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Review

Marination as a Hurdle to Microbial Pathogens and Spoilers in Poultry Meat Products: A Brief Review

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Abstract: Poultry meat, due to its low price and nutritional value, is a healthy and easily accessible option for many households worldwide. Poultry consumption is, therefore, expected to continue to grow. However, this increase may lead to the rising numbers of cases of bacterial gastroenteritis, as poultry meat often carries foodborne pathogens such as *Campylobacter* spp. and *Salmonella* spp. While the current on-farm biosecurity programs and food safety management systems implemented by the poultry industry are intended to mitigate the presence of these pathogens, some find their way to the retail level, posing a risk to the consumer. A safeguard for the consumer could potentially result from meat marination. However, the current marinated meat products sold on the market aim to extend the shelf life and overall taste and tenderness of the meat rather than its safety. Marination could be optimised not only to reduce any foodborne pathogen present in the meat but also to increase the shelf life reducing waste at the retail level. Formulations composed of various ingredients with different active principles may be used to achieve this objective. Wines present a superb component for marinades. Due to their complex nature, wines possess organic acids, phenolic compounds, and ethanol, all of which own significant antimicrobial potential. Essential oils may be another option. By combining different active principles in a marinade, we could potentially reduce the concentrations of the overall bactericidal ingredients. The objective of this review was to analyse the recent studies in this field and try to understand the best options for developing a convenient, natural-based bactericidal marinade.

Keywords: food safety; natural antimicrobial compounds; essential oils; organic acids; phenolic compounds; *Campylobacter*; *Salmonella*

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1. Introduction

1.1. Growth in Poultry Meat Consumption and Its Risks

Poultry is the meat of choice in many households worldwide, due to its relatively low price and being a healthy source of high-quality protein, minerals, vitamins, and polyunsaturated fatty acids such as omega-3 [1,2]. Thus, consumer preferences have shifted towards the consumption of white meats such as poultry over red meats such as beef, veal, pork, and lamb [3]. In the last 20 years, meat consumption has increased by 29% in developed nations and 54% in developing countries [4]. Even with the impact of the COVID-19 pandemic, global poultry production remained stable across the year 2020 [5]. Although briefly experiencing a decrease in demand, aviary meats remain the primary driver in the surge of meat consumption, albeit less impactful than in the past decade. Of the additional meat production output, 84% will come from developing regions in response to the surge in meat consumption in the said emergent regions and the rest of the globe [6]. However, some of these countries possess weak food safety monitoring infrastructures, which may not be prepared to handle the increase in production, leading to an increased incidence of infections by common foodborne pathogens such as *Campylobacter* spp. and *Salmonella* spp. [7].

1.2. Campylobacter and Salmonella, Foodborne Pathogens

Since 2005, campylobacteriosis is the most routinely reported zoonosis in humans across the European Union (EU), with 120,946 confirmed cases, representing 40.35 cases per 100,000 people in 2020 [8]. According to the last EU zoonoses report, the prevalence of *Campylobacter*-positive non-RTE turkey and broiler samples was 30.5% and 21.5%, respectively, the highest prevalence rates for all the fresh meats in the same class.

Although many *Campylobacter* species are the causative agents of gastrointestinal diseases in humans, *Campylobacter jejuni* and *Campylobacter coli* are implicated in most infections originating from contaminated foods, such as poultry meat [9–11]. The vast majority of campylobacteriosis cases are self-limiting, with few instances requiring treatment with antibiotics [12]. Farm-based studies have shown that the major routes of *Campylobacter* transmission to poultry are the environment and the horizontal dissemination between flock mates [10].

During the slaughter process, cross-contamination can effortlessly happen among the various processing steps of the carcass: plucking, evisceration, carcass washing, and refrigeration. These steps are crucial control points since they provide a path for bacteria to relocate from the intestines to the carcass or the processing environment [13]. In the pores of the removed feathers, *Campylobacter* will find a microaerophilic environment that will shield this microorganism from atmospheric oxygen and low refrigeration temperatures [14]. Factors such as the protection offered by the food matrix, the low infectious dose, the capability to form monoculture and mixed-culture biofilms, and the viable but non-culturable (VBNC) state justify the perception of poultry meat as a primary reservoir of *Campylobacter*.

In the EU, salmonellosis is the primary cause of foodborne outbreaks, remaining the second most commonly reported zoonoses, with 52.702 confirmed cases in 2020, representing 13.7 occurrences per 100,000 individuals [8]. According to the 2020 EU zoonoses report, the prevalence of *Salmonella*-positive non-RTE broiler samples was around 8%, much less prevalent than *Campylobacter* but still significant. Salmonellosis is a self-limiting gastroenteritis syndrome, typically caused by non-typhoidal *Salmonella enterica* serotypes. *Salmonella* Typhimurium and *S. enteritidis* are considered the main cause of foodborne salmonellosis.

