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Review Article

Biological control of *Salmonella* on egg surfaces using plant-based compounds: A review

Nurten Yılmaz[1,2]

[1]*Department of Medicinal and Aromatic Plants, Vocational School of Karaisali, Cukurova University, Adana, Türkiye;* [2]*Biotechnology Research and Application Center, Çukurova University, Adana, Türkiye*

Abstract

Salmonella contamination of shell eggs is a major public health concern worldwide and continues to challenge the poultry industry. Although conventional chemical sanitizers are effective, concerns regarding chemical residues, environmental impact, and consumer demand for clean-label products have accelerated interest in plant-derived antimicrobials. This review summarizes recent advances in the application of essential oils and plant extracts for controlling *Salmonella* on eggshell surfaces. Particular attention is given to the antimicrobial mechanisms of major bioactive compounds, including thymol, carvacrol, eugenol, cinnamaldehyde, and phenolic-rich plant extracts. The review also discusses practical application strategies, including washing, spraying, nanoemulsion-based delivery, and active packaging, highlighting their effectiveness in enhancing antimicrobial stability and prolonging egg shelf life. Finally, current challenges related to formulation standardization, industrial scalability, and regulatory approval are addressed, together with future perspectives for integrating plant-derived antimicrobials into sustainable egg sanitation systems.

Keywords: Active packaging, nanoemulsion, natural antimicrobials, plant extracts, *Salmonella enterica*

Introduction

Despite their exceptional nutritional value, eggs remain highly susceptible to microbial contamination during production, handling, transportation, and storage. Among the diverse foodborne pathogens associated with eggs, *Salmonella enterica*, particularly *Salmonella* Enteritidis, represents one of the most significant public health concerns because of its remarkable ability to survive on eggshell surfaces, penetrate the shell structure, and ultimately contaminate internal egg contents (Illera et al., 2022; Oliveira et al., 2022). Consequently, effective decontamination of eggshell surfaces has become a critical prerequisite for reducing foodborne outbreaks, improving consumer safety, and extending the commercial shelf life of table eggs. Although synthetic sanitizers are capable of reducing microbial loads under industrial conditions, their widespread use has generated increasing concern regarding chemical residues, occupational exposure, environmental contamination, deterioration of eggshell quality, and the possible selection of tolerant bacterial populations after repeated application. Formaldehyde fumigation, for example, remains one of the most effective sanitization approaches for

* **Correspondence:** N. Yilmaz (ntoy@cu.edu.tr).
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hatching eggs but has been increasingly criticized because of its toxicity toward both humans and developing embryos, motivating intensive research into safer alternatives (El-kashef & El Sabry, 2025; El-Sabrout et al., 2026).

Growing consumer preference for minimally processed foods and clean-label preservation strategies has substantially accelerated the development of naturally derived antimicrobial compounds for food protection. Instead of relying solely on synthetic disinfectants, contemporary food preservation increasingly exploits bioactive compounds extracted from plants, microorganisms, and renewable biological materials (Alkan & Yemenicioğlu, 2016). Essential oils (EOs), bacteriocins, edible biopolymers, plant phenolics, organic acids, and antimicrobial peptides have attracted considerable attention because they combine broad-spectrum antimicrobial activity with relatively favorable toxicological profiles and compatibility with sustainable food production systems (Karnwal & Malik, 2024; Teshome et al., 2022)

Natural antimicrobial compounds exhibit several advantages over conventional chemical sanitizers. Rather than acting through a single cellular target, many phytochemicals simultaneously disrupt bacterial membranes, interfere with ATP generation, alter membrane permeability, induce oxidative stress, inhibit quorum sensing, and suppress biofilm formation (Zhang et al., 2026). Such multi-target antimicrobial mechanisms considerably reduce the probability of bacterial adaptation while providing broad antimicrobial spectra against Gram-positive and Gram-negative pathogens, including *Salmonella*, *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* (Raikwar et al., 2024). Among naturally occurring antimicrobials, EOs have emerged as particularly promising candidates for eggshell sanitation. Phenolic constituents such as thymol, carvacrol, eugenol, cinnamaldehyde, limonene, citral, and allyl isothiocyanate exhibit potent bactericidal activity by rapidly penetrating bacterial membranes, disrupting phospholipid bilayers, increasing membrane permeability, and causing leakage of intracellular constituents (Allen et al., 2023; Upadhyaya et al., 2013).

