* O157:H7 onto beef meat surfaces according to Carpenter et al. [62]. In fact, these organic acid washes decreased the pathogen by 0.6 to 1 log/cm^2 compared to control samples (no-wash meats) or water-wash meat samples and prevented its residual growth.

These same organic acids (lactic and acetic acids at 1 and 2%) and their salts (sodium lactate and sodium acetate at 2.5%) were assessed for their effects on the chemical, microbiological, and sensory qualities of raw beef meat stored at 4°C [63]. Results revealed the efficient antimicrobial activity of these additives against the proliferation of aerobic and psychrotrophic bacteria as well as Enterobacteriaceae. The chemical analysis showed a significant ($P < 0.05$) reduction in the pH of treated beef samples. Regarding the sensory quality of treated beef meats, the organic acids/salts addition improved the colour, flavour, and texture properties with highest scores shown for 1% acetic acid and 1% lactic acid.

In addition, it was reported that 2% potassium lactate could ensure microbial quality of roast beef towards the proliferation of *L. monocytogenes* and inoculated *Salmonella* cocktail composed by *Salmonella typhimurium*, *Salmonella* Heidelberg, and *Salmonella* Enteritidis [64].

A more recent research [65] indicated that lactic, acetic, and citric acids at 1, 2, and 3% reduced *Salmonella* Enteritidis, *E. coli*, and *L. monocytogenes* counts in beef meat. Significant ($P < 0.05$) reductions were observed with 3% concentration, and the most efficient organic acid was lactic acid, followed by acetic acid and citric acid.

Moreover, regarding lactic and acetic acids at 3%, it has been found that their spraying on bovine carcasses significantly ($P < 0.05$) decreased the counts of spoilage psychrotrophic germs and pathogenic bacteria (*Pseudomonas* spp., *Aeromonas* spp., *Yersinia* spp., and Enterobacteriaceae) during 14 days [66]. The most sensitive bacteria towards the lactic and acetic acids were *Aeromonas* spp.

3.2.2. Pork Meat. The addition of sodium lactate at 0, 1, 2, and 3% was found to depress aerobic total plate counts, anaerobic total plate counts, and anaerobic lactic acid producers on vacuum-packaged pork sausages stored at 4°C for 31 days [67]. In addition, this organic salt at 1% extended the shelf-life of pork sausages by 1 week compared to controls, and samples containing 2 and 3% of sodium lactate had not reached spoilage level ($\log_{10}$ 7.0 CFU/g). Regarding its effects on physicochemical characteristics, sodium lactate reduced the pH of pork samples. On the other hand, it was found that the addition of sodium lactate generally increased salty taste and prevented the loss of pork flavour over time but had no effect ($P > 0.05$) on sour or bitter flavours.

Further study was performed with sodium lactate at 1.5 and 3% to evaluate its effects on the sensory characteristics and shelf-life of fresh ground pork [68]. As a result, the sodium lactate increased the salty flavour intensity but remained less perceptible as "salty" than the other salt additive of NaCl. It also increased juiciness and enhanced ground pork flavour. Additionally, sodium lactate significantly ($P < 0.05$) reduced aerobic plate counts in fresh ground pork over the retail storage of 25 days, and meat samples formulated with 3% sodium lactate exhibited a great extending of shelf-life by about 12 days compared to controls.

Similarly, it has been found that packaged ground pork meat, aerobically stored at 4°C for 21 days and formulated to contain 3% of sodium lactate, had the lowest aerobic plate counts and its initial pH was best maintained [69]. Moreover, meat red colour was best preserved by 2 and 3% of sodium lactate concentrations.

On the other hand, acetic or lactic acids at 2.5 or 5% and some organic salts (sodium acetate, sodium diacetate, sodium lactate, potassium sorbate, and potassium benzoate) at different concentrations (5 or 10%) were used as aqueous dipping to control *L. monocytogenes* on sliced and vacuum-packaged pork Bologna stored at 4°C for up to 120 days [31]. Results showed no significant ($P > 0.05$) growth of *L. monocytogenes* on pork Bologna slices treated with 2.5 or 5% acetic acid, 5% sodium diacetate, and 5% potassium benzoate from days 0 to 120. Meat products treated with 5% potassium sorbate and 5% lactic acid were stored for 50 and 90 days, respectively.

In addition, sodium lactate, sodium acetate, and sodium diacetate were previously assessed for their antimicrobial activity against *L. monocytogenes* growth on frankfurters stored at 4°C in vacuum packages [70]. The results revealed that 6% sodium lactate and 0.5% sodium diacetate had bactericidal effects for 120 days. Then, sodium lactate at 3% prevented listerial growth for at least 70 days, while 0.25% sodium diacetate or sodium acetate at 0.25 or 0.5% inhibited the pathogen growth for 20 to 50 days. Hence, according to this study, the tested organic salts could strongly be applied to control listerial postprocessing contamination on vacuum refrigerated frankfurters.

Furthermore, it has been reported that the microbial stability of refrigerated fresh ground pork meat was enhanced by the addition of 2% sodium or potassium lactates without deleterious effects on its colour or fat stability during 15 days of storage at 2°C [71].

Besides, sodium lactate at 1.8% and sodium diacetate at 0.25% displayed antilisterial effects in pork frankfurter samples without affecting the flavour and the overall acceptability of the meat products [72].

Moreover, it was reported by Carpenter et al. [62] that spray washing with 2% of lactic or acetic acids as decontamination solutions showed efficacy in reducing *Salmonella* populations on pork belly and in protecting meats against later growth of this pathogen.

In the study of Hwang et al. [73], it was shown that 1, 2, and 3% of lactate significantly ($P < 0.05$) inhibited the growth of *L. monocytogenes*, *E. coli* O157:H7, and *Salmonella* spp. in cooked ham stored at refrigerated and abuse temperatures (4–15°C), and reduction effects were more pronounced at low storage temperatures. Therefore, it has been deduced that these lactate concentrations (1–3%) could be eventually used to enhance microbiological safety of ready-to-eat ham products.

Added to that, it was demonstrated that potassium lactate at 2% inhibited the growth of *L. monocytogenes* and *Salmonella* spp. in cured pork meats for 49 days of refrigerated storage [64].

A recent study [74] on the residual antimicrobial effect of weak organic acids (lactic and acetic acids at 3%) on spoilage psychrotrophic germs in pig carcasses reported that the spraying decontamination of porcine carcasses with 3% of lactic or acetic acids resulted in an obvious reductions of psychrotrophs, *Pseudomonas* spp., and Enterobacteriaceae germs and the most sensitive bacteria were *Aeromonas* spp. and *Yersinia* spp. which were completely inhibited after 24 h of acid treatment.

Acetic, lactic, and citric acids at concentrations of 1, 2, or 3% were also assessed for their antimicrobial effects against *S.* Enteritidis, *L. monocytogenes*, *C. jejuni*, *E. coli*, and *Y. enterocolitica* bacteria in the decontamination operation of meat pork [75]. Analyses revealed that all of the tested organic acids could diminish the pathogen counts with great reductions shown with the concentration of 3%. The most efficient organic acid was lactic acid, followed by acetic acid and then citric acid.

Finally, González Sánchez [76] evaluated the effectiveness of formic acid (1.5%) and peroxyacetic acid (400 ppm) as antimicrobial spray formulations to control *Salmonella enterica* growth in chilled pork jowls. Overall, the acid spray treatments were effective in reducing *Salmonella* counts immediately after application and after 24 h of refrigerated storage at 4°C.

3.2.3. Sheep Meat. Decontamination of sheep carcasses by spraying lactic acid at 2% after slaughter and one-day cold storage resulted in significant ($P < 0.05$) reduction rates of total viable bacteria, coliforms, and *E. coli*, suggesting that the application of lactic acid at 2% with proper hygiene and handling procedures could provide safer sheep meat [77].

Recently, it has been found that sodium lactate marinating at 2% improved the water-holding capacity, solubility of the protein fraction, and marinade uptake of sheep meat [78].

Moreover, the addition of citric acid in sheep "Buchada" resulted in the reduction of microbial growth (thermotolerant coliforms, *Staphylococcus* spp., and *Salmonella* sp.), pH, moisture, and TBARS value and did not negatively affect the sensory attributes (odour, flavour, appearance, and tenderness) [57].

Finally, the antibacterial effect of lactic and acetic acid spray treatments, at 1, 1.5, and 2%, was studied towards the aerobic plate count, Enterobacteriaceae, coliform, and *Staphylococcus* counts on fresh sheep carcasses surfaces. The findings showed significant reductions in the microbial growth of the investigated microorganisms after sheep meat exposition to organic acids with specifically higher effect of 2% lactic acid spraying wash [79].

3.2.4. Poultry Meat Products. In chicken meat vacuum-infused with acetic, citric, lactic, malic, and tartaric acids (each at 75.0 or 150.0 mM) over 12 days of storage at 4°C, the *E. coli* O157:H7, *L. monocytogenes*, and *Salmonella typhimurium* populations were significantly ($P < 0.05$) reduced by 1–6 log CFU/g, and 150.0 mM was the most effective antimicrobial concentration [80]. In addition, the effects of lactic acid at 0.2, 0.3, 0.5, 0.6, 0.8, and 1% and its sodium lactate salt at 1, 1.5, 2, 2.5, and 3% were assessed on chemical, microbiological, and sensory properties of marinated chicken thighs stored at 4°C for 15 days [81]. The results revealed that these additives were efficient against the proliferation of different spoilage and pathogenic microorganisms such as aerobic and psychrotrophic bacteria, *Pseudomonas* spp., *Salmonella* spp., Enterobacteriaceae, and *Staphylococcus aureus*. Chemical assessment indicated that the tested organic acid and its salt generally reduced the pH value (≈6.06 at the end of the storage period) and the total volatile basic nitrogen contents (TVBN) (with 0.2, 0.5, and 1% of lactic acid, and 1, 2, and 3% of sodium lactate) in treated chicken samples. Furthermore, lactic acid and sodium lactate improved the sensory attributes (odour, flavour, colour, and texture) with highest overall acceptability score (7.94 out of 10-point hedonic scale note) observed with 1% lactic acid followed by 0.8% lactic acid (score of 7.38) and 3% sodium lactate (score of 6.94). All of these results allowed a significant prolongation of the shelf-life of the refrigerated chicken products with the general order of the used organic preservatives as lactic acid > sodium lactate.