1.3. Food Loss and Spoilage Bacteria

Despite the increasing breakthroughs in food science over the years, meat spoilage remains a global problem due to the complexity of factors involving physical, chemical, and biological events which lead to meat deterioration [15,16]. Due to its high-water activity, low acidity, high nutritive content ideal for microbial growth, presence of autolytic enzymes, and high amounts of fat and lipids benefiting oxidation and spoilage, meat presents itself as a highly perishable food that quickly spoils [17].

The slaughter process will promote oxidative lipid and protein deterioration, also inducing enzymatic autolytic spoilage. As a consequence of these oxidative biochemical reactions, the produced free radicals will develop the off-flavour in the product. Additionally, meat-handling processes such as cutting and mincing induce spoilage reactions [18].

Microorganisms present in meat microbiota will also play a crucial part in meat spoilage, especially those with proteolytic activity since after depleting glucose and exhausting lactate, bacteria will have to catabolise amino acids. In bacterial terms, the initial meat microbiome is filled with spoilage organisms such as *Acinetobacter*, lactic acid bacteria (LAB), Gram-positive spore formers (*Clostridium*), Gram-positive bacilli (*Brochothrix*), *Enterobacteriaceae* (e.g., *Escherichia*), Gram-negative bacilli (*Pseudomonas*), Gram-positive cocci (e.g., *Enterococcus*, *Staphylococcus*, and *Streptococcus*) [19].

Pseudomonas spp. is known for its chief role in meat spoilage under aerobic conditions, often accounting for the vast majority of the spoilage microbiome, by out-competing other bacteria [20,21]. If the meat is stored at refrigeration temperatures, then, *Brochothrix thermosphacta* will reign supreme. This facultative anaerobe, a close relative to the psychrotrophic

Listeria monocytogenes, will quickly outgrow its competitors while breaking down the meat in order to produce various metabolites associated with off-odours [22].

After exhausting all the available carbon sources, *Pseudomonas* spp. will catabolise amino acids, leading to a foul and putrid odour. The metabolic activities of *Pseudomonas fluorescence* and *Pseudomonas aeruginosa* also lead to characteristic meat discolouration patterns, such as the yellow-greenish colour provided by pyoverdine, a siderophore employed as an iron chelator [23], or even the blueish colour given by two particular pigment genes associated with the tryptophan pathway of certain *P. fluorescence* strains [24]. Nonetheless, the early predominance and rapid growth of *Pseudomonas* species lead to oxygen depletion, allowing facultative anaerobes to thrive (e.g., *Acinetobacter* and *Enterobacteriaceae*).

In oxygen-deprived environments, such as the ones provided by vacuum-packaged products, LAB, *Enterobacteriaceae* family members, and *Clostridium* species are the major contributors to meat degradation. Lactic acid bacteria lead to the formation of slime and a reduction in the pH value due to lactic acid production [25]. Together with *Clostridium* spp., LAB produce gases leading to the "blown packaging" effect [26]. Additionally, the hydrogen sulphide produced by some members of the *Enterobacteriaceae* family leads to the sulfuric odours experienced during meat spoilage [15].

The spoilage of meat leads to significant economic hindrances. In Europe, it is estimated that annually, nearly 24% of all meat products end up wasted across the food chain, with the prime stages responsible for this waste being distribution and retail (9%) and the consumer itself (11%) [27]. In the US, 41 k tonnes of meat products were spoiled at the retail level, while 330 k tonnes were lost in the hands of the consumer throughout 2019 [28]. To this extent, reducing food spoilage would align with the second and twelfth sustainable development goals set by the United Nations, which aim at reducing hunger and achieving responsible production and consumption while ensuring food security worldwide [29].

Although meat spoilage is less frequent than produce spoilage, meat production is resource-intensive, making it a greenhouse gas-intensive product. Accordingly, the carbon footprint of spoiled meat is the highest among all food products [30]. Consequently, preventing meat spoilage at the retail and consumer levels will undoubtedly reduce the carbon footprint posed by the waste of meat products, partially fulfilling the thirteenth sustainable development goal aimed at reducing the carbon footprint of major industries [29].

1.4. Current Safety Measures against Foodborne Pathogens in Poultry Meat

Throughout the food chain, mitigation strategies have been adopted to limit the presence of *Campylobacter* spp. and *Salmonella* spp. in poultry meat. We can divide the farm-to-fork continuum into three major stages: pre-processing, processing, and post-processing. Each level possesses many entry points for foodborne pathogens to colonise poultry meat.

At the pre-processing stage, the main focus is to ensure that no foodborne pathogen enters the production facility and colonises the chickens' gut; biosecurity measures are the defensive frontline against these pathogens [31–33]. However, the effectiveness of these measures is often in line with renewal rates, cleaning efficiency, and personnel training [34].