Several experimental investigations have demonstrated that plant-derived antimicrobials can achieve remarkable reductions in *Salmonella* contamination within extremely short exposure periods (Elkomy et al., 2023; Upadhyaya et al., 2016). Despite these considerable advances, several technological challenges remain before natural antimicrobial interventions can be fully integrated into commercial egg production. Variability in EOs composition, limited stability of volatile bioactive compounds, interactions between antimicrobials and coating matrices, possible alterations in sensory quality, regulatory approval, industrial scalability, and economic feasibility continue to require comprehensive investigation (Konfo et al., 2023; Y. Zhang et al., 2026). Nevertheless, continuous progress in formulation technologies, nano-delivery systems, smart active packaging, and multidisciplinary preservation strategies strongly suggests that natural antimicrobial compounds will become integral components of future egg sanitation systems. Accordingly, this review critically summarizes current knowledge regarding the biological control of *Salmonella* on eggshell surfaces using natural antimicrobial compounds, emphasizing antimicrobial mechanisms, application technologies, coating systems, operational limitations, and future perspectives for sustainable egg safety.

Mechanisms of *Salmonella* contamination in eggs

Eggshell contamination primarily occurs after oviposition when freshly laid eggs are exposed to fecal material, litter, dust, contaminated nesting environments, processing equipment, and human handling. During this stage, *S.* Enteritidis readily colonizes the shell surface, where its subsequent fate depends largely on environmental conditions including temperature, relative humidity, storage duration, and the integrity of the eggshell cuticle (El-Sabrout et al., 2026; Oliveira et al., 2022). Initial bacterial attachment to the shell surface involves reversible physicochemical interactions that develop into irreversible adhesion through exopolysaccharides, fimbriae, and surface proteins. Subsequent biofilm formation enhances bacterial resistance to disinfectants, desiccation, UV exposure, and other stresses, reducing the effectiveness of conventional sanitization methods and contributing to persistent contamination (Shah et al., 2025). The eggshell cuticle is the first natural barrier against microbial invasion, reducing pore accessibility and bacterial penetration. However, its protective function declines due to abrasion, washing, storage, and improper sanitization. Damage to the cuticle enhances bacterial attachment and migration, highlighting the importance of preserving cuticle integrity in alternative biological sanitation strategies (Harris et al., 2022). The shell matrix itself provides partial mechanical resistance against bacterial migration through its complex calcium carbonate architecture. Nevertheless, microscopic cracks, structural irregularities, and enlarged pore openings substantially reduce this protective capacity (Supaphol, 2026). These contamination mechanisms also explain why simple aqueous washing frequently provides limited microbial reduction. Water alone cannot efficiently disrupt firmly established bacterial adhesion or biofilm matrices and may even facilitate bacterial movement through shell pores if inappropriate washing temperatures are used (Gole et al., 2014; Samiullah et al., 2013). Consequently, modern biological sanitation strategies increasingly incorporate compounds capable of simultaneously damaging bacterial membranes, inhibiting biofilm formation, and maintaining prolonged antimicrobial activity on the shell surface (Melo et al., 2019).

