Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 32s (2025)
https://www.jneonatalsurg.com

Mechanistic Insights into Antioxidant and Antimicrobial Actions of Citrus and Medicinal Plant-Based Extracts for Meat Preservation

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.Cite this paper as: G Gnanavel, Prathika A, Ardra P, Thansimol T, Arivumathi S, (2025) Mechanistic Insights into Antioxidant and Antimicrobial Actions of Citrus and Medicinal Plant-Based Extracts for Meat Preservation. *Journal of Neonatal Surgery*, 14 (32s), 2960-2971.

ABSTRACT

The application of natural preservatives, especially citrus extracts and plant-source essential oils, has developed into a viable option compared to synthetic preservatives to extend the lifespan of flesh products. With high levels of bioactive compounds, natural preservatives are recognized for having excellent antioxidant and antimicrobial activity, inhibiting microbial growth and hindering lipid oxidation. According to studies, citric-based preservatives, i.e., lemon, lime, and pomelo peel extracts, were greatly effective in achieving shelf life under different storage conditions. Importantly, treating citrus extracts with an oxygen absorber (0.1-0.2 ml/100g) increased the lifespan of ground chicken by about 4 to 6 days at 4°C. Adding lime peel extracts containing 0.25% oil effectively maintained the standard of chicken cakes when kept at 4°C for nine days. Lemongrass, chitosan, and citrus essential oil nano-emulsion coatings (1.5%) also increased chicken breast fillets' lifespan by 5 days through cold storage. A comprehensive meta-analysis found that incorporating citrus additives at concentrations ranging from 0.2% to 1.5% effectively extended the lifespan of raw chicken flesh by 21 days under refrigeration at 4°C. Other treatments, including citrus by-product extracts (5 mg/mL) and alginate films carrying cinnamon and rosemary essential oils (5 mg/mL), successfully extended lifespan by 9 days and 2 days, respectively. These findings indicate that the highest-performing concentrations of citrus-based additives promise to improve meat preservation by slowing spoilage and preserving sensory characteristics. Combining natural preservatives with novel delivery systems, such as nanoemulsion, presents a valuable strategy for the meat industry to address consumer pressure for clean-label, naturally preserved products. There is a need for future studies to optimize such methods for wider-scale commercial application, mitigating sensory impacts and regulatory requirements.

Keywords: *Meat preservation, Essential oils, Nano emulsion, Antioxidant& antimicrobial activity, Shelf-life*

1. INTRODUCTION

Consuming contaminated food poses significant health risks, affecting millions of individuals annually and leading to severe illnesses and fatalities (Yu et al., 2021). According to the WHO, unsafe food contributes to 600 million cases of disease and 420,000 deaths each year, particularly impacting young children under five, with 125,000 lives lost to foodborne diseases. Chemical, synthetic preservatives, and allergens contribute to this burden, reducing global healthy life expectancy by 33 million years. However, adopting simple, everyday safety measures can significantly reduce the incidence of foodborne illnesses and prevent unnecessary health risks.

Meat and its derived products are indispensable parts of our daily diet, providing high-quality proteins, essential amino acids, vitamin B12, and key minerals like iron and zinc (Budiarto et al., 2024). However, because meat is highly perishable, it serves as a fertile ground for the rapid growth of dangerous bacteria, including *Staphylococcus aureus, Clostridium botulinum, Campylobacter jejuni, Cryptosporidium hominis, Bacillus cereus, Escherichia coli O157: H7 & Listeria monocytogenes,* thereby raising significant food safety concerns (Teshome, 2022). To preserve freshness and delay spoilage, the meat industry commonly employs cost-effective synthetic antioxidants, such as sodium ascorbate, propyl gallate, sodium erythorbate, tert-butylhydroquinone (TBHQ), butylated hydroxyanisole (BHA), and butylated hydroxytoluene (BHT), alongside curing salts like nitrite and nitrate. While these substances are both affordable and readily accessible, their prolonged use has been associated with various adverse health effects, including allergies, asthma, hyperactivity, neurological damage, and an increased possibility of cancer (Bellucci et al., 2022).