The separation of the flocks from other animals is also an important measure to fulfil. Compartmentalised flocks with small elements and low density can also reduce the risk of horizontal transmission [35]. Surveillance is another crucial factor in the safety of poultry [36]. During their growth, the fledglings can be subjected to probiotic formulas to create a healthy microbiome in the nestling's gut, which may prevent bacterial colonisation through various mechanisms [37,38].

Even with various integrated overlapping control strategies, foodborne pathogens still find their way into the production facilities and the chicken's gut, reaching the meat [33]. Thus, they create the constant need to develop new hurdles against said pathogens. Many studies have shown the effectiveness of bacteriophages and bacteriocins in reducing the levels of *Salmonella* and *Campylobacter* in the chicken's gut [39–42]. Their usage, however, still requires more information since many questions remain to be answered, and a proper regulatory framework has not yet been approved.

During the processing stage, new challenges emerge. As previously mentioned, evisceration is a pivotal control point. If not carried out per recommended good practices, cross-contamination from the gut onto other processing surfaces and the carcass can occur. Performing systematic biofilm removal, disinfection, and cleaning will address possible fomite transmission. All the machinery used in the evisceration process is designed from the ground up to be easily accessible by the cleaning agents. This way, the removal of any present biofilm can be assured [43].

At the carcass level, the preventive measures diverge. Carcass decontamination with chlorine, chlorine dioxide, trisodium phosphate, and lactic acid is legal in certain countries, namely the US [44]. However, in the case of the EU, chlorine and organic acids cannot be used in carcass decontamination, and the latter is only allowed for surface decontamination [45]. Other routine procedures widely used around the world are carcass and crust freezing. Carcass freezing does not aim at reducing the bacterial levels on the carcass, even though some bacterial reduction may occur [46], preventing only the proliferation of any microorganisms present on the meat surface. Meanwhile, crust freezing is employed to achieve a suitable product texture to prevent any losses or tearing of the meat due to mechanical processing, and its use is not intended to decrease the overall microbiological safety of the product [47].

The post-processing phase will eventually lead to the consumption of the poultry product. In this phase, most of the safeguards fall on the consumer. Refrigeration at around 4 °C will prevent the proliferation of most pathogens, including *Salmonella* spp. [48]. During cooking, temperatures of around 70 °C should be reached evenly throughout the poultry meat for 3 min [49], ensuring the destruction of any vegetative cells. The methods used by the consumer to monitor meat doneness, such as the evaluation of the inner colour or texture of the poultry, have been proven ineffective in determining pathogen destruction [50]. The non-reflective handling of poultry products may also lead to cross-contamination in the consumers' kitchens. Practices such as carcass washing will transfer any pathogen present in the meat to the surrounding surfaces, which will then work as fomites for further cross-contamination events. Furthermore, reusing cleaning cloths, using the same utensils for two completely different tasks without prior cleaning, and poor surface cleaning are other frequent handling mistakes carried out by the average consumer [51]. Hence, the products requiring minimal manipulation, such as pre-cut or prepacked marinated ready-to-oven products, reduce the likelihood of cross-contamination.

2. Marination

Marination, as a process, involves the soaking of foods in a salted liquid with seasonings such as oregano, thyme, laurel, garlic, and others. The acidity of many marinades comes from the employment of organic acids, usually from sources such as lemon juice, soy sauce, vinegar, wines, and others. Nowadays, marination is a concept that varies from country to country and culture to culture. Sometimes, simply salting a product is viewed as a marination process. In other instances, the products containing inorganic phosphates or spices are considered marinated products. Plumping, the process of injecting raw poultry with salt water, chicken stock, or any other flavouring substance, can also be considered a form of marination [52].

Even though acquiring various meanings through history and cultures, marinated products are still a current and modern fashion adopted in large commercial markets. In Finland, 80% of the poultry meat sold at retail had some form of marination [52]. The current success of marination is owing to three factors: profits, waste, and consumer expectations. Regarding the first and second aspects, marinated products aim to increase consumers' taste experience, enticing them to buy the product over other non-marinated offers. At the same time, marinated products are less wasteful since marinades can reduce the number of spoilage bacteria present in meat, sustaining its texture and flavour for an extended time [53,54]. Marination might be highly beneficial to the meat industry and retail chains since it contributes to increasing product shelf life, thus decreasing food waste. Additionally, these products are usually ready-to-cook, with no further preparation required. Besides this aspect, the lack of additional handling by the consumer, which reduces the likelihood of cross-contamination events in the consumer's kitchen, is a safety feature of these products that is hardly ever considered.

Although possessing many advantages, marinades have some shortcomings. Commercially available marinades might hold some antimicrobial activity against some foodborne pathogens, but this is not the norm, with marinade formulations not being designed with this purpose in mind. At the retail stage, the product safety and shelf-life of the vast majority of marinated products are ensured by synthetic food preservatives. Therefore, there would be an economic interest for companies to develop clean-label marinated products that achieve their safety and shelf-life by employing marinades containing natural ingredients.