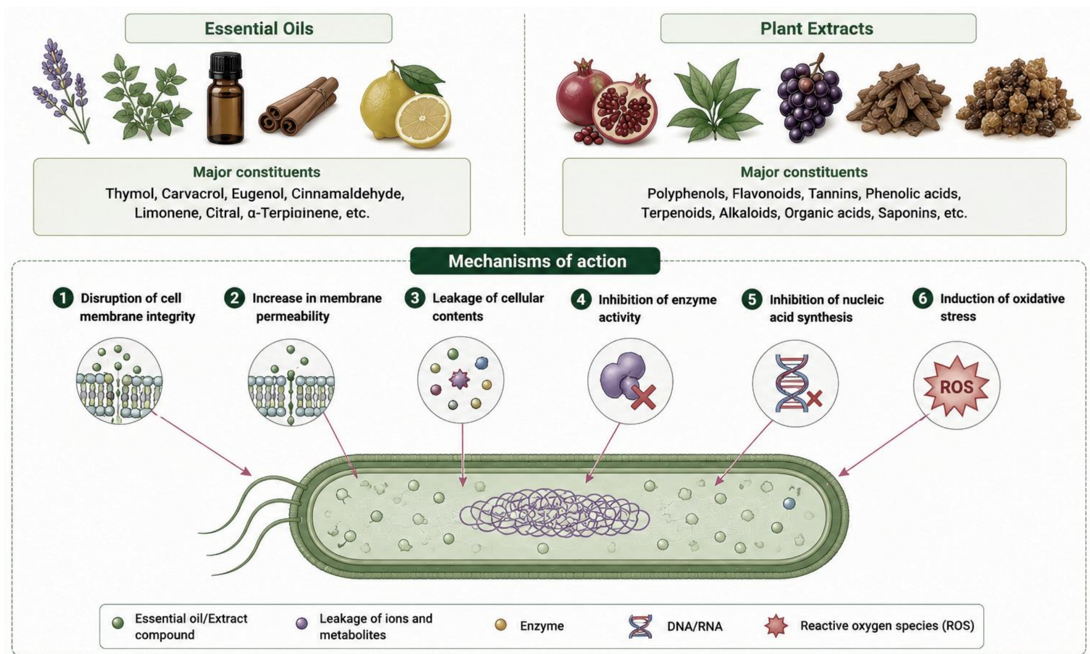

Figure 1. Mechanisms of action of natural antimicrobials against *Salmonella.*

Natural plant based antimicrobial agents

Essential oils

The antimicrobial efficacy of EOs primarily depends on their hydrophobic nature, which facilitates penetration through the outer membrane of Gram-negative bacteria such as *Salmonella* (Dai et al., 2026). After diffusing into the phospholipid bilayer, bioactive compounds disrupt membrane integrity, increase permeability, collapse the proton motive force, interfere with ATP synthesis, and promote leakage of intracellular constituents including nucleic acids, proteins, and ions. At higher concentrations, irreversible membrane damage ultimately results in bacterial cell death (**Fig. 1**) (Guimarães et al., 2019). Besides membrane disruption, several EOs constituents also interfere with quorum sensing pathways and inhibit biofilm formation, thereby reducing bacterial persistence on eggshell surfaces (Nesa et al., 2025).

Thymol and carvacrol

Among all phytochemicals investigated for eggshell sanitation, thymol and carvacrol are consistently reported as two of the most potent antimicrobial compounds. These structurally related phenolic monoterpenes, predominantly found in thyme and oregano EOs, exhibit exceptional antimicrobial activity because their hydroxyl groups interact strongly with bacterial membrane phospholipids, resulting in severe membrane destabilization and rapid cytoplasmic leakage (Guimarães et al., 2019). Experimental evidence demonstrates that carvacrol rapidly inactivates *S.* Enteritidis on contaminated shell eggs. In one of the earliest postharvest washing studies, treatments containing carvacrol at concentrations of 0.5% and 0.75% completely eliminated detectable *S.* Enteritidis, even when eggshells were artificially contaminated with 3% chicken fecal material, outperforming conventional chlorine washing under identical experimental conditions (Upadhyaya et al., 2013). Similar observations were reported in subsequent investigations where postharvest washing with 0.25–0.50% carvacrol reduced *S.* Enteritidis to undetectable levels within only 30 seconds, highlighting the rapid antimicrobial kinetics of this phytochemical (Upadhyaya et al., 2014). The effectiveness of thymol has likewise been demonstrated in edible coating systems. Sweet potato starch coatings incorporating thyme EOs at concentrations of 2%, 4%, and 6% significantly inhibited *S. enterica* during storage (Sharaf Eddin & Tahergorabi, 2019). Although the 6% formulation maintained bacterial populations below detectable levels throughout storage, the 4% concentration was identified as the optimum formulation because it provided strong antimicrobial activity while maintaining desirable coating characteristics and overall egg quality. Beyond direct bactericidal activity, thymol also contributes to biofilm inhibition. Recent evidence indicates that thymol combined with bacteriophage CAU-SEP-3 synergistically disrupted *S.* Enteritidis biofilms on quail eggs without negatively affecting egg quality. Such synergistic approaches are particularly attractive because they permit lower concentrations of each antimicrobial agent while simultaneously improving efficacy against mature biofilms that are otherwise highly resistant to conventional disinfectants (Han et al., 2024).

Trans-cinnamaldehyde

Trans-cinnamaldehyde, the principal aromatic aldehyde of cinnamon EO, has emerged as one of the most extensively investigated phytochemicals for eggshell decontamination. Its antimicrobial activity originates from disruption of membrane-associated proteins, inhibition of energy metabolism, alteration of intracellular pH homeostasis, and suppression of biofilm-associated gene expression, making it highly effective against *Salmonella* under both planktonic and sessile conditions (Shah et al., 2025). Several studies have demonstrated remarkable antimicrobial performance of cinnamaldehyde-based treatments. Washing shell eggs with trans-cinnamaldehyde at concentrations between 0.25% and 0.75% rapidly eliminated *S.* Enteritidis, while fumigation with 1% trans-cinnamaldehyde for 20 min reduced *Salmonella* to undetectable levels on embryonated eggshells and prevented bacterial recovery until day 18 of incubation (Upadhyaya et al., 2015). These findings indicate that gaseous delivery systems may provide highly uniform antimicrobial coverage across complex eggshell surfaces while minimizing excessive liquid exposure. The introduction of nanoemulsion technology has further enhanced cinnamaldehyde performance. Allen et al. (2023) reported that trans-cinnamaldehyde nanoemulsions containing only 0.06–0.48% active compound achieved approximately 2–2.5 $\log_{10}$ CFU/egg reductions after only 1 min of washing without altering eggshell color. Such improvements largely arise from the reduced droplet size of nanoemulsions, which increases surface contact area, enhances bacterial membrane interactions, and improves aqueous dispersion of this highly hydrophobic compound.