Another study in this context was previously conducted by Carpenter et al. [62] to evaluate the efficacy of washing chicken skin and turkey roll surfaces with solutions formulated with acetic or lactic acid at 2% for *Salmonella* and *L. monocytogenes* decontaminations, respectively [62]. The results revealed that lactic acid was the best organic agent in lowering the numbers of *Salmonella* on chicken skin and *L. monocytogenes* on turkey roll. On the other hand, acetic acid provided effective residual protection against later growth of these pathogenic bacteria than that displayed by lactic acid.

Moreover, it was shown that 2% potassium lactate strongly reduce *L. monocytogenes* and *Salmonella* spp. counts in refrigerated chicken Bologna samples, thus maintaining their microbial stability and shelf-life until 49 days of chilled storage [64].

Then, it was demonstrated that lactic acid (1 or 2%) inhibited the microbial growth of aerobic mesophilic, psychrotrophic, coliforms, and faecal coliforms bacteria as well as *E. coli* and *S. aureus* in broiler chicken breasts at 3°C [82]. Also, this organic acid could significantly ($P < 0.05$) reduce the TBARS and TVBN values compared to control samples, and the most pronounced reductions were provided by 2% lactic acid.

İlhak et al. [83] evaluated the effects of lactic acid or sodium lactate at 2 or 4% on psychrophilic bacteria and *Salmonella* spp. on chicken drumstick meats. In fact, spraying 4% lactic acid or 4% sodium lactate was most efficient than that applied with 2% concentration. In addition, the data showed immediate significant reductions of the *Salmonella* spp. counts by 1.3 and 1.1 $\log_{10}$ CFU/ml, respectively, and psychrophilic bacteria by 1.8 and 1.3 $\log_{10}$ CFU/ml, respectively, on chicken samples.

The application of lactic acid at 1% demonstrated interesting preservative effects on the quality of refrigerated chicken broiler fillets in terms of freshness (significant decrease of TVBN and TBARS values), great control of microbial parameters (reduction of total psychrotrophic bacteria and Enterobacteriaceae loads), and inhibition of biogenic amine formation which increase the acceptability of refrigerated chicken meat up to 12 and 15 days at 4°C [84].

Findings of a recent study [76] on the decontamination efficacy of formic acid (1.5%) and peroxyacetic acid (550 ppm) against *C. jejuni* growth in chicken wings stored at 4°C for 24 h by immersion and spraying indicated that acid treatments were effective in decreasing the *C. jejuni* counts regardless of the antimicrobial application method.

Therefore, considering all of the abovementioned applications of organic acids (lactic, citric, acetic, formic, malic, and tartaric acids) and their salts as shelf-life extenders and bioagents in the preservation of different meat matrices during refrigerated storage, it has been indicated that mostly the weak organic acids and their salts were commonly used in such purposes. In fact, these latter are the most well-studied agents, more effective than other organic acids/salts, more available and naturally abundant, and finally legislatively allowed to be applied with *quantum satis* which favour their use in meat industry to replace the commonly used and expensive chemical preservatives, ensure their safety, improve their quality, and safely extend their shelf-life. Table 5 summarises some research results found around the globe about applications of organic acids and their salts for the preservation of various meat systems.

4. Application Types

Organic acids and their salt application in several meat models to control the microbial growth could be realised using different methods: spraying, dipping, injection, and incorporation into bioactive packaging films.

4.1. Spraying, Dipping, and Injection. Spraying of meat products with organic acid/salt solutions was found to offer significant protection against several bacteria and fungi. This application method is usually used in the early steps of meat carcass processing: after hide removal and before or after evisceration, but before the carcasses are chilled [3]. Moreover, organic acid spray is typically applied as a rinse to the entire carcass surface. The most common types of organic acid spray solutions widely available for carcass decontamination rinses are acetic and lactic acids, as well as sodium lactate [66, 74, 79, 83]. To ensure the success of the antimicrobial rinse, several steps should be performed carefully. Firstly, the carcass should be washed from top to bottom with warm water, followed by a five-minute dip. Then the organic acid/salt solution should be applied from top to bottom in two passes with a spray nozzle within 12 inches of the carcass surface, using a gentle sweeping motion, to cover the carcass completely (organic acid dip is a sign that the surface is saturated with organic solution).

Organic acid dipping represents another application type aiming to preserve microbial and sensory qualities of different meat matrices. It consists of immersion of the meat samples into organic acid/salt solutions at adequate concentrations for a time period (in minutes) [76]. Of the organic acids/salts evaluated in the literature, lactic, citric, and malic acids have been the most widely accepted as antimicrobial dip solution [85].

On the other hand, solutions of organic acids/salts could be injected into meat using a needle and syringe to improve its microbial, physicochemical, and sensory quality properties [86].

4.2. Incorporation of Organic Acids/Salts in Bioactive Packaging Films. Innovative concept of antimicrobial packaging has been introduced as a response to market trends and consumer desire. It consists of an active packaging where the antimicrobial agents are incorporated into the package material and from there migrate into the food through diffusion and partitioning. Direct incorporation of organic acids/salts as preservatives into bioactive packaging (by extrusion, compression moulding, casting, or coating) is an advanced technology responding to many problems and an economical method for manufacturing antimicrobial packaging. Effectively, they were proposed to overcome the loss of organic acid/salt activity when directly applied into meat samples due to the interaction with meat components (e.g., fat, skin, and enzymes). These techniques depend on the release of such acidic agents from the packaging to the meat matrix, thus avoiding direct contact with the meat product which responds to the consumer desire of having safe meats free of preservatives or with few or natural ones. However, it is important to keep in mind that there is always a dose-effect relation, so preservative agents should be applied in sufficient amounts, to obtain high effect, which is furthermore dependent on the meat properties [6]. Furthermore, the thickness of the material and the storage conditions in terms of temperature and time should be properly taken into account as important factors on which depend the antimicrobial/preservative actions of the active packaging containing organic acids/salts.

Other possible methods for the application of organic acids include the use of edible antimicrobial films: this method has received attention as a potential intervention strategy against pathogens in various meat muscle samples [3]. These antimicrobial films were prepared by dissolving chitosan into hydrochloric acid and organic acid solutions such as formic, acetic, lactic, and citric acid solutions.

5. Combinations between Organic Acids/Their Salts and Other Antimicrobials or Preservation Methods

The main objective of the combinations between organic acids/salts with other control measures (chemical, physical, and biological treatments) is to obtain potent synergistic activities in terms of antimicrobial effect enhancement, sensory quality improvement, and meat shelf-life extending which is quite beneficial to meat industries.

5.1. Combination of Organic Acids/Their Salts with Chemicals. The most common practice previously applied in this context is the addition of sodium chloride (NaCl) salt with

Table 5: Applications of organic acid and their salts in meat preservation.

Meat products	Organic acid/salt	Concentration	Lipid and protein oxidation inhibition activity	Effective antimicrobial activity	Sensory attributes	Shelf-life extension	Reference
Raw beef during vacuum-packaged storage at 2°C for 21 days	Sodium lactate	3 g/kg	TBARS value not affected	Reduction of aerobic plate counts, psychrotrophic counts, LAB, Enterobacteriaceae	—	Up to 15 days against 8 days for control	[59]
Beef trimmings	Potassium lactate	3%	TBARS value not affected	—	Improvement of odour, taste, colour, tenderness, and cooking yield	—	[60]
Roast beef	Potassium lactate	2%	—	Decrease of *L. monocytogenes*, *Salmonella* spp.	—	—	[64]
Raw beef meat stored at 4°C	Lactic acid Acetic acid Sodium lactate Sodium acetate	1–2% 1–2% 2.5% 2.5%	—	Reduction of aerobic plate and psychrotrophic counts, Enterobacteriaceae	Improvement of colour, flavour, texture	Significant extension of shelf-life	[63]
Fresh ground pork stored at 2°C and −20°C	Sodium or potassium lactates	2%	TBARS value not affected	Enhancement of microbial stability	No negative effect on colour	15 days (at 2°C) and up to 70 days (at −20°C)	[71]
Pork frankfurters	Sodium lactate Sodium diacetate	1.8% 0.25%	—	Decrease of *L. monocytogenes*	No negative effect on flavour	—	[72]
Porcine carcasses	Lactic acid Acetic acid	3% 3%	—	Decline of psychrotrophs, *Pseudomonas* spp., Enterobacteriaceae, *Aeromonas* spp., *Yersinia* spp.	—	—	[75]
Chilled pork jowls	Formic acid	1.5%	—	Reduction of *Salmonella enterica*	—	—	[76]
Sheep “Buchada” meat	Citric acid	1%	Reduction of TBARS value	Reduction of *Salmonella* spp., Staphylococcus spp., and thermotolerant coliforms	No negative effect on odour, flavour, appearance, and tenderness	—	[57]
Marinated chicken thighs stored at 4°C for 15 days	Lactic acid Sodium lactate	0.2–1% 1–3%	Reduction of TVBN contents	Reduction of aerobic and psychrophilic bacteria, Enterobacteriaceae, *Salmonella* spp., *S. aureus*, and *Pseudomonas* spp.	Improvement of odour, flavour, colour, and texture	Significant extension of shelf-life	[81]
Refrigerated chicken Bologna	Potassium lactate	2%	—	Decrease of *L. monocytogenes* and *Salmonella* spp.	—	Until 49 days	[64]
Broiler chicken breasts chilled at 3°C	Lactic acid	1 or 2%	Reduction of TVBN and TBARS values	Reduction of aerobic mesophilic bacteria, psychrotrophic counts, coliforms and faecal coliforms, *E. coli,* and *S. aureus*	—	Significant extension of shelf-life	[82]
Chicken broiler fillets refrigerated at 4°C	Lactic acid	1%	Decrease of TVBN and TBARS values	Decrease of total psychrotrophic bacteria and Enterobacteriaceae	Inhibition of biogenic amine formation	Up to 12 and 15 days	[84]

some organic acids or organic acid salts [3]. Effectively, Tan and Shelef [71] indicated that the combinations of sodium lactate or potassium lactate at 2% with NaCl at 1 or 2% were more effective than lactates alone at 2% in inhibiting the growth of spoilage microorganisms on refrigerated fresh ground pork meat. In addition, these combinations improved the fat stability by reducing the prooxidant effects of NaCl and significantly enhanced the red colour of meat after their immediate addition.