Additionally, alongside the marination process, we can incorporate supplemental strategies for food preservation, with some of the available procedures enhancing marinade absorption. A case in point is marinade uptake, which has been shown to be improved by combining other technologies, such as sous-vide [55], ultrasounds [56], and high hydrostatic and hydrodynamic pressure [57,58]. Furthermore, in the instances of some preservation technologies, exposure to the marination solution increases the sensitivity of the meat microbiota to the stabilisation procedure (e.g., thermal inactivation) [59].

Several studies have been carried out to evaluate the antimicrobial activity of different marinade recipes and techniques. Some of these studies are summarised in Table 1.

Table 1. Studies evaluating antimicrobial activity of different marinade recipes and techniques.

Marinade Composition	Concentrations Applied	Microorganisms Tested	Major Effects	Tested Matrix	Marination and Storage Conditions	References
Teriyaki sauce (TS): soy sauce, vinegar, wine, garlic, onion powder, spices, water, and high fructose corn syrup. With or without carvacrol (CV) or thymol (TM)	Carvacrol (0.3%), Thymol (0.5%), Teriyaki sauce (1:1 *w*/*v*)	*Salmonella* Typhimurium, *Escherichia coli* O157:H7, *Listeria monocytogenes*	Counts of *S.* Typhimurium significantly reduce after 7 days at 4 °C both TS + CV and TS + TM.	Chicken breast	Immersion for 7 days at 4 °C.	[60]
Homemade marinade: table wine, balsamic vinegar, tomato paste, salt, black pepper, red pepper, and garlic powder		*Salmonella* spp., Total coliform count, Total aerobic mesophilic bacteria, Yeast and moulds	HPP treatment on the marinated chicken reduced the early *Salmonellae* and total coliform counts (3.53 ± 0.12 and 6.59 ± 0.11 log10 CFU/g) to undetectable levels.	Chicken breast	HPP exposure in the following conditions: 400 MPa/15 min and 600 MPa for 5, 10, and 15 min.	[61]
Homemade marinade: tomato paste, red and black pepper, cumin, lemon juice, garlic	Yucca schidigera (0.5% *w*/*v*), Thyme oil (0.1 and 0.2% *w*/*v*), Marinade (2:1 *v*/*w*)	*S.* Typhimurium, *L. monocytogenes*	*S.* Typhimurium counts decreased between 0.9 and 1.4 log10 CFU/g at the end of storage. Bacteriostatic effect against *L. monocytogenes*.	Chicken breast, wings, and drumsticks	Dry rub and storage for 10 days at 4 °C.	[62]
Lemon juice and *Yucca schidigera* extract marinade enhanced with thyme oil		Five *Salmonella* serovars: Enteritidis, Heidelberg, Typhimurium, Gaminara, Oranienburg	Marinades with thyme oil showed higher antimicrobial activity against *Salmonella* after 8 h (2.62–3.91 log10 CFU/sample reductions) than marinades only containing lemon juice (1.12 log10 CFU/sample reduction) and yucca extract (1.42 log10 CFU/sample reduction). Synergetic action between EOs and organic acids is suggested.	Chicken breast	Immersion for 8 h at 22 °C.	[63]
Six marinade types: four containing (thyme, rosemary, basil, and marjoram) one commercially available marinade, and one commercially available marinade enhanced with bioactive compounds		*Campylobacter jejuni*	The studied marinades showed weak antimicrobial action. Thyme-based marinade achieves the greatest antibacterial activity reducing 1.04 log10 CFU/g after 7 days at 4 °C.	Broiler wings	Dry rub marinade 1, 3, 4, and 7 days at 4 °C.	[64]
Commercial teriyaki marinade		*L. monocytogenes* Five *Salmonella* serovars: Thompson, Hadar, Montevideo, Heidelberg, Typhimurium, Copenhagen	Marination enhanced the sensitivity of the tested pathogens to the lethal heat conditions of the sous-vide process.	Chicken breast	Chicken breasts were immersed and vacuum sealed at 4 °C for 18 h and then thermally processed.	[59]
Food marinating ingredients added with different organic acids: tartaric, acetic, lactic, malic, and citric acid	0.3 to 10%	*C. jejuni*	On the broth models, organic acids exerted higher antimicrobial activity than on food matrices. On chicken fillets, organic acid marinades resulted in a 1.2 log10 CFU/g after 3 days at 4 °C.	In vitro, chicken fillets, and medallions	Chicken fillets were immersed. On Medallions, acid was spread.	[54]
Marinades containing koruk juice (KJ), dried koruk pomace (KP) with or without salt (S), and thyme (T)	KJ: 25 and 50% KP: 1 and 2% S: 1% T: 0.1%	*L. monocytogenes*, *E. coli* O157:H7 *S.* Typhimurium	For the samples inoculated with low pathogen levels, the reduction from the marination leads to a decrease below the detection limit.	Poultry meat	Immersion for 2, 24, and 48 h at 4 °C.	[65]
Marination sauce supplemented with Citricidal® liquid concentrate	50, 100, 200 ppm	*Clostridium perfringens*	In marinated samples with 200 ppm of Citricidal® at storage temperatures, *C. perfringens* spores experienced lower growth rates after germination. Furthermore, the marinade-supplemented chicken samples did not experience major changes in meat colour or shear force of lipid oxidation.	Chicken breast	The marinade was added to the chicken breast, mixed for 2′, and vacuum sealed. Afterwards, the bags were thermally processed at 71.1 °C for 1 h.	[66]