The food and agriculture industries have increasingly leaned toward employing natural preservatives derived from fruits and plant materials to limit the proliferation of foodborne pathogens. This shift is largely attributed to growing consumer demands for products that are more ethical, healthier, and environmentally sustainable (Domínguez et al., 2021). Fruits and herbal extracts are exceptionally rich in bioactive substances. They contain a variety of polyphenolic compounds, including flavanols, anthocyanins, benzoic acid, tannins, lignin, stilbenes, cinnamic acid, and other phenolic acids, along with terpenoids such as carotenoids, terpenes, triterpenes, phytosterols, and iridoids. Additionally, these natural sources offer organosulfur compounds and alkaloids, which collectively provide significant antioxidant and antimicrobial benefits. As a result, they serve as effective natural agents that can supplement or fully replace conventional synthetic food preservatives (Awad, 2022).

Citrus essential oils boast a diverse blend of phenolic substance like flavonoids (including flavanones, flavones & flavanols), anthocyanins, and coumarins that impart intrinsic antimicrobial effects against an array of bacteria, yeasts, and molds in both liquid and vapor states, while their inherent antioxidant capacity makes them particularly valuable for natural food preservation and traditional medicinal applications (Mexis et al., 2012; Alzaidi Mohammed Awad et al., 2021).

Extending freshness of flesh products without sacrificing their safety or quality remains a major challenge, yet emerging evidence suggests that bioactive compounds from citrus fruits and other plant extracts can enhance nutritional value, improve flavor and oxidative stability, and counteract free radical damage that may lead to chronic diseases, offering a promising natural strategy to prolong shelf life (Olvera-Aguirre et al., 2023).

Table 1: Major Pathogens Linked to Meat and Meat Products: Diseases and Sources

Pathogen	**Associated Disease**	**Common Source**
Clostridium botulinum	Botulism	Improperly canned meats
Staphylococcus aureus	Food poisoning (enterotoxins)	Poor handling of meat
Campylobacter jejuni	Campylobacteriosis	Undercooked poultry
Bacillus cereus	Diarrheal and emetic syndrome	Cooked meat left at room temperature
Listeria monocytogenes	Listeriosis	Deli meats, hot dogs
Escherichia Coli O157: H7	Hemorrhagic colitis, hemolytic Uremic Syndrome (HUS)	Undercooked ground beef
Cryptosporidium hominis	Cryptosporidiosis	Contaminated water, meat

2. ADVANCES IN NATURAL PRESERVATIVE APPLICATION FOR MEAT PRODUCTS: MECHANISTIC INSIGHTS AND INNOVATIVE STRATEGIES

The methods used to preserve meat in ancient periods were salting, curing, drying, or fermentation. Salting and curing increase the lifespan of flesh and flesh products. Salting can inhibit the growth of microorganisms by removing water content in the organism (Arokiyaraj et al., 2024). Drying is one of the older techniques; it can remove the water content through evaporation, so organisms don't grow and can extend their lifespan. The major limitation of using this method is that the colour, odour, and flavour will change because of contamination and cause health issues (Arokiyaraj et al., 2024; Talib, 2024; Shaltout, 2024). Synthetic preservatives were added to overcome this problem and enhance the shelf life. Nonetheless, the health hazards posed by incorporated additives, growing microbial resistance, and the need for clean-label products have underscored the shortcomings of traditional methods. So, the scientists changed to natural preservative methods by using new technologies such as nanoemulsion, Nanoencapsulation, Cold Plasma Treatment, Electrospun Nanofibers, Smart biodegradable films, and Pickering emulsions (Shaltout, 2024).

Nanoemulsions, emerging from nanotechnology, are engineered by blending oil, water, and emulsifiers into ultrafine droplets that efficiently transport bioactive compounds from food to the human body, offering benefits such as antibacterial, antioxidant, and flavor-enhancing properties in meat products; however, their application in the food industry is constrained by toxicity concerns associated with their droplet sizes (typically less than 200 nm) (Walker et al., 2015; Abbas et al., 2013; Ozogul et al., 2022). Antimicrobial nanoemulsions are crafted based on the type and placement of antimicrobial agents: one strategy relies on an oil phase that naturally exhibits antimicrobial properties (like essential oils), another involves dissolving a lipophilic antibiotic such as a polyphenol in a neutral oil (for example, corn oil), a third approach uses a specialized antibiotic emulsifier to both create and stabilize the nanoemulsion, and finally, combining different antimicrobials at distinct spatial locations within a single formulation can significantly boost its effectiveness. The antimicrobial drugs can transfer from the nanoparticles to the microbial surfaces through molecular diffusion, micellar diffusion, or collisions (Ujilestari et al., 2023).