Sallam and Samejima [59] reported that the combination (20 + 20 g/kg) of sodium lactate and NaCl on raw ground beef could be successfully used to reduce the growth of aerobic plate, psychrotrophic, LAB, and Enterobacteriaceae counts, maintain its physicochemical quality by reducing the oxidative changes caused by NaCl, and considerably prolong its shelf-life during refrigerated storage to 21 days compared to control (only 8 days).

Furthermore, it was reported by Entani et al. [87] that the application of acetic acid in the form of vinegar with NaCl resulted in a great synergistic effect towards the inhibition of *E. coli* O157:H7. This antimicrobial activity was explained by the fact that NaCl induced *E. coli* O157:H7 sensitivity to the acid environment. Indeed, it was stated by Casey and Condon [88] that NaCl decreases the antimicrobial activity of lactic acid on this tested pathogen by increasing its cytoplasmic pH. Hence, the presence of NaCl protected *E. coli* O157:H45 against the inhibitory effect of acid pH. This aspect seems to be of considerable importance in food safety as it falls in the abovementioned resistance mechanisms of some microorganisms (such as the case of *E. coli* O157:H45) to counteract acidification, escape to the bactericidal effect of the used organic acid, and cause illnesses by surviving in the food product.

Otherwise, some other preservation methods that are safer and more effective could be proposed to meat industry. In fact, it was indicated by Barmpalia et al. [89] that the combination of 1.8% sodium lactate + 0.125% sodium diacetate + 0.125% glucono-delta-lactone (GDL) significantly inhibited the growth of *L. monocytogenes* and spoilage LAB in pork Bologna meats stored at 4 or at 10°C as a mildly abusive storage temperature. Furthermore, Jo et al. [90] reported that combined treatments of silver ion (at 0.1 or 0.3 or 0.5 or 1 ppm) with (0.05% or 0.1%) organic acid (lactic or citric or succinic or maleic or tartaric) enhanced the inhibitory effect of *E. coli* O157:H7 and the more effective combination was 1 ppm silver ion +0.1% organic acid.

5.2. Combinations of Organic Acids Together, or Organic Salts Together or Organic Acids with Organic Salts. The use of mixtures containing different organic acids together or formulations with several organic acid salts together or combinations of organic acids with their organic salts could also be useful technological strategies in enhancing not only the antimicrobial activity but also preservative effect on the treated meat product.

For instance, the combinations of 2.5% sodium lactate +0.3% diacetate and 2.5% sodium lactate +0.1% diacetate provided significant antilisterial activity on turkey slurries stored at 25°C and 4°C, respectively, compared to treatments containing sodium lactate or diacetate alone [91].

Then, it was reported by Mbandi and Shelef [92] that synergistic effect between sodium lactate and sodium diacetate on microbial growth occurred in beef meat. Indeed, the combination of sodium lactate and sodium diacetate, respectively, at 2.5 and 2%, was bacteriostatic to *L. monocytogenes* and bactericidal to *Salmonella* Enteritidis after 20 days of beef storage at 10°C. On the other hand, 1.8% sodium lactate +0.1% sodium diacetate provided a listeriostatic effect, while the *Salmonella* counts were less than 10 cells/g after 30 days of refrigerated storage at 5°C. In addition, antimicrobial activity against both tested pathogens was strongly enhanced by the application of 0.2% sodium acetate in combination with 1.8 or 2.5 % sodium lactate.

Later, Mbandi and Shelef [93] stated similar results regarding the rapid and efficient decrease of *Salmonella* counts in beef Bologna meat when lactate and diacetate were combined and applied as meat preservative formulation.

Furthermore, it has been demonstrated that a spray washing method with 2% lactic acid + 1.5% propionic acid or 1.5% acetic acid + 1.5% propionic acid combinations remarkably declined total viable counts to undetectable levels during storage of fresh sheep/goat meats compared to the single acid treatments [94]. Added to that, the shelf-life of meat samples treated with the binary organic acids combinations was increased to 11 days *versus* 3 days in untreated meats.

On the other hand, in a study undertaken by Juneja and Thippareddi [95], it was indicated that the combinations of sodium diacetate with sodium lactate, or sodium acetate or buffered sodium citrate significantly inhibit the germination and outgrowth of *C. perfringens* from spores in processed chilled turkey products.

Barmpalia et al. [72] evaluated the control of *L. monocytogenes* on refrigerated pork frankfurters by applying a combination containing 1.8% sodium lactate and 0.125% or 0.25% sodium diacetate followed or not by a dipping in 2.5% lactic acid or acetic acid solutions. The findings revealed that the combinations with acid dipping resulted in marked reductions of *L. monocytogenes*, LAB, yeasts, and moulds populations, with highest antimicrobial effects (complete inhibition) shown with 0.25% sodium diacetate over 12 days. In addition, using sodium lactate and sodium diacetate in combination, with or without organic acid dipping, did not affect the flavour and the overall acceptability of pork products compared to controls.

Similarly, Barmpalia et al. [89] indicated that 1.8% sodium lactate + 0.25% sodium diacetate combination controlled the proliferation of *L. monocytogenes* and spoilage LAB in refrigerated pork Bologna more effectively than the treatments when the organic acid salts were used as single antimicrobial agent.

Drosinos et al. [96] highlighted enhanced inhibitory activity against spoilage flora in both culture medium and cured cooked meat products when two or three organic acid salts were combined together as follows: 2% sodium lactate + 0.5% sodium acetate, 2% sodium lactate + 0.15% potassium sorbate, and 2–4% sodium lactate + 0.5% sodium acetate + 0.15% potassium sorbate.

Likewise, the combination of citric, malic, and tartaric acids at 150 mM strongly reduced the growth of *E. coli* O157: H7, *L. monocytogenes*, and *Salmonella typhimurium* populations by $>5>2$ and 4–6 log CFU/g and significantly extended the shelf-life of chicken breast pieces [80].

In addition, Samoui et al. [81] found that the combination of 0.9% sodium lactate and 0.09% lactic acid is the most effective in delaying the proliferation of spoilage bacteria (aerobic plate counts, psychrotrophic populations, Enterobacteriaceae, *Pseudomonas* spp., *S. aureus*, and *Salmonella* spp.), preventing the generation of undesirable chemicals (TVBN), improving the sensory quality of chicken meats (highest scores for the colour, flavour, and texture), and extending the shelf-life during chilled storage.

Recently, it has been found that the combinations of 1.5% acetic acid + 400 ppm peroxyacetic acid and 1.5% formic acid + 400 ppm peroxyacetic acid were highly effective in declining the *Salmonella* counts on chicken wings, while *C. jejuni* were mostly sensitive to the combination containing 1.5% formic acid + 550 ppm peroxyacetic acid [76].

5.3. Combinations of Organic Acids/Their Salts with Bacteriocins. Schlyter et al. [91] reported that diacetate at 0.3 or 0.5% combined with pediocin (5000 AU/ml) provided a listericidal effect on turkey slurries at 4°C and 25°C, respectively.

Acetic acid at 3 or 5 g/100 ml, or sodium diacetate at 3 or 5 g/100 ml, or potassium benzoate at 3 g/100 ml combined with nisin (5000 IU/ml) as dipping solutions have been described to cause an important reduction of *L. monocytogenes* populations in sliced cured pork Bologna meats with a significant increase of their shelf-life for 90–120 days [32].

Khalafalla et al. [82] studied the combination of lactic acid (1%) with nisin at 50 μg or 100 μg strongly improved the microbial (aerobic mesophilic, aerobic psychrophilic, coliforms, faecal coliforms, *E. coli*, and *S. aureus* counts) and physicochemical (pH, TBARS) qualities of chicken breast samples and significantly extended their shelf-life to 12 days during refrigerated storage at 3°C.

5.4. Combinations of Organic Acids/Their Salts with Essential Oils or Aromatic/Phenolic Compounds Obtained from Plants. In this line, de Souza et al. [97] reported that the combined application of *Origanum vulgare* L. essential oil (MIC × ½: 0.3 μl/ml) and acetic acid (MIC × ½: 0.3 μl/ml) inhibited the growth of *S. aureus* populations on bovine meat steaks.

İlhak et al. [83] proposed an effective technological concept against the proliferation of undesirable bacteria in refrigerated chicken drumstick samples consisting of the combination between lactic acid (4%) + thymol (0.25%, w/v) applied by spraying method. The results showed a significant and immediate decline of *Salmonella* spp. and psychrophilic numbers by 1.4 and 1.8 $\log_{10}$ CFU/ml on day 0, respectively, with an interesting pH stability of the meats during the refrigerated storage at 4°C as compared to treatments with lactic acid or thymol alone. Indeed, the synergistic antimicrobial effect of these two antimicrobials could be explained by the fact that the phenolic compound thymol could contribute to facilitating the diffusion of lactic acid into the microorganism's cytoplasm through disintegration of its outer membrane, thus increasing the permeability of the cytoplasmic membrane [98]. However, the use of thymol (or other aromatic compounds such as eugenol, carvacrol, geraniol, and citral) at higher concentrations, when they are applied individually for sufficient antimicrobial activity, could negatively affect the meat flavour, thus being unacceptable to consumers. That is why combinations of essential oils with other preservative agents in meats (such as organic acids/salts) have been applied to strongly minimise the application concentrations required.

Recent research by Gómez-García et al. [16] reported similar results concerning the enhancement of antimicrobial effects towards swine *Salmonella* spp. for formic acid-carvacrol and formic acid-thymol binary combinations.