3. Antimicrobial Activity of Natural Compounds

Using natural compounds as antimicrobial agents in food is not a new idea. For ages, humans have used a variety of compounds, ranging from organic acids, essential oils (EOs), and wines to salts and seasonings, all with the intent of improving the sensorial experience and the product's lifespan.

Essential oils, present in numerous seasonings (e.g., garlic, oregano, thyme, and rosemary), and the organic acids present in various fruits (e.g., grapes, tomatoes, and citrus fruits), have been studied for their natural preservative properties.

Lastly, heavily complex fermented substances, such as vinegar, wines, and sauces such as soy sauce, that possess various known antimicrobial compounds are also frequently used. Although some of the substances mentioned above mainly have high concentrations of organic acids, others, such as wines, hold highly complex matrices containing several compounds known for their antimicrobial activity.

3.1. Essential Oils and Extracts from Aromatic Herbs

Although most studies reporting the antimicrobial activity of aromatic herbs delve into EOs, studies employing plant extracts have also been conducted. However, there is still a lack of knowledge on how the extraction processes affect the bioactivity of most aromatic plant extracts. Nonetheless, the plant extracts from common aromatic herbs such as oregano and thyme have shown antimicrobial activity against foodborne pathogens and spoilage bacteria.

Jovanović et al. (2021) studied the inhibitory and bactericidal activity of two polyphenol-rich wild thyme extracts against seven foodborne pathogens. Of all the tested bacteria, *Enterococcus faecalis* was the most susceptible to inhibition from the tested extracts, with a minimum inhibitory concentration (MIC) of 0.313 mg/mL. Moreover, *L. monocytogenes* and *Bacillus cereus* presented the highest tolerances, with MIC values of 0.625 mg/mL for both organisms. *Staphylococcus aureus* and *Yersinia enterocolitica* were considerably less susceptible to the inhibitory effect of the wild thyme extracts (MIC 1.25 mg/mL). Regarding the bactericidal effect, *L. monocytogenes* proved to be the most susceptible of all the tested microorganisms, with a minimum bactericidal concentration (MBC) of 2.5 mg/mL. On the other hand, *S. aureus* and *Y. enterocolitica* showed the highest resistance to the extracts, with an MBC value of 10 mg/mL [67].

Teixeira et al. (2013) evaluated the antimicrobial activity of oregano extracts and the EOs obtained through hot water extraction against seven foodborne pathogens and spoilage bacteria. The tested extracts inhibited the growth of the tested bacteria. Nonetheless, the EOs inhibited the growth (MIC value < 5 mg/mL) and reduced the levels of the tested microorganisms [68].

Essential oils are volatile and aromatic oily liquids extracted from plant components (e.g., leaves or seeds, fruits, stems, roots, and buds) and possess hundreds of low molecular weight secondary metabolites [69]. Among all the compounds in EOs, we can distinguish two noteworthy classes of active compounds: terpenes and phenols.

Although terpenes and terpenoids are the most prevalent class in EOs [70], with phenolic compounds only representing a smaller fraction of the total constituents of EOs, the phenolic contents of an EO have been found to be directly correlated with its antimicrobial activity [56]. Nonetheless, studies have shown that terpenes such as carvacrol and thymol present in oregano and thyme possess promising antimicrobial capacity [71–74]. For instance, Thanissery et al. (2014) tested, in vitro, the antimicrobial capabilities of rosemary, clove, thyme, and orange EOs against *Salmonella* spp., *C. coli*, and *C. jejuni*. Overall, *Campylobacter* isolates proved to be more susceptible to the antibacterial activity of the tested EOs, with synergistic effects occurring between the EOs [75].

Additionally, along with terpenes and phenylpropanoids, flavonoids and alkaloids also demonstrated significant antimicrobial activity when administered isolated or as part of an extract [76–78].