Atmospheric cold plasma is gaining recognition as an innovative nonthermal decontamination method that inactivates pathogens without applying heat, though its application has been linked to increased lipid oxidation in meat products (McClements, 2021; Gao, 2021). In practice, plasma dielectric barrier discharge is used for antimicrobial treatment before the products are sealed in their packages (Gao, 2019; Pankaj, 2014), establishing this approach as a green alternative. The process unfolds in three sequential stages: first, as stored gases revert to their natural state, they facilitate the release of antibiotic components; next, bactericidal molecules are integrated into the packaging, enhancing contact with the target microorganisms; and finally, the interaction among the final product, the packaging material, the package design, and the headspace environment collectively contributes to a substantial reduction in the microbial population (Keener & Klockow, 2013).

Atmospheric cold plasma is recognized as an innovative nonthermal method that deactivates pathogens without employing heat (McClements, 2021), although this technique has been noted to increase lipid oxidation in meat products (Gao, 2021); by using plasma dielectric barrier discharge for antimicrobial treatment before sealing the products (Gao, 2019; Pankaj, 2014), this eco-friendly approach operates in three stages—first, it allows the stored gases to revert naturally and release antibiotic components, then it integrates bactericidal molecules within the package, and finally, through the combined effects of the product, packaging material, design, and headspace environment, it achieves a significant reduction in microbial populations (Keener & Klockow, 2013).

The requirement for natural and biodegradable packaging substances is increasing, though the synthetic and petroleum-based products create health issues. These petroleum-based products, plastics, trouble the environment (Atiwesh et al., 2021; Huda, 2025). For that, developing the gelatin-based filling film using natural plant extracts that contain antibiotic substances in contact with food items stops the prevalence of foodborne pathogens, which helps sustainable food packaging (Wakte, 2011). Wall substance drawn out from plant cell walls is utilized in packaging films (Hadidi, 2022; Salimiraad et al., 2022; Siriamornpun et al., 2016). The wall material, polysaccharides, proteins, and lipids can provide better mechanical strength and excellent oxygen barrier properties. Ultrasonic-assisted gelatin-based filling films with 1–2 % extract were generated to assess their mechanical and physical properties, and biologically active compounds allow them to remain in a liquid medium (Ghosal et al., 2018).

Pickering mixtures are a type of emulsion that supplements the nutritional and sensory attributes of flesh, also increasing the lifespan of flesh (Sobral et al., 2001; Cheng, 2024). They summarize water-loving and water-repellent composites, giving a multipurpose perspective on food conservation that meets the requirement for natural, environment-friendly, and secure methods (Wigati, 2023). It can preserve fruits, vegetables, meat, and seafood (Yang, 2025; Bai, 2023). Pickering emulsions are effective carriers for encapsulating active substances, increasing bioavailability, and controlling release rates. Controlled release mechanisms extend the efficacy of antimicrobials and antioxidants, remarkably expand the lifespan and secure (Klojdová & Stathopoulos, 2022) (Delmar, 2025) (Zhang, 2022). As a maintainable, well-organized & versatile strategy, Pickering emulsions label traditional technique restrictions and agree with clean and health-aware, gathering the claim for secure, nutritious, and non-perishable food products (Jiang et al., 2020).

3. PHYTOCHEMICAL PROFILES OF CITRUS FRUITS AND MEDICINAL PLANTS USED IN MEAT PRESERVATION

Phytochemicals, including phenolic compounds, alkaloids, terpenoids, coumarins, saponins, steroids, essential oil components, etc, are present in plants, fruits, and vegetables. These compounds help to preserve meat or vegetables. It has antioxidant, antimicrobial, and anti-inflammation activities, making it a suitable alternative for synthetic preservatives.