Finally, it is quite important to mention that the combination of more than two antimicrobials is also possible to achieve preservative efficacy of tested meat systems by either synergistic or additive effects and therefore ensure both safety and quality of meat products. In this context, Ghabraie et al. [99] tested the antilisterial effects of antibacterial formulations containing organic acid salts, essential oils, nisin, and nitrite combined at different concentrations in fresh beef and fresh pork sausages. The results demonstrated that the formulation A (mixed organic acid salts: sodium acetate and potassium lactate at 1.55% (w/w)) + mixed Chinese cinnamon and cinnamon bark essential oils (EO) at 0.05% (v/w) + nisin at 12.5 ppm + nitrite at 100 ppm) and formulation B (mixed organic acid salts (1.55%, w/w) + mixed EOs (0.025%, v/w) + nisin (12.5 ppm) + nitrite (100 ppm)) remarkably ($P < 0.05$) reduced *L. monocytogenes* numbers. The two formulations (A and B) were also organoleptically (texture, smell, and taste) accepted in both fresh pork and beef sausages.

5.5. Combinations of Organic Acids/Their Salts with Plant Extracts. The antimicrobial effectiveness of the combination between tartaric acid (37.5 mM) and grape seed (GS) or green tea (GT) extracts (at 5 or 10 or 20 or 40 mg/ml) was studied by Over et al. [80]. The findings revealed that all binary combinations strongly decreased the numbers of *Salmonella typhimurium*, *L. monocytogenes*, and *E. coli* O157:H7. However, these high antibacterial activities of tartaric acid combined with GS or GT were observed in BHI broths, and it was suggested to assess the effect of the highest antimicrobial combination on microbial, physicochemical, and organoleptic properties of poultry meat system (chicken breasts).

The study of Kim et al. [100] was conducted to improve the quality of cured pork loin with a combination of an organic acid (ascorbic, malic, citric, or tartaric acids) at 0.06% and fermented spinach (FS) as green nitrite source at 0.08%. The results showed that cured pork meats treated with fermented spinach (natural nitrite) with each organic acid possessed higher redness values than control on cooked meat. In addition, all combinations significantly reduced the lipid oxidation (TBARS and TVBN) except the citric acid when combined to FS. Among the combinations, ascorbic acid + FS was found to provide the highest efficacy on quality attributes of cured pork meat samples.

5.6. Combinations of Organic Acids/Their Salts with Bacteriophages. Wang et al. [34] stated in their recent study that the combination of potassium sorbate (2 mg/g) + nisin (5000 IU/g) + bacteriophage (9 log PFU) significantly reduced *Salmonella* counts, total viable counts, TVBN, and TBARS on fresh chilled pork. In addition, this combination strongly reduced odour and maintained good organoleptic properties of fresh pork meat, thus extending its shelf-life up to 14 days. It has been shown too that no adverse effect of the phage on meat samples was observed.

Otherwise, Shebs et al. [101] evaluated the effect of the combination between peroxyacetic acid (PAA, 400 ppm) and bacteriophage (P, 7 MS phages at 10^8 PFU/ml) against Shiga toxin-producing *E. coli* (STEC) (O157:H7 and O145, O121, O111, O103, O45, and O26) on beef meat. The findings showed that this combination led to a significant STEC reduction by 1.49 log compared to control and treatment with PAA alone.

5.7. Combinations of Organic Acids/Their Salts with High Pressure Processing (HPP). Similarly, Rodríguez-Calleja et al. [102] have demonstrated the synergetic effect of a mix of organic acids (lactic and acetic acids + sodium diacetate) and HPP (300 MPa) in extending the shelf-life of skinless chicken breast fillets up to 28 days. A remarkable maintain of the microbiological quality (total viable counts, LAB, coliforms, *E. coli*, *Pseudomonas*, and *Brochothrix thermosphacta*) and sensory properties (colour, tenderness, and overall acceptability) was reported.

Recently, O′ Neill et al. [103] evaluated the effectiveness of a combination between 0.3% of the commercial mix of organic acids named Inbac^{TM} (mainly composed of 43% sodium acetate and 7% malic acid and other fatty acids and technological coadjuvants) and high HPP as preservative technique to extend the shelf-life of frankfurters and cooked ham. As a result, it has been observed that the combinations of HPP at 580 MPa or 535 MPa for 5 min and 0.3% Inbac^{TM} organic acid mixture significantly decrease the total aerobic viable counts, total coliforms, *E. coli*, and *Salmonella* spp. in frankfurters and cooked ham, respectively. Hence, these combinations (organic acids + HPP) greatly extended the shelf-life of frankfurters by 51% and cooked ham by 97% compared to control samples from the microbiological point of view; however, no significant improvement effects were detected for physicochemical and sensory qualities in terms of pH and TBARS values, colour, flavour, off-flavour intensity, texture, juiciness, tenderness, saltiness, and overall acceptability.

5.8. Combinations of Organic Acids/Their Salts with Heat or Ultraviolet Light (UV). Some interventions such as pasteurization with steam or hot water combined with organic acid solutions were among the advanced processes to improve the meat safety that resulted in more effective reductions of spoilage and pathogenic microorganisms on meat carcasses or meat end-products [104].

On the other hand, it was reported that, under vacuum and aerobic conditions, the application of peroxyacetic acid (PAA, 400 ppm) in combination with ultraviolet light (UV, 30 s at 2.5 ± 0.3 cm height) provided high STEC reductions on beef meat samples compared to the results obtained with samples treated only with 400 ppm PAA [101].

5.9. Combinations of Organic Acids/Their Salts with Modified Atmosphere Packaging (MAP) or Bioactive Packaging Films. Regarding MAP preservation technique, it has been shown previously that application of 1% acetic acid solution combined with MAP in a 70% CO_2/30% N_2 on chicken breasts portions reduced microbial growth and maintained pleasant flavour at the end of the storage period (21 days at 4°C) [105].

Likewise, the microbial stability (total viable counts, LAB, coliforms, *E. coli*, *Pseudomonas*, and *Brochothrix thermosphacta*) of fresh chicken breast fillets was significantly enhanced by the combination between a commercial organic acid mixture composed principally of lactic acid, acetic acid, and sodium acetate, and MAP (30% CO_2/70% N_2) [102]. Hence, a prolongation of shelf-life was observed to be two weeks *versus* one week for untreated chicken fillets. Besides, in this same study, it was shown that the organic acids + MAP (30% CO_2/70% N_2) + HPP (300 MPa) combination was the most efficient preservative strategy in inhibiting spoilage bacteria, maintaining organoleptic attributes in high scores, and extending the shelf-life of chicken samples.

Otherwise, organic acids/salts could be incorporated, alone or in combination, in bioactive packaging (by extrusion, compression moulding, casting, or coating) as advanced antimicrobial application in meat industry. According to the published literature, the incorporation of organic acids/salts during the extrusion or plastic compressing moulding is the most economical technique since it did not require additional processing steps [6]. However, the applicability of this approach is not feasible with all organic acids/salts as some of them are characterised by a liquid state at room temperature or by heat sensitivity. Hence, it has been indicated that sorbic acid and potassium sorbate are the commonly used agents into such packaging. Occasionally, some issues could be encountered regarding the direct incorporation of organic acid/salts into packaging. For instance, incompatibility between the organic acid/salt and some biopolymers (low-density polyethylene (LDPE) or linear low-density polyethylene (LLDPE)) could be happened leading to the loss of antimicrobial effect [106], or causing loss of transparency of biofilms after extrusion [6]. For this reason, their indirect incorporation by casting or coating was suggested.

Regarding the inclusion of organic acids/slats into packaging films by casting, nonpolar polymers (e.g., polyethylene and cellulose polymers) and polar polymers (starch, alginate, chitosan, and carrageenan) could be used in the process [6]. In fact, Limjaroen et al. [33] reported a marked *L. monocytogenes* inhibition for up to 28 days in refrigerated beef Bologna sausages packed with polyvinylidene chloride (nonpolar) films containing 1.5% sorbic acid. Furthermore, Zinoviadou et al. [107] indicated that total viable counts and *Pseudomonas* spp. populations were significantly reduced on fresh beef cut portions stored at 5°C for 12 days in whey protein (polar) films containing 2% sodium lactate. Similarly, da Rocha et al. [29] showed that protein-based films containing 1.5% sorbic or benzoic acid are strongly efficient to decline *E. coli* and *L. monocytogenes* counts by 5–6 log-cycles on meat samples stored at 5°C for 12 days.

Concerning the incorporation of organic acids/slats into packaging films by coating, it has been shown by Hauser and Wunderlich [108] that sorbic acid coating incorporated in polyvinyl acetate lacquer on LDPE films strongly decreased *E. coli* counts in pork loin meats stored at 8°C up to 7 days.

On the other hand, it could be important to mention the existence of other rare techniques used for incorporating organic acids into polymer films such as the immersion of polyamide films into solution of lactic acid followed by a drying step as performed by Smulders et al. [109]. These films were effective in inhibiting the growth of *E. coli* O157: H7 on refrigerated fresh beef cuts by 1 log-cycle, reaching a final 2 log reduction after 14 days.

Therefore, all of these organic acid-based antimicrobial packaging systems seem to be low-cost technologies and easy to apply which makes them a promising additional approach useful in meat preservation. Moreover, the use of such active packaging is regulated in Europe by the Regulation (EC) No. 450/2009 on Active and Intelligent Materials [110] and the organic acids/salts used to be incorporated into antimicrobial packaging films for release into food (such as meat) have to be listed as food preservative agents in the Regulation (EC) No. 1333/2008 on Food Additives which also regulates their migration limits [8]. Finally, concerning the labelling of antimicrobial additives (such as organic acids/salts) in food packaging materials, the Regulation (EC) No. 450/2009 (article 11) declares that every released active substance is imperatively considered as a food ingredient and must be declared accordingly [110].

6. Limits of Organic Acids and Their Salts Use in Meat Biopreservation

The main purpose of organic acids and their salts use as preservative agents in meat and meat products was to control the growth of spoilage and pathogenic bacteria and extend the shelf-life of meat products without causing sensory changes. However, it is well known that the concentrations of organic acids/salts applied to obtain efficient antimicrobial activity in meats should be higher than those used in laboratory media. Hence, this increase in concentrations could dramatically change the sensory quality (colour, odour, flavour, and taste) of meat samples [19].