The mechanisms behind the antimicrobial activity of EOs vary, either leading to a bacteriostatic effect, where the bacterial growth inhibition occurs, or to a bactericidal action, where EOs kill the bacterial cells. Essential oils most commonly target the cytoplasmic membrane, damaging it while disrupting efflux pumps and other proteins embedded into the cell membrane, leading to leakage of intracellular components and subsequent membrane rupture and cell death [2,79]. Carvacrol, thymol, and garlic extracts were shown to exert this mechanism of antimicrobial action [80,81]. Essential oils can also exhibit antibacterial activity through other means. For instance, andrographolide, a terpene, can interfere with protein and DNA synthesis [82], while quercetin inhibits the biosynthesis of unsaturated fatty acids [83]. The United States Food and Drug Administration (FDA) classifies several EOs as generally recognised as safe (GRAS).

However, as with any other compound, using EOs as antimicrobials in meat products has certain limitations. Meat is a complex matrix that encompasses high quantities of saturated fatty acids and proteins, which may decrease the activity of EOs due to their high binding capacity of volatile compounds present in the EO. Consequently, they lead to the need to administer higher concentrations of EOs in meat products, raising another question; adding high concentrations of EOs to meat products creates powerful and unpleasant aromas and off-flavours, making them unacceptable to the consumer.

The use of EOs in edible coatings, active packaging, microencapsulation, and nanoparticles has been proposed [84–87]. Nonetheless, although many of these approaches are highly effective, they carry intrinsic costs which increase the price of an otherwise relatively inexpensive product. Hence, industries dissent from adopting these methods on a large scale.

A summary of the studies evaluating the antimicrobial activity of the EOs of different plants and the various delivery methods is presented in Table 2.

Table 2. Studies evaluating the antimicrobial activity of essential oils (EOs) of different plants.

EOs Employed	Concentrations Applied	Microorganisms Tested	Major Effects	Matrix	Marination and Storage	References
21 different EOs and several combinations	0.50%	Spoilage bacteria	Only eight of all tested EOs produced antimicrobial activity. The optimal compound spices extract, for reducing spoilage bacteria, consisted of 2.4 µL/mL of cassia bark EO, 1.0 µL/mL of cinnamon EO, 3.5 µL/mL of tea tree EO, and 9.0 µL/mL of angelica EO.	In vitro	The essential oils were directly applied on plates coated with putrefying bacteria liquid.	[88]
Thyme and orange EOs		*Salmonella* Enteritidis *Campylobacter coli*	Treatments with thyme, orange oils, and vacuum tumbling significantly reduced the viable counts of *S.* Enteritidis and *C. coli* by 2.3–2.6 and 3.1–3.6 log_{10} CFU/g, respectively.	Chicken breast fillets and wings	Vacuum tumbling for 20′ with a10% (*v*/*w*) pre-chilled (4 °C) marinade solution.	[89]
Thyme and orange EOs	1.0% (*w*/*w*)	*Escherichia coli* *Staphylococcus aureus*	Treatments with EOs and atmospheric cold plasma (APC), along with their combinations, reduced bacterial growth. EOs contributed to the increased sensibility of *E. coli* to APC treatment.	Chicken breast fillets	Immersion in a marinade solution for 2 min followed by storage at 4 °C and exposure to APC.	[90]
Carvacrol (CA) and thymol (TH)	0.4 and 0.8% (*v*/*w*)	*Pseudomonas* spp. *Brochothrix thermosphacta* *E. coli* Yeast and moulds Total coliforms Total viable count (TVC)	Together with vacuum packaging, EOs at 0.8% delayed the growth of spoilage bacteria. The combination of EOs at 0.4% with both packaging methods increased the products' shelf-life by 6 to >12 days.	Chicken breast fillets	Immersion in a marinade solution with storage at 4 °C under aerobic or vacuum packaging.	[91]
Carvacrol, cinnamaldehyde (CI) and thymol	1.0 and 2.0% (*v*/*v*)	*Listeria monocytogenes* *Salmonella* spp. *E. coli* O157:H7	The marination decreased all pathogen counts. EOs did not enhance the antimicrobial action against *L. monocytogenes*. 1.0% CI decreased *Salmonella* counts by 1.0 log10 CFU/g. For *E. coli* O157:H7 EOs lead to a $\leq$2.4 log_{10} CFU/g reduction.	Chicken breast	Immersion in a marinade solution with storage at 4 or 10 °C for 1, 4, and 7 days.	[92]
Propolis extract	4.0, 8.0, 12.0% (*v*/*w*)	*S. aureus* *E. coli* Yeast and moulds TVC	During storage, bacterial growth was decreased by the propolis extracts, with higher concentrations yielding higher antimicrobial activities. Furthermore, propolis reduced the changes in meat texture quality throughout the storage period.	Chicken breast	Immersion in a marinade solution with storage at 4 °C for 3, 6, 9, and 12 days.	[93]

3.2. Organic Acids

Like EOs, organic acids are granted GRAS status by the EU and the FDA [93,94], allowing their use in various technical purposes for poultry products, from preservatives and antioxidants to pH adjusters and flavouring agents [95]. Recipes such as Ceviche, a Peruvian dish containing raw fish, rely for their safety on the large quantities of organic acids added, citric acid in the case of Ceviche [96]. In addition, vinaigrette, besides improving the flavour of meat, has a high acetic acid content, which presents another hurdle for bacteria to overcome.