Table 2: Mechanisms and Benefits of Key Phytochemicals in Meat Shelf-Life Extension

Phytochemical	Source	Structure/class	Mechanism of action in meat preservation	Notable activities	Reference
Phenolic compounds	Plant-based: citrus fruits, herbs, vegetables	Aromatic rings with hydroxyl groups; includes gallic, vanillic, and syringic acids	Antioxidant; scavenge free radicals; prevent lipid oxidation; antimicrobial	Antioxidant, antimicrobial, anti-inflammatory	(Cesar, 2010) [46
Flavonoids	Widely found in fruits, vegetables, and herbs	Polyphenolic compounds;	Scavenge free radicals; interfere with microbial membranes; inhibit lipid/ protein degradation	Antioxidant, antimicrobial	(Lattanzio, 2013)
Terpenoids	Camphor, ginger, citrus oils, oregano, thyme	Isoprene units include camphene limonene	Disrupts microbial cell membranes; strong antifungal and antibacterial effects	Antibacterial, antifungal, anticancer	(August & Santos, 2020) (Girola, 2015)
Alkaloids	Medicinal plants like Senecio vulgaris, vinblastine sources	Nitrogen-containing heterocyclic compounds: pyrrolizidine, camptothecin	Target microbial DNA/proteins; used pharmaceutically as bioactive agents	Antimicrobial, anticancer, sedative	(Mohammadi-Cheraghabadi & Hazrati, 2023) (Anis, 2011)
Coumarins	Rutaceae(citrus), Apiaceae, leguminous	Benzopyrene derivatives are formed via the shikimate pathway	Insecticidal, antimicrobial activity; disrupts cellular processes in microbes	Antimicrobial, selective insecticidal	(Ahmed, 2017)
Saponins	Roots, seeds, leaves	Glycosides with triterpenoid or steroid backbone and sugar moieties	Form emulsions; disrupts microbial membranes; improves antioxidant stability of emulsions	Emulsifier, antioxidant, antimicrobial	(Pavela et al., 2021)

4. APPLICATIONS OF PLANT AND CITRUS-BASED NATURAL PRESERVATIVES IN FLESH AND FLESH PRODUCTS

In recent years, ensuring food quality has become increasingly challenging as the industry contends with a wide variety of harmful microorganisms, including *Salmonella* spp., *Shigella* spp., *Enterococcus faecalis*, *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Campylobacter jejuni*, *Yersinia enterocolitica*, *Vibrio parahaemolyticus*, *E. coli* O157:H7, and *Clostridium botulinum* (Doost, 2019). This persistent microbial threat has spurred a shift toward natural preservation methods. Particularly, extracts derived from plants and fruits have gained attention due to their rich content of bioactive compounds, which not only retard microbial growth but also help extend the shelf life of food products. The following review explores the various plant extracts and fruit-based preservatives successfully employed to meet these challenges (Rai et al., 2016)

Polyphenols are widely recognized for their antimicrobial properties, even though their exact mode of action is not completely understood. Previous literature, including the review by (Pateiro et al. 2021), suggests several potential mechanisms. For instance, one pathway involves the action of hydroxyl groups (OH^-) that disrupt the integrity of bacterial cell membranes. This disruption leads to the leakage of key intracellular materials, the deactivation of vital metabolic enzymes, and a subsequent collapse in ATP production. Another proposed mechanism involves alterations in the local pH. By increasing the concentration of protons in the environment, these compounds lower the intracellular pH, a change that affects enzyme activity and membrane permeability. In addition, organic acids present in certain plant extracts may interfere with the oxidation process of NADH, thereby diminishing the reducing agents essential for the electron transport chain (Lee & Paik, 2016). This multifaceted antimicrobial action of polyphenols illustrates their potential as effective natural antibiotics, offering promising insights for developing food preservation strategies and alternative therapeutics.

The spoilage occurring in flesh and flesh products is susceptible to oxidation reactions, mostly those that call for the degradation of lipids (Hongyan et al., 2025). The antioxidant is a must for preserving meat. For that, different medicinal, aromatic plants and citrus fruits can be used. Those polyphenols can be favorable due to their efficacy as scavengers of radicals and the additional health benefits they bring to meat products (Domínguez et al., 2019).