Otherwise, the insufficiency or lack of antimicrobial/preservative effect of organic acids and their salts added to meat and meat products could depend not only on the concentration parameter but also on possible interferences between the meat matrix, via its intrinsic parameters (nonhomogeneous, moisture content, pH relatively high, high content of protein and fat, and quantity and types of occurred microorganisms), and the used acid antimicrobials which represent a further concern associated with the application of organic acids and their salts in meat.

Another limit that could also be mentioned here is the incompatibility between organic acids/salts and other inoculated antimicrobial or preservative agents in meats. For this reason, strict assessments of this aspect should be carefully performed before such applications. In addition to this, despite the fact that organic acids have been proven for many years to be effective as biopreservatives in meat industry, there is increasing indication that some microorganisms possess various mechanisms to counteract the effects of such acid agents, thus allowing for resistance to antimicrobial activity and/or to severe acidic conditions [3, 6]. Therefore, it has been noted that this fact resulted in the emergence of acid-tolerant food-borne pathogens [111]. In fact, resistance mechanisms are known to be stress mechanisms at the cellular activity level implicating, for example, the expression of specific stress-response genes. For instance, *E. coli*, *Salmonella typhimurium*, and *L. monocytogenes* have the possibility to develop cells inducing acid tolerance response (ATR) mechanisms at low pH levels after preliminary adaptation at moderately acidified conditions [6]. These acid-adapted cells are more resistant and so more infective under stress conditions. Other acid-tolerant microorganisms developed cross-resistance to other environmental stresses such as salt, osmosis, and heat [3]. On the other hand, some other microorganisms (e.g., *P. aeruginosa*, *Aspergillus* spp., and *Penicillium roqueforti*) exhibit different counteracting mechanisms towards organic acids/salts which could be degraded by some bacterial or fungal enzymes [3, 6, 112]. These enzymatic degradations could thus unfavourably affect the organoleptic characteristics of meats. Otherwise, the yeast species of *Zygosaccharomyces bailii*, which is known to be more resistant to organic acids than *S. cerevisiae*, was able to reduce the diffusion of weak organic acids across the membrane by adjusting its cell envelop confirmation [113, 114].

Furthermore, although there are wide numbers of potent organic acids and salts newly characterised for their effectiveness as powerful natural preservatives (other than the most frequently used ones in meat industry until now), relatively few ones are suitable in practice and so are legally approved as preservatives in meats by international food legislations to become commercially used. This could be mainly explained by the strict requirements taken from regulatory agencies prior to final approval of possible use of an organic acid/salt in meat products. Effectively, this process implicates detailed data regarding the functionality, the application method, and the safety aspects of the proposed organic acid/salt. Unfortunately, this approval procedure is very time-consuming because of its complexity in collecting all of these informative data after performing numerous *in vitro* and *in vivo* studies that could take many years and could also be expensive which limits the use of new organic acids/salts in meat biopreservation.

Besides, it is important to mention in this context that food legislation continued to restrict both changes in allowed organic acid/salt levels in meats even after completing rigorous studies and the use of some newly accepted ones as preservatives. For instance, despite regulatory approval, some organic acids/salts are not widely accepted in commercial practice particularly in meat decontamination. In fact, meat hygiene regulations within the European Union (EU) do not permit any method of decontaminated formulations other than washing meat carcasses with potable water [3]. A very good example of this is the peroxyacetic acid (also known as peracetic acid or PAA) which is approved in the United States and Australia and prohibited in the EU [115].

Moreover, despite the GRAS status of the organic acids/salts legislatively approved as food preservative agents, their innocuousness still raises questions regarding undesirable toxicological effects on human health after ingestion of meat products treated with these bioagents. In fact, according to the literature, some *in vitro* and *in vivo* studies on the toxicity of sorbic and benzoic acids and/or salts revealed no mutagenic, genotoxic, and/or carcinogenic effects, while some other researchers reported genotoxic effects of the two mentioned acids as well as their sodium and potassium salts [6]. This controversial safe status is not the case for lactic, citric, or propionic acids, maybe because they are natural intermediates of plants, animal, and human metabolisms, thus suggesting their harmlessness. Hence, this dual trait of being sometimes innocuous and sometimes toxic raises a great worry and a big issue regarding the use of organic acids/salts in meat preservation since a final elucidation about their toxicity is not yet established. Deep research is strongly recommended in this way.

Finally, it is quite important to notice that data on the effectiveness of organic acids and their salts applied in actual commercial practice for meat preservation are limited which are of glaring need to evaluate their continued efficiency basing on recent circumstances and to accurately improve their sustainability.

For these reasons, it is almost indisputable that, in some cases, the use of the commonly approved organic acids or their salts solely applied in meats could not result in sufficient or desired preservative effects. Consequently, to enhance their efficacy in meat preservation, their application in combination with other antimicrobials (organic acids, organic acid salts, proteins, bacteriocins, bacteriocinogenic LAB, plant extracts, essential oils, nanoparticles, bacteriophages, etc.), or chemicals (e.g., salts: NaCl) or diverse physical techniques (pressure, UV, hot water, pasteurization with steam, MAP, and bioactive packaging) is strongly recommended. These promising preservation strategies could open new pathways and opportunities for the successful use of efficient, safe, and cost-effective preservative formulations in meat preservation.

7. Conclusion

This review highlights the interesting attributes of organic acids and their salts as natural antimicrobials with high preservative effects in meat industry based on several conducted studies and published research, making them innovative bioagents instead of chemical preservatives. In fact, it has been demonstrated that the organic acids/salts are GRAS agents (when used in respect to the specified amounts) approved by EU legislation as preservatives (and other categorised technological agents: acidifiers, antioxidants, colour stabilisers, flavour enhancers, etc.) useful for meat applications (and other food matrices). These bioagents could strongly ensure the overall safety of meat products. They could inhibit or delay a wide range of spoilage and pathogenic microorganisms, improve the physicochemical properties of meats (TBARS, TVBN, and pH reductions), and improve their organoleptic attributes (stability of red colour, enhancement of flavour, suppression of rancidity and undesirable off-odour, inhibition of slime formation and gas production, improvement of tenderness and juiciness, etc.). In addition, it is important to keep in mind that the use of organic acids/salts as biopreservatives will not replace good manufacturing and hygienic practices and procedures.

However, despite all of these advantages, it has been shown, until now, that relatively few organic acids/salts are suitable in practice. Why? To answer this key question, many studies have been worldwide undertaken, and laboratory tests on food indicated the existence of possible problem areas regarding the effectiveness of organic acids/salts in meat biopreservation due to several factors implicating organic acid/salt characteristics (form, concentration, antimicrobial activity, etc.), meat (type, composition, microbial loads, pH, A_w, etc.), and environmental conditions (temperature, humidity, storage, packaging, etc.). In addition, extensive use of organic acids could result in bacterial adaptation, making some microorganisms acid-tolerant and resistant in some other ways, which represent challenges for their use as food preservatives, particularly in meats. This dilemma regarding the organic acids/salts dual trait of being sometimes good preservative agents and sometimes not suggests strict *in vitro* and *in vivo* assessments in terms of antimicrobial activity, preservative effects on physicochemical and sensory qualities, shelf-life prolongation, and safety aspects to accurately select efficient candidates, and much more importantly, well-adapted agents to each meat type where they will be applied. Moreover, it is crucial to achieve a better understanding of how pathogens or spoilage microorganisms respond to organic acids/salts when added to meat to develop optimal solutions and overcome related issues. Therefore, combinations of organic acids/salts with other control or preservative techniques (chemical, physical, and biological) were proposed to design improved preservation strategies based on potent synergistic activities or additional effects that could benefit the meat industries at cost level and meet the modern consumer trends for safe and “bio” meat products.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] A. Lucera, C. Costa, A.. , C. Conte, and M. A. Del Nobile, "Food applications of natural antimicrobial compounds," *Frontiers in Microbiology*, vol. 3, pp. 287–301, 2012.

[2] D. Rai, A. S. Adelman, W. Zhuang, G. P. Rai, J. Boettcher, and B. Lönnerdal, "Longitudinal changes in lactoferrin concentrations in human milk: a global systematic review," *Critical Reviews in Food Science and Nutrition*, vol. 54, no. 12, pp. 1539–1547, 2014.

[3] M. M. Theron and J. F. R. Lues, "Organic acids and meat preservation: a review," *Food Reviews International*, vol. 23, no. 2, pp. 141–158, 2007.

[4] P. M. Davidson, H. B. Cekmer, E. A. Monu, and C. Techathuvanan, "The use of natural antimicrobials in food: an overview," *Handbook of Natural Antimicrobials for Food Safety and Quality*, pp. 1–27, 2015.

[5] M. B. Jamilah, K. A. Abbas, and R. A. Rahman, "A review on some organic acids additives as shelf life extenders of fresh beef cuts," *American Journal of Agricultural and Biological Sciences*, vol. 3, no. 3, p. 566574, 2008.

[6] C. Hauser, J. Thielmann, and P. Muranyi, "Organic acids: usage and potential in antimicrobial packaging," in *Antimicrobial Food Packaging*, pp. 563–580, Academic Press, Cambridge, MA, USA, 2016.

[7] M. M. Theron and J. R. Lues, *Organic Acids and Food Preservation*, CRC Press, Boca Raton, FL, USA, 2010.

[8] European Commission, "Regulation (EC) No 1333/2008 of the European parliament and of the council of 16 december 2008 on food additives," *Official Journal of the European Communities*, vol. 50, p. 18, 2008.

[9] A. J. Pellissery, P. G. Vinayamohan, M. A. R. Amalaradjou, and K. Venkitanarayanan, "Spoilage bacteria and meat quality," in *Meat Quality Analysis*, pp. 307–334, Academic Press, Cambridge, MA, USA, 2020.