There are two main phenomena responsible for the antimicrobial activity of organic acids. The first one, cytoplasm acidification, hinders cellular metabolic reactions. The second process, the intracellular accumulation of toxic dissociated acid forms, prompts the cell to pointlessly spend large amounts of energy to counteract the natural acid influx, leading to its demise [97–100].

As previously mentioned, some problems arise when using organic acids in meat products. Generally, meat possesses a high buffering capacity, allowing the maintenance of a relatively high pH even when exposed to acidic solutions, with poultry meat having an average pH value of approximately 6. Under these conditions, organic acids dissociate and, in this form, lose their ability to enter the cell, reducing their effectiveness [54]. The addition of organic acids at higher concentrations would overcome this limitation. However, this would impose new obstacles. High concentrations of organic solutions would considerably alter meat properties such as its colour, smell, taste, water holding capacity, and binding capacity, thus creating a darker meat product with a pungent acidic smell and taste, losing significant amounts of water when cooked and being more brittle when cut [101].

The studies evaluating organic acid's antimicrobial activity are presented in Table 3.

Table 3. Studies evaluating the antimicrobial activity of organic acids.

Organic Acids Employed	Concentrations Applied	Microorganisms Tested	Major Effects	Food Matrix	Exposure Conditions	References
Malic acid (MA) and Acetic acid (AC)	5 mg/mL	Five *Salmonella* serovars: Typhimurium, Heidelberg, Copenhagen, Enteritidis, and Kentucky.	At 4 °C, the solutions containing both malic and acetic acid were able to ensure a 5-log reduction in *Salmonella* on the chicken breast while also reducing mesophilic aerobic bacteria and lactic acid bacteria.	Chicken breast	Immersion for 5 min with shaking at 150 rpm/min followed by storage at 4 °C for 10 days.	[102]
Vinegar (Acetic acid-AC) and lemon juice (Citric acid-CA)	4%, 2%, 1.5%, 1% and 0.5% (*v*/*v*)	Three *Salmonella* serovars: Typhimurium, Enteritidis and Infantis.	Higher concentrations of organic acids (2–4% *v*/*v*) were the most effective against the tested pathogens. The effect of AC on the pathogen was more pronounced compared to CA. The response to acid stress was strain-dependent.	Chicken breast fillets	Immersion for 1 h at 4 °C. Storage at 4, 8, 12 and 16 °C for 9 days.	[103]
Citric acid (CA), Latic acid (LA)	0.2–10%	Chicken skin microbiota: mesophilic and psychotropic bacteria, coliforms, yeasts, and moulds.	The organic acids improved the shelf life of the tested carcasses while significantly reducing the microbial load of the carcass.	Chicken skin	Immersion for 1 min followed by storage for 3 days at 6 ± 2 °C.	[104]
LA, MA and Fumaric acid (FA)	3%	*Salmonella* spp.	All tested acids reduced *Salmonella* counts by more than 1 $\log_{10}$ CFU/g, with FA being the most effective one.	Chicken breast	Immersion for 15 s followed by storage at 4 °C for 10 days.	[105]
LA and CA	0.5%, 1.0%, 1.5%, 2.0% (*w*/*v*)	Chicken meat natural microbiota, *Salmonella* spp. and *Staphylococcus aureus*.	After the administration of the spray-washing treatment with lactic acids and citric acid, microbial loads on the chicken drumsticks significantly decreased—most effective: 0.5% LA, 1% CA, spray-washing for 30 s.	Chicken drumstick	Spray-washing for 15, 30, 45, 60 s.	[106]

3.3. Wines

The literature extensively reports wine as a digestion aid and protector against infections from common foodborne pathogens such as *C. jejuni*, *Salmonella* spp., *E. coli* O157:H7, *B. cereus*, and *L. monocytogenes* [107–110].

The antimicrobial mechanism of wines is still not fully understood. Wine is an exceedingly complex matrix possessing low pH, high content of organic acids (such as malic and tartaric acid), and high ethanol concentration [111]. In addition, polyphenols and fatty acids are also present in wines [112], alongside sulphur dioxide, often added to wines as an antioxidation agent [113]. All these compounds are known for possessing antimicrobial action.

The antibacterial activity of wine might not be due to one single constituent but the overall combination of such components. Just and Daeschel (2003) observed that the wine and grape juice from the same grapes had similar pH levels and showed different antimicrobial strengths against *E. coli* O157:H7 and *Salmonella* spp. Furthermore, although the notion that ethanol could have been chiefly involved in the wine's bactericidal effect was perfectly valid, it was disproven by the lack of antimicrobial activity shown by ethanol solutions diluted to concentrations commonly found in wines (10 to 15% ethanol) [109].