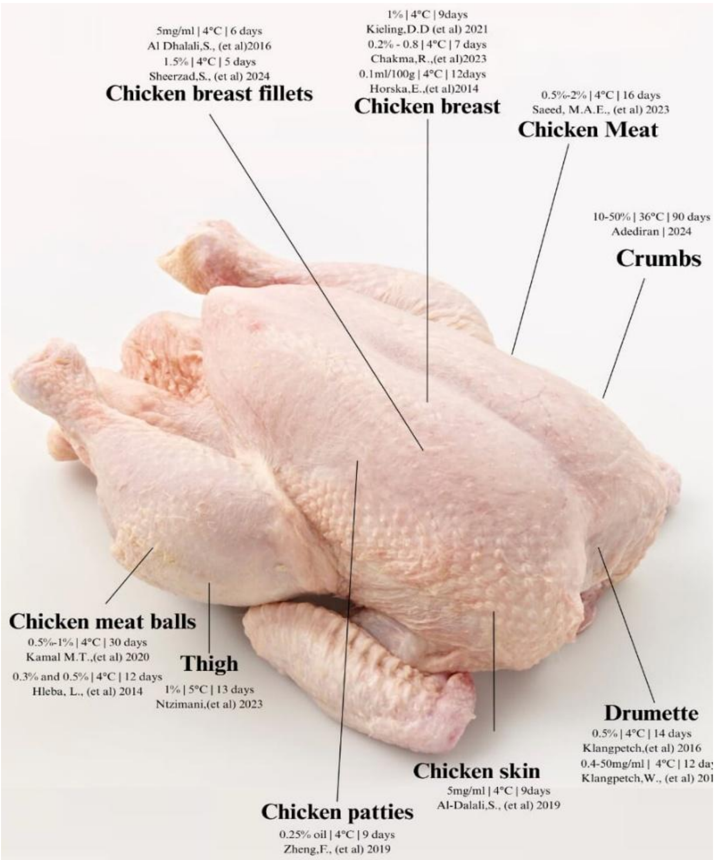
Table 3: Impact of plant extracts and essential oils on microbial growth and oxidation in Chicken Flesh

Sources	Concentration	Flesh part/ products	Storage parameters	Main outcomes	Reference
Citrus extract + O_2 absorber	0.1 and 0.2 ml/100 g	Ground chicken flesh	4 °C, +2 days (from approximately 4 to 6 days)	Decrease total viable count; shelf +2 days	(Mexis et al., 2012)
Lemongrass & lime peel extracts	0.25% oil	Chicken patties	4 °C, 9 days	Decrease Thiobarbituric acid reactive substance, pH; maintained sensory	(Al-Dalali et al., 2019)
Whey Protein Isolate-Nano Chitosan coating + citrus essential oil	1.5%	Chicken breast fillets	4 °C, +5 days	Decrease microbial growth; maintain colour	(Sheerzad et al., 2024)
Meta-analysis of citrus additives	0.2- 1.5%	Raw chicken meat	4 °C, 14–21 days ext.	Decrease aerobic bacteria, total viable count, and improved acceptability	(Budiarto et al., 2024)

Citrus by-product extracts	5 mg/mL	Chicken skin	4 °C, 9 days	Decrease foodborne pathogens	(Al-Dalali et al., 2019)
Alginate film with cinnamon & rosemary EO	5 mg/mL each	Chicken breast	4 °C, approximately 6days	Increased lifespan by approximately 2 days	(Al-Dalali et al., 2019)
Starch nanocrystals + lemon peel extract	2–10%+ 2.5–12.5%	chicken fillets	12 days, cold storage	Shelf life extended	(Alizadeh et al., 2019)
Kaffir lime, lime, pomelo peel EO	0.4–50 mg/mL	Chicken drumettes	4 °C, 14 days	Decrease total viable count; Decrease Thiobarbituric acid reactive substance; Decrease; maintain sensory	(Klangpetch et al., 2016)
Gondhoraj (Citrus hystrix) EO coating	0.2%, 0.4%, and 0.8%	Chicken breast	4°C, 7 days	Improved oxidative stability & sensory	(Chakma, 2023)
Sweet orange, lemon, lime rind EO	200–400 mg/mL	Infected chicken meat	Ambient, 24 h	Decrease 1.1–7.9 log CFU of pathogens; no sensory change	(Irokanulo et al., 2022)
Various EOs cinnamon, mint , etc.)	0.5%- 2%	Chicken meat	4 °C, up to 16 days	Increase shelf life by 4–12 days; variable sensory	(Saeed et al., 2023)
Lemon extract	0.5%- 1%	Chicken meatballs	4 °C, up to 30 days	Decrease lipid peroxidation; Increase shelf life	(Disha et al., 2020)
Clove powder & lemongrass	0.2%-1%	Raw chicken emulsion	4 °C, 9 days	Best combo: Decrease microbial & oxidation	(Singh et al., 2014)
Chitosan + Citrus limon EO coating	2 % and 4 %	beef meat	Cold storage, 16 days	Improved quality & shelf life	(Isvand et al., 2024)