[10] A. Bonetti, B. Tugnoli, B. Rossi, G. Giovagnoni, A. Piva, and E. Grilli, "Nature-identical compounds and organic acids reduce *E. coli* K88 growth and virulence gene expression *in Vitro*," *Toxins*, vol. 12, no. 8, pp. 468–479, 2020.

[11] M. H. Hounhouigan, A. R. Linnemann, M. M. Soumanou, and M. A. J. S. Van Boekel, "Effect of processing on the quality of pineapple juice," *Food Reviews International*, vol. 30, no. 2, pp. 112–133, 2014.

[12] B. S. Chanukya, M. Prakash, and N. K. Rastogi, "Extraction of citric acid from fruit juices using supported liquid membrane," *Journal of Food Processing and Preservation*, vol. 41, no. 1, Article ID e12790, 2017.

[13] V. Okatan, "Antioxidant properties and phenolic profile of the most widely appreciated cultivated berry species: a comparative study," *Folia Horticulturae*, vol. 32, no. 1, pp. 79–85, 2020.

[14] I. Nuryana, A. Andriani, and P. Lisdiyanti, "Analysis of organic acids produced by lactic acid bacteria," in *IOP Conference Series: Earth and Environmental Science*vol. 251, no. 1, IOP Publishing, Article ID 012054, 2019.

[15] L. Kovanda, W. Zhang, X. Wei et al., "In vitro antimicrobial activities of organic acids and their derivatives on several species of gram-negative and gram-positive bacteria," *Molecules*, vol. 24, no. 20, pp. 3770–3385, 2019.

[16] M. Gómez-García, C. Sol, P. J de Nova et al., "Antimicrobial activity of a selection of organic acids, their salts and essential oils against swine enteropathogenic bacteria," *Porcine Health Management*, vol. 5, no. 1, pp. 1–8, 2019.

[17] S. Stanojević-Nikolić, G. Dimić, L. Mojović, J. Pejin, A. Djukić-Vuković, and S. Kocić-Tanackov, "Antimicrobial activity of lactic acid against pathogen and spoilage microorganisms," *Journal of Food Processing and Preservation*, vol. 40, no. 5, pp. 990–998, 2016.

[18] A. El Baaboua, M. El Maadoudi, A. Bouyahya et al., "Evaluation of antimicrobial activity of four organic acids used in chicks feed to control *Salmonella* Typhimurium: suggestion of amendment in the search standard," *International Journal of Microbiology*, vol. 2018, Article ID 7352593, 9 pages, 2018.

[19] E. Mani-López, H. S. García, and A. López-Malo, "Organic acids as antimicrobials to control *Salmonella* in meat and poultry products," *Food Research International*, vol. 45, no. 2, pp. 713–721, 2012.

[20] A. Guimarães, A. Venancio, and L. Abrunhosa, "Antifungal effect of organic acids from lactic acid bacteria on *Penicillium nordicum*," *Food Additives & Contaminants: Part A*, vol. 35, no. 9, pp. 1803–1818, 2018.

[21] R. Hassan, S. El-Kadi, and M. Sand, "Effect of some organic acids on some fungal growth and their toxins production," *International Journal of Advanced Biological and Biomedical Research*, vol. 2, no. 1, pp. 1–11, 2015.

[22] M. Selwet, "Effect of organic acids on numbers of yeasts and mould fungi and aerobic stability in the silage of corn," *Polish Journal of Veterinary Sciences*, vol. 11, no. 2, pp. 119–123, 2008.

[23] M. Raftari, F. A. Jalilian, A. S. Abdulamir et al., "Antibacterial activity of organic acids on *Salmonella* and *Listeria*," *Asia Life Sciences*, vol. 21, no. 1, pp. 13–30, 2012.

[24] S.-H. Park, M.-R. Choi, J.-W. Park et al., "Use of organic acids to inactivate *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* on organic fresh apples and lettuce," *Journal of Food Science*, vol. 76, no. 6, pp. M293–M298, 2011.

[25] D. E. Conner, J. S. Kotrola, W. B. Mikel, and K. C. Tamblyn, "Effects of acetic-lactic acid treatments applied to beef trim on populations of *Escherichia coli* O157:H7 and *Listeria monocytogenes* in ground beef," *Journal of Food Protection*, vol. 60, no. 12, pp. 1560–1563, 1997.

[26] M. R. Rosmini, F. Perlo, J. A. Pérez-Alvarez et al., "TBA test by an extractive method applied to 'paté'," *Meat Science*, vol. 42, no. 1, pp. 103–110, 1996.

[27] R. L. Buchanan and M. H. Golden, "Interaction of citric acid concentration and pH on the kinetics of *Listeria monocytogenes* inactivation," *Journal of Food Protection*, vol. 57, no. 7, pp. 567–570, 1994.

[28] M. Nielsen and N. Arneborg, "The effect of citric acid and pH on growth and metabolism of anaerobic *Saccharomyces cerevisiae* and *Zygosaccharomyces bailii* cultures," *Food Microbiology*, vol. 24, no. 1, pp. 101–105, 2007.

[29] M. d. Rocha, M. R. Loiko, E. C. Tondo, and C. Prentice, "Physical, mechanical and antimicrobial properties of Argentine anchovy (*Engraulis anchoita*) protein films incorporated with organic acids," *Food Hydrocolloids*, vol. 37, pp. 213–220, 2014.

[30] M. R. Mecteau, J. Arul, and R. J. Tweddell, "Effect of organic and inorganic salts on the growth and development of *Fusarium sambucinum*, a causal agent of potato dry rot," *Mycological Research*, vol. 106, no. 6, pp. 688–696, 2002.

[31] J. Samelis, J. N. Sofos, M. L. Kain, J. A. Scanga, K. E. Belk, and G. C. Smith, "Organic acids and their salts as dipping solutions to control *Listeria monocytogenes* inoculated following processing of sliced pork bologna stored at 4°C in vacuum packages," *Journal of Food Protection*, vol. 64, no. 11, pp. 1722–1729, 2001.

[32] J. Samelis, G. K. Bedie, J. N. Sofos, K. E. Belk, J. A. Scanga, and G. C. Smith, "Combinations of nisin with organic acids or salts to control *Listeria monocytogenes* on sliced pork bologna stored at 4°C in vacuum packages," *LWT - Food Science and Technology*, vol. 38, no. 1, pp. 21–28, 2005.

[33] P. Limjaroen, E. Ryser, H. Lockhart, and B. Harte, "Inactivation of *Listeria monocytogenes* on beef bologna and cheddar cheese using polyvinyl-idene chloride films containing sorbic acid," *Journal of Food Science*, vol. 70, no. 5, pp. M267–M271, 2005.

[34] C. Wang, J. Yang, X. Zhu, Y. Lu, Y. Xue, and Z. Lu, "Effects of *Salmonella* bacteriophage, nisin and potassium sorbate and their combination on safety and shelf life of fresh chilled pork," *Food Control*, vol. 73, pp. 869–877, 2017.

[35] O. Ben Braïek, P. Cremonesi, S. Morandi, S. Smaoui, K. Hani, and T. Ghrairi, "Safety characterisation and inhibition of fungi and bacteria by a novel multiple enterocin-producing *Enterococcus lactis* 4CP3 strain," *Microbial Pathogenesis*, vol. 118, pp. 32–38, 2018.

[36] M. Fourati, S. Smaoui, H. Ben Hlima, K. Elhadef, A. Chakchouk Mtibaa, and L. Mellouli, "Variability in phytochemical contents and biological potential of pomegranate (*Punica granatum*) peel extracts: toward a new opportunity for minced beef meat preservation," *Journal of Food Quality*, vol. 2020, Article ID 8853196, 14 pages, 2020.

[37] Y. Qian, L. Bian, K. Wang et al., "Preparation and characterization of curdlan/nanocellulose blended film and its application to chilled meat preservation," *Chemosphere*, Article ID 128948, 2020.

[38] R. J. da Costa, F. L. S. Voloski, R. G. Mondadori, E. H. Duval, and Â. M. Fiorentini, "Preservation of meat products with bacteriocins produced by lactic acid bacteria isolated from meat," *Journal of Food Quality*, vol. 2019, Article ID 4726510, 12 pages, 2019.

[39] M. Flores and F. Toldra, "Chemistry, safety, and regulatory considerations in the use of nitrite and nitrate from natural origin in meat products - invited review," *Meat Science*, vol. 171, Article ID 108272, 2021.

[40] U. Gonzales-Barrona, S. Coelho-Fernandesa, G. Santos-Rodriguesa et al., "Microbial deterioration of lamb meat from European local breeds as affected by its intrinsic properties," *Small Ruminant Research*, vol. 195, Article ID 106298, 2020.

[41] S. Roller, *Natural Antimicrobials for the Minimal Processing of Foods*, Elsevier, Amsterdam, Netherlands, 2003.

[42] A. McDermott, P. Whyte, N. Brunton, J. Lyng, J. Fagan, and D. J. Bolton, "The effect of organic acid and sodium chloride dips on the shelf-life of refrigerated Irish brown crab (*Cancer pagurus*) meat," *Lwt*, vol. 98, pp. 141–147, 2018.

[43] M. Stratford, G. Nebe-von-Caron, H. Steels, M. Novodvorska, J. Ueckert, and D. B. Archer, "Weak-acid preservatives: pH and proton movements in the yeast *Saccharomyces cerevisiae*," *International Journal of Food Microbiology*, vol. 161, no. 3, pp. 164–171, 2013.

[44] T. A. Anyasi, A. I. O. Jideani, J. N. Edokpayi, and C. P. Anokwuru, "Application of organic acids in food preservation," in *Organic Acids*, pp. 1–45, Nova Science Publishers, Hauppauge, NY, USA, 2020.

[45] I. Sánchez-Ortega, B. E. García-Almendárez, E. M. Santos-López, A. Amaro-Reyes, J. E. Barboza-Corona, and C. Regalado, "Antimicrobial edible films and coatings for meat and meat products preservation," *The Scientific World Journal*, vol. 2014, Article ID 248935, 18 pages, 2014.

[46] S. Brul and P. Coote, "Preservative agents in foods: mode of action and microbial resistance mechanisms," *International Journal of Food Microbiology*, vol. 50, no. 1-2, pp. 1–17, 1999.