The work of Santoro et al. (2020), assessing the antimicrobial activity of various wines tested on a fish matrix, also supported the notion that the antimicrobial capacity of wine may come from a synergistic action of its components rather than a particular constituent. None of the tested wine constituents matched the wines' antimicrobial action [114].

The antimicrobial activity of wine was evaluated in broth models in which a selected concentration of pathogens was added directly to the wine or to the wine solution. In these environments, variables such as matrix protection are not observed or even considered. As such, any compound will achieve its highest antimicrobial potential. Therefore, when performing the same experiment on food matrices, we may not reach the same result due to the protection offered by the food matrix. The parallelism between broth models and food matrices does not translate well. Isohanni et al. (2010) demonstrated that, in a broth model, wine reduced *Campylobacter* by 7 log cycles in just 15 min. However, when applied to a food matrix, the same wine only decreased *Campylobacter* by 1 log cycle after 48 h of exposure [115].

According to Friedman et al. (2007), wine acts as a good solvent for EOs, for instance, thymol and carvacrol. Accordingly, wine may be used not only for its bactericidal effect but also as a solvent for EOs, thus enabling the creation of complex solutions containing organic acids and EOs. The synergistic effect of these compounds would lead to effective antimicrobial action by the marinade without resorting to synthetic food preservatives [116].

In Table 4, summaries of the various studies evaluating the antimicrobial activity of wines are presented.

Table 4. Studies evaluating the antimicrobial activity of wines.

Wine Employed	Microorganisms Tested	Major Effects	Matrix	Exposure Conditions	References
Red wine (Sauvignon Blanc) and White wine (Cabernet Sauvignon)	*Campylobacter jejuni* *Campylobacter coli*	For the broth models, white wine reduced up to 7 log10 CFU/mL of *Campylobacter* spp. in just 15 min. However, in the food matrix, the identical wine only reduced *Campylobacter* loads by 1.0 log10 CFU/mL over 48 h.	Broth model and Chicken breast fillets	Immersion for 10, 15, and 30 min, and 1, 3 h at room temperature. 24 and 48 h at 4 °C.	[115]
Red wine (Douro)	*C. jejuni*	In broth, undiluted wine and its components drastically reduced the *C. jejuni* counts by approximately 7.0 log10 CFU/g. Furthermore, ethanol and the organic acids present in the wine is suggested to work synergistically. Additionally, in the stomach model, the wine enhanced the antimicrobial activity of the gastric fluid against *C. jejuni*.	Broth and stomach model	The pathogen was directly exposed to the wine solution both in broth and in the stomach model.	[107]
Red wine (Pinot Noir) and white wine (Chardonnay)	*Escherichia coli* O157:H7 *Salmonella* Typhimurium	When added directly into wine solutions, both pathogens were rapidly inactivated after 1 h for *E. coli* and half an hour for *Salmonella*. However, in the stomach model, the wine showed no antimicrobial action against *E. coli* O157:H7, whereas *Salmonella* was reduced to undetectable levels after 2 h of exposure to the wine. For *Salmonella*, the primary antimicrobial activity of the tested wine showed to be acid related.	Broth and stomach model	The pathogen was directly exposed to the wine solution both in broth and in the stomach model.	[109]
Red wine (Cabernet) and white wine (Chardonnay)	*E. coli* O157:H7 *Listeria monocytogenes* *S.* Typhimurium *Staphylococcus aureus*	Of all the tested pathogens, *Salmonella* was the most susceptible pathogen to red wine, with *S. aureus* presenting itself as the least susceptible to both wines. Ethanol and organic acids appeared to work synergistically with one another.	Broth model	The pathogen was directly exposed to the wine solution.	[117]

4. Conclusions

The available scientific information shows that the marination processes involving natural ingredients rich in organic acids or EOs can indeed prevent the growth of common foodborne pathogens such as *Campylobacter* spp. and *Salmonella* spp. in poultry meat, as well as promote their inactivation. In addition to reducing pathogen counts, marination processes have demonstrated significant capability in extending the shelf life of meat products and the overall taste experience.

On average, marinades lead to a pathogen reduction of about 1.0 to 2.0 log10 CFU/g. While noteworthy, this activity does not guarantee the absolute safety of the product. Furthermore, in the instances of pathogens mitigation solely due to the antimicrobial activity of organic acids, EOs, and wines, questions arise regarding the acceptability of the product after treatment. Hence, the need arises to simultaneously focus on consumer experience while attempting to achieve significant antimicrobial action.

Lastly, when used in combination with other preservation processes, marination increases the sensitivity of common foodborne pathogens to such treatments. Attending to these factors, if correctly tuned in their compositions, and when employed alongside other preservation methods, marinades may act as valuable and relatively inexpensive hurdles that further increase product safety and stability.

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