Lemon extract powder	0.5–1%	Pork sausages	2–3 °C, 30 days	Decrease Thiobarbituric acid reactive substance; Decrease Aerobic plate count; maintain color.	(Bae et al., 2021)
Citrus extract	1%	chicken thighs	13 days at 5 °C	Increase shelf life, decrease total viable count.	(Ntzimani et al., 2023)
Tropical citrus peel extracts	0.5%	Raw chicken drumettes	4 °C, 14 days	Decrease minimum inhibitory concentration 0.4–50 mg/mL; Decrease Thiobarbituric acid reactive materials	(Klangpetch et al., 2016)
Sweet lime peel nano-capsules	0.5–1% v/v	Irradiated patties	−5 °C, 14 days	Decrease Peroxide value, Total volatile basic nitrogen, Decrease Thiobarbituric Acid reactive substance; improved stability	(Hanif et al., 2025)
Lemongrass extract	1%	Shredded breast	4 °C, 9 days	Inhibited Staphylococcus & Salmonella	(Kieling et al., 2021)
Oregano & thyme EOs + vacuum	0.1 mL/100 g	Breast meat	4 °C, 12 days	Lifespan increases by 1 day; Decrease total viable count.	(Pavelková et al., 2014)
Lemon Juice Marination in Chicken Crumbs	Lemon juice at 10–50 %	Chicken crumbs	Room temperature, 90 days	10% lemon juice reduced oxidative rancidity to 1.63 mg/g compared to 3.77 mg/g in the control; improved water holding capacity and pH stability.	(Adediran et al., 2024)
Grapefruit Seed Extract in Cured Chicken Breast	0.05 – 0.5%	Cured chicken breast	Cold storage		(Kang et al., 2017)

				Improved flavour and acceptability, reduced lipid peroxidation and volatile basic nitrogen; enhanced water holding capacity and texture.	
Thyme and cumin EOs	0.4 & 0.8% v/w	Chicken meat burgers	2 °C, 27 days	A composite of EOs and vacuum packaging significantly expands the lifespan.	(Karam et al., 2019)
Rosemary EO	0.3% and 0.5%	Chicken meatballs	4 °C, 12 days	REO-coated vacuum packaging improved microbiological and sensory quality.	(Pavelková et al., 2014)
Thyme leaf extract	250, 500, and 1000 ppm	Chicken and lamb patties	4 °C, 12 days	Thyme extract, particularly at 500 ppm, significantly stopped lipid oxidation and microbial growth, enhancing lifespan.	(Baker et al., 2014)



5. CONCLUSION

In summary, organic preservatives, namely citrus essence and essential oils of plant origin, are good alternatives to synthetic additives for meat preservation. Rich in phenolics, they possess strong antioxidant and antimicrobial activities that effectively stop microbial growth and lipid oxidation, increasing the lifespan of flesh products. Of the different approaches tried, nano-emulsion-based coatings with chitosan and citrus essential oils proved the most effective. These nanoemulsions increase the stability and controlled release of active ingredients, resulting in great reductions in microbial numbers and oxidative degradation with the preservation of the sensory attributes of meat during cold storage. Combining such innovative delivery systems with natural bioactive agents not only enhances preservation efficiency but also addresses consumer preference for clean-label, naturally preserved meat products. Future studies should aim to refine these techniques for commercial use, resolve sensory effects, and meet regulatory requirements to enable wider use in the food industry.

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