[47] M. Stratford, A. Plumridge, G. Nebe-von-Caron, and D. B. Archer, "Inhibition of spoilage mould conidia by acetic acid and sorbic acid involves different modes of action, requiring modification of the classical weak-acid theory," *International Journal of Food Microbiology*, vol. 136, no. 1, pp. 37–43, 2009.

[48] M. Halm, T. Hornbæk, N. Arneborg, S. Sefa-Dedeh, and L. Jespersen, "Lactic acid tolerance determined by measurement of intracellular pH of single cells of *Candida krusei* and *Saccharomyces cerevisiae* isolated from fermented maize dough," *International Journal of Food Microbiology*, vol. 94, no. 1, pp. 97–103, 2004.

[49] H.-L. Alakomi, E. Skyttä, M. Saarela, T. Mattila-Sandholm, K. Latva-Kala, and I. M. Helander, "Lactic acid permeabilizes gram-negative bacteria by disrupting the outer membrane," *Applied and Environmental Microbiology*, vol. 66, no. 5, pp. 2001–2005, 2000.

[50] G. K. York and R. H. Vaughn, "Mechanisms in the inhibition of microorganisms by sorbic acid," *Journal of Bacteriology*, vol. 88, no. 2, pp. 411–417, 1964.

[51] B. Zhang, T. Xia, W. Duan et al., "Effects of organic acids, amino acids and phenolic compounds on antioxidant characteristic of *Zhenjiang* aromatic vinegar," *Molecules*, vol. 24, no. 20, pp. 3799–3810, 2019.

[52] P. R. Quiroga, V. Nepote, and M. T. Baumgartner, "Contribution of organic acids to α-terpinene antioxidant activity," *Food Chemistry*, vol. 277, pp. 267–272, 2019.

[53] M. Gąsecka, Z. Magdziak, M. Siwulski, and M. Mleczek, "Profile of phenolic and organic acids, antioxidant properties and ergosterol content in cultivated and wild growing species of *Agaricus*," *European Food Research and Technology*, vol. 244, pp. 259–268, 2018.

[54] M. Grashorn, R. Gruzauskas, A. Dauksiene et al., "Influence of dietary organic acids on quality and sensory attributes of chicken eggs," *Archiv für Geflügelkunde*, vol. 77, no. 1, pp. 29–34, 2013.

[55] M.-W. Kang, S.-J. Chung, H.-S. Lee, Y. Kim, and K.-O. Kim, "The sensory interactions of organic acids and various flavors in ramen soup systems," *Journal of Food Science*, vol. 72, no. 9, pp. S639–S647, 2007.

[56] I. H. Chowdhury, S. Kundu, and M. K. Naskar, "Effect of organic acids on the physicochemical properties of titania and its photodegradation efficiency of methyl orange," *Journal of Physics and Chemistry of Solids*, vol. 121, pp. 367–374, 2018.

[57] G. N. Albuquerque, R. G. Costa, F. J. Barba et al., "Effect of organic acids on the quality of sheep "Buchada": from food safety to physicochemical, nutritional, and sensorial evaluation," *Journal of Food Processing and Preservation*, vol. 43, no. 3, Article ID e13877, 2019.

[58] S. Smaoui, H. Ben Hlima, A. Mtibaa et al., "Pomegranate peel as phenolic compounds source: advanced analytical strategies and practical use in meat products," *Meat Science*, vol. 158, Article ID 107914, 2019.

[59] K. I. Sallam and K. Samejima, "Microbiological and chemical quality of ground beef treated with sodium lactate and

sodium chloride during refrigerated storage," *LWT - Food Science and Technology*, vol. 37, no. 8, pp. 865–871, 2004.

[60] S. A. Quilo, F. W. Pohlman, A. H. Brown et al., "Effects of potassium lactate, sodium metasilicate, peroxyacetic acid, and acidified sodium chlorite on physical, chemical, and sensory properties of ground beef patties," *Meat Science*, vol. 82, no. 1, pp. 44–52, 2009.

[61] H. Walsh, S. Martins, E. E. O'Neill, J. P. Kerry, T. Kenny, and P. Ward, "The effect of sodium lactate, potassium lactate, carrageenan, whey protein concentrate, yeast extract and fungal proteinases on the cook yield and tenderness of bovine chuck muscles," *Meat Science*, vol. 85, no. 2, pp. 230–234, 2010.

[62] C. E. Carpenter, J. V. Smith, and J. R. Broadbent, "Efficacy of washing meat surfaces with 2% levulinic, acetic, or lactic acid for pathogen decontamination and residual growth inhibition," *Meat Science*, vol. 88, no. 2, pp. 256–260, 2011.

[63] F. A. Shaltout, M. T. Gerges, and A. A. Shewail, "Impact of organic acids and their salts on microbial quality and shelf life of beef meat," *Global Journal of Agriculture and Food Sciences Research*, vol. 1, pp. 360–370, 2014.

[64] G. Casco, T. M. Taylor, and C. Z. Alvarado, "Evaluation of novel micronized encapsulated essential oil-containing phosphate and lactate blends for growth inhibition of *Listeria monocytogenes* and *Salmonella* on poultry bologna, pork ham, and roast beef ready-to-eat deli loaves," *Journal of Food Protection*, vol. 78, no. 4, pp. 698–706, 2015.

[65] S. D. Dan, M. Mihaiu, O. Reget, D. Oltean, and A. Tăbăran, "Pathogens contamination level reduction on beef using organic acids decontamination methods," *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Veterinary Medicine*, vol. 74, no. 2, pp. 212–217, 2017.

[66] S. D. Dan, M. Mihaiu, O. Reget, D. Oltean, and A. Tabaran, "Organic acids effect on spoilage psyhrotrophic microflora during the shelf life of bovine carcasses," *Lucrări tiinţifice*, vol. 280, 2017.

[67] M. S. Brewer, F. K. McKeith, and G. Sprouls, "Sodium lactate effects on microbial, sensory, and physical characteristics of vacuum-packaged pork sausage," *Journal of Muscle Foods*, vol. 4, no. 3, pp. 179–192, 1993.

[68] P. L. O'Connor, M. S. Brewer, F. K. Mckeith, J. E. Novakofski, and T. R. Carr, "Sodium lactate/sodium chloride effects on sensory characteristics and shelf-life of fresh ground pork," *Journal of Food Science*, vol. 58, no. 5, pp. 978–980, 1993.

[69] M. S. Brewer, B. K. Rostogi, L. Argoudelis, and G. K. Sprouls, "Sodium lactate/sodium chloride effects on aerobic plate counts and color of aerobically packaged ground pork," *Journal of Food Science*, vol. 60, no. 1, pp. 58–62, 1995.

[70] G. K. Bedie, J. Samelis, J. N. Sofos, K. E. Belk, J. A. Scanga, and G. C. Smith, "Antimicrobials in the formulation to control *Listeria monocytogenes* postprocessing contamination on frankfurters stored at 4°C in vacuum packages," *Journal of Food Protection*, vol. 64, no. 12, pp. 1949–1955, 2001.

[71] W. Tan and L. A. Shelef, "Effects of sodium chloride and lactates on chemical and microbiological changes in refrigerated and frozen fresh ground pork," *Meat Science*, vol. 62, no. 1, pp. 27–32, 2002.

[72] I. M. Barmpalia, I. Geornaras, K. E. Belk et al., "Control of *Listeria monocytogenes* on frankfurters with antimicrobials in the formulation and by dipping in organic acid solutions," *Journal of Food Protection*, vol. 67, no. 11, pp. 2456–2464, 2004.

[73] C. A. Hwang, S. Sheen, and V. Juneja, "Effects of sodium lactate on the survival of *Listeria monocytogenes, Escherichia coli* 0157:H7 and *Salmonella* spp., in cooked ham at refrigeration and abuse temperatures," *Food and Nutrition Sciences*, vol. 2, pp. 464–4702011, 2016.

[74] S. D. Dan, M. Mihaiu, O. Reget, and A. Tabaran, "Residual antimicrobial effect of week organic acids on spoilage psychrotrophs at pig carcasses," *Lucrari Stiintifice-Medicina Veterinara*," *Universitatea de Stiinte Agricole si Medicina Veterinara "Ion Ionescu de la Brad" Iasi*, vol. 60, pp. 258–264, 2017.

[75] S. D. Dan, M. Mihaiu, O. Reget, D. Oltean, and A. Tabaran, "Influence on week organic acids on pathogens on swine carcasses," *Lucrari Stiintifice-Medicina Veterinara*," *Universitatea de Stiinte Agricole si Medicina Veterinara "Ion Ionescu de la Brad" Iasi*, vol. 60, pp. 265–273, 2017.

[76] S. V. González Sánchez, "Efficacy of antimicrobial treatments against *Salmonella enterica* on pork and Campylobacter jejuni on poultry," Doctoral Dissertation, Colorado State University, Fort Collins, CO, USA, 2020.

[77] D. Beyaz and M. Tayar, "The effect of lactic acid spray application on the microbiological quality of sheep carcasses," *Journal of Animal and Veterinary Advances*, vol. 9, no. 13, pp. 1858–1863, 2010.

[78] D. B. Vlahova-Vangelova, S. G. Dragoev, D. K. Balev, B. K. Assenova, and K. J. Amirhanov, "Quality, microstructure, and technological properties of sheep meat marinated in three different ways," *Journal of Food Quality*, vol. 2017, Article ID 5631532, 10 pages, 2017.

[79] S. M. Saad, F. S. Hassanin, A. M. Salem, and E. A. E. Saleh, "Efficiency of some organic acids as decontaminants in sheep carcasses," *Benha Veterinary Medical Journal*, vol. 38, no. 2, pp. 116–119, 2020.

[80] K. F. Over, N. Hettiarachchy, M. G. Johnson, and B. Davis, "Effect of organic acids and plant extracts on *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Salmonella* Typhimurium in broth culture model and chicken meat systems," *Journal of Food Science*, vol. 74, no. 9, pp. M515–M521, 2009.

[81] S. Smaoui, H. Ben Hlima, R. Ben Salah, and R. Ghorbel, "Effects of sodium lactate and lactic acid on chemical, microbiological and sensory characteristics of marinated chicken," *African Journal of Biotechnology*, vol. 10, no. 54, pp. 11317–11326, 2011.

[82] F. A. Khalafalla, F. Ali, and A. H. A. E. Hassan, "Quality improvement of broiler chicken breasts by nisin and lactic acid," *Journal of World's Poultry Research*, vol. 37, no. 2, pp. 37–47, 2016.

[83] O. I. İlhak, G. K. İncili, and H. Durmuşoğlu, "Evaluation of effect of thymol combined with lactic acid or sodium lactate on psychrophilic bacteria and *Salmonella* spp. on chicken drumstick," *Annals of Animal Science*, vol. 17, no. 1, pp. 271–280, 2017.

[84] M. A. Hussein, W. R. El-Ghareeb, and M. A. F. Nasr, "The effect of rosemary extract and lactic acid on the quality of refrigerated broiler fillets," *Journal of Food Science and Technology*, vol. 55, no. 12, pp. 5025–5034, 2018.

[85] H. B. Coban, "Organic acids as antimicrobial food agents: applications and microbial productions," *Bioprocess and Biosystems Engineering*, vol. 43, no. 4, p. 569, 2019.

[86] O. O. Eniolorunda, E. S. Apata, O. E. Ogunlesi, and A. O. Okubanjo, "Quality evaluation of beef preserved with food grade organic acids at room temperature," *Journal of Food Research*, vol. 3, no. 5, 2014.

[87] E. Entani, M. Asai, S. Tsujihata, Y. Tsukamoto, and M. Ohta, "Antibacterial action of vinegar against food-borne

pathogenic bacteria including *Escherichia coli* O157:H7," *Journal of Food Protection*, vol. 61, no. 8, pp. 953–959, 1998.
[88] P. G. Casey and S. Condon, "Sodium chloride decreases the bacteriocidal effect of acid pH on *Escherichia coli* O157:H45," *International Journal of Food Microbiology*, vol. 76, no. 3, pp. 199–206, 2002.
[89] I. M. Barmpalia, K. P. Koutsoumanis, I. Geornaras et al., "Effect of antimicrobials as ingredients of pork bologna for *Listeria monocytogenes* control during storage at 4 or 10°C," *Food Microbiology*, vol. 22, no. 2-3, pp. 205–211, 2005.
[90] S.-C. Jo, A.-R. Rim, H.-J. Park, H.-G. Yuk, and S.-C. Lee, "Combined treatment with silver ions and organic acid enhances growth-inhibition of *Escherichia coli* O157:H7," *Food Control*, vol. 18, no. 10, pp. 1235–1240, 2007.
[91] J. H. Schlyter, K. A. Glass, J. Loeffelholz, A. J. Degnan, and J. B. Luchansky, "The effects of diacetate with nitrite, lactate, or pediocin on the viability of *Listeria monocytegenes* in Turkey slurries," *International Journal of Food Microbiology*, vol. 19, no. 4, pp. 271–281, 1993.
[92] E. Mbandi and L. A. Shelef, "Enhanced inhibition of *Listeria monocytogenes* and *Salmonella* Enteritidis in meat by combinations of sodium lactate and diacetate," *Journal of Food Protection*, vol. 64, no. 5, pp. 640–644, 2001.
[93] E. Mbandi and L. A. Shelef, "Enhanced antimicrobial effects of combination of lactate and diacetate on *Listeria monocytogenes* and *Salmonella* spp. in beef bologna," *International Journal of Food Microbiology*, vol. 76, no. 3, pp. 191–198, 2002.
[94] Z. B. Dubal, A. M. Paturkar, V. S. Waskar et al., "Effect of food grade organic acids on inoculated *S. aureus, L. monocytogenes, E. coli* and *S. Typhimurium* in sheep/goat meat stored at refrigeration temperature," *Meat Science*, vol. 66, no. 4, pp. 817–821, 2004.
[95] V. K. Juneja and H. Thippareddi, "Inhibitory effects of organic acid salts on growth of *Clostridium perfringens* from spore inocula during chilling of marinated ground Turkey breast," *International Journal of Food Microbiology*, vol. 93, no. 2, pp. 155–163, 2004.
[96] E. H. Drosinos, M. Mataragas, A. Kampani, D. Kritikos, and I. Metaxopoulos, "Inhibitory effect of organic acid salts on spoilage flora in culture medium and cured cooked meat products under commercial manufacturing conditions," *Meat Science*, vol. 73, no. 1, pp. 75–81, 2006.
[97] E. L. D. Souza, J. C. D. Barros, M. L. D. Conceição, N. J. Gomes Neto, and A. C. V. D. Costa, "Combined application of *Origanum vulgare* L. essential oil and acetic acid for controlling the growth of *Staphylococcus aureus* in foods," *Brazilian Journal of Microbiology*, vol. 40, no. 2, pp. 387–393, 2009.
[98] J. Xu, F. Zhou, B.-P. Ji, R.-S. Pei, and N. Xu, "The antibacterial mechanism of carvacrol and thymol against *Escherichia coli*," *Letters in Applied Microbiology*, vol. 47, no. 3, pp. 174–179, 2008.
[99] M. Ghabraie, K. D. Vu, T. Huq, A. Khan, and M. Lacroix, "Antilisterial effects of antibacterial formulations containing essential oils, nisin, nitrite and organic acid salts in a sausage model," *Journal of Food Science and Technology*, vol. 53, no. 6, pp. 2625–2633, 2016.
[100] T.-K. Kim, K.-E. Hwang, M.-A. Lee, H.-D. Paik, Y.-B. Kim, and Y.-S. Choi, "Quality characteristics of pork loin cured with green nitrite source and some organic acids," *Meat Science*, vol. 152, pp. 141–145, 2019.
[101] E. L. Shebs, F. M. Giotto, M. J. Lukov, S. T. Laidler, and A. S. D. Mello, "Effects of bacteriophage, ultraviolet light, and organic acid applications on STEC O157:H7 and the big six in beef packaged under vacuum and aerobic conditions," *Meat and Muscle Biology*, vol. 3, no. 2, p. 140, 2019.
[102] J. M. Rodríguez-Calleja, M. C. Cruz-Romero, M. G. O'Sullivan, M. L. García-López, and J. P. Kerry, "High-pressure-based hurdle strategy to extend the shelf-life of fresh chicken breast fillets," *Food Control*, vol. 25, no. 2, pp. 516–524, 2012.
[103] C. M. O'Neill, M. C. Cruz-Romero, G. Duffy, and J. P. Kerry, "Shelf life extension of vacuum-packed salt reduced frankfurters and cooked ham through the combined application of high pressure processing and organic acids," *Food Packaging and Shelf Life*, vol. 17, pp. 120–128, 2018.
[104] M. Koohmaraie, T. M. Arthur, J. M. Bosilevac, M. Guerini, S. D. Shackelford, and T. L. Wheeler, "Post-harvest interventions to reduce/eliminate pathogens in beef," *Meat Science*, vol. 71, no. 1, pp. 79–91, 2005.
[105] S. M. Jiménez, M. S. Salsi, M. C. Tiburzi, R. C. Rafaghelli, and M. E. Pirovani, "Combined use of acetic acid treatment and modified atmosphere packaging for extending the shelf-life of chilled chicken breast portions," *Journal of Applied Microbiology*, vol. 87, no. 3, pp. 339–344, 1999.
[106] F. Devlieghere, L. Vermeiren, A. Bockstal, and J. Debevere, "Study on antimicrobial activity of a food packaging material containing potassium sorbate," *Acta Alimentaria*, vol. 29, no. 2, pp. 137–146, 2000.
[107] K. G. Zinoviadou, K. P. Koutsoumanis, and C. G. Biliaderis, "Physical and thermo-mechanical properties of whey protein isolate films containing antimicrobials, and their effect against spoilage flora of fresh beef," *Food Hydrocolloids*, vol. 24, no. 1, pp. 49–59, 2010.
[108] C. Hauser and J. Wunderlich, "Antimicrobial packaging films with a sorbic acid based coating," *Procedia Food Science*, vol. 1, pp. 197–202, 2011.
[109] F. J. M. Smulders, P. Paulsen, S. Vali, and S. Wanda, "Effectiveness of a polyamide film releasing lactic acid on the growth of *E. coli* O157:H7, Enterobacteriaceae and Total Aerobic Count on vacuum-packed beef," *Meat Science*, vol. 95, no. 2, pp. 160–165, 2013.
[110] E. Union, "Commission Regulation No 450/2009/EC of May 2009 on active and intelligent materials and articles intended to come into contact with food," *Official Journal of the European Union*, vol. L135, pp. 3–9, 2009.
[111] S. Quintavalla and L. Vicini, "Antimicrobial food packaging in meat industry," *Meat Science*, vol. 62, no. 3, pp. 373–380, 2002.
[112] A. Plumridge, M. Stratford, K. C. Lowe, and D. B. Archer, "The weak-acid preservative sorbic acid is decarboxylated and detoxified by a phenylacrylic acid decarboxylase, PadA1, in the spoilage mold *Aspergillus niger*," *Applied and Environmental Microbiology*, vol. 74, no. 2, pp. 550–552, 2008.
[113] N. Arneborg, L. Jespersen, and M. Jakobsen, "Individual cells of *Saccharomyces cerevisiae* and *Zygosaccharomyces bailii* exhibit different short-term intracellular pH responses to acetic acid," *Archives of Microbiology*, vol. 174, no. 1-2, pp. 125–128, 2000.
[114] P. Piper, C. O. Calderon, K. Hatzixanthis, and M. Mollapour, "Weak acid adaptation: the stress response that confers yeasts with resistance to organic acid food preservatives," *Microbiology*, vol. 147, no. 10, pp. 2635–2642, 2001.
[115] B. P. Harp and J. N. Barrows, "US regulation of color additives in foods," in *Colour Additives for Foods and Beverages*, pp. 75–88, Woodhead Publishing, Sawston, UK, 2015.