Eugenol

Eugenol, the principal phenolic constituent of clove oil, represents another highly effective antimicrobial compound for eggshell sanitation. Similar to carvacrol, eugenol destabilizes bacterial membranes by disrupting phospholipid organization and increasing membrane permeability. Additionally, its phenolic hydroxyl group contributes to oxidative stress induction and protein denaturation, enhancing bactericidal activity against Gram-negative pathogens (Guimarães et al., 2019). Postharvest washing experiments consistently demonstrate excellent efficacy of eugenol against *Salmonella*. Concentrations of 0.5% and 0.75% completely eliminated detectable *S.* Enteritidis from contaminated shell eggs, including under conditions simulating heavy organic contamination with chicken droppings (Upadhyaya et al., 2013). Likewise, eugenol treatments at concentrations as low as 0.25–0.50% reduced *Salmonella* below detectable limits within 30 seconds of washing (Upadhyaya, 2014). More recently, vapor-phase delivery systems have significantly expanded the practical applications of eugenol. Incorporation of clove oil vapor into antimicrobial paper egg trays at approximately 40 μg/g, followed by UV-C irradiation, extended egg shelf life by approximately five-fold while exhibiting potent antibacterial activity against *Salmonella*, *E. coli*, and *S. aureus*. These findings demonstrate that continuous vapor release during storage may provide long-term antimicrobial protection beyond the immediate effects achieved by conventional washing treatments (Phothisuwan et al., 2020).

Limonene and other citrus EOs

Citrus-derived EOs have recently attracted considerable attention because of their pleasant aroma, low toxicity, and compatibility with active packaging systems (Bertolo et al., 2025). Among them, limonene exhibits broad antimicrobial activity by disrupting bacterial membranes and altering membrane-associated enzyme systems while offering superior consumer acceptance compared with some strongly aromatic phenolic compounds. Cold limonene vapor generated from nanoemulsions has demonstrated particularly impressive antimicrobial performance. Nanoemulsion concentrations of 0.04%, 0.08%, and 0.12% were evaluated, with 0.08% representing the minimum effective concentration when combined with ultraviolet treatment (Matan & Khunjan, 2026). Under these conditions, bacterial populations of *Salmonella* Enteritidis and *Staphylococcus aureus* decreased by approximately 6–7 $\log_{10}$, indicating nearly complete microbial elimination while preserving egg quality. Comparable success has been reported for citronella EOs. Vaporized citronella nanoemulsions applied at 40, 80, and 120 μL/mL generated thin antimicrobial films on quail eggs, with 80 μL/mL applied for 10 min providing the optimal balance between antimicrobial efficacy and coating uniformity while extending storage life (Kabploy et al., 2025). Similarly, orange oil incorporated into antimicrobial paper egg trays at concentrations between 0.001% and 0.004% (w/w) effectively suppressed pathogenic bacteria for up to 14 days, illustrating the considerable potential of volatile EOs in active packaging systems (Krittika Kabploy et al., 2023).

Plant and fruit extracts

Unlike purified EOs constituents, plant extracts contain diverse mixtures of phenolic acids, flavonoids, tannins, alkaloids, organic acids, and other secondary metabolites that collectively exert antimicrobial and antioxidant activities. The simultaneous presence of multiple bioactive compounds frequently generates synergistic interactions, enabling broader antimicrobial spectra while reducing the concentrations required for effective bacterial inhibition. Moreover, many plant extracts exhibit lower volatility than EOs, making them particularly suitable for incorporation into edible coatings intended for prolonged storage (Teshome et al., 2022).

Green tea (*Camellia sinensis*) is among the most extensively investigated botanical extracts for egg preservation because of its exceptionally high concentration of catechins, particularly epigallocatechin gallate, which possesses potent antimicrobial and antioxidant properties. These polyphenols interact with bacterial membranes, increase membrane permeability, inhibit essential enzymes, and induce oxidative stress, ultimately resulting in bacterial death (Friedman et al., 2006). Songsamoe et al. (2022) evaluated combinations of green tea extract and peppermint EOs for sanitizing eggs stored at ambient temperature. Among all formulations tested, a combination containing 10% green tea extract and 0.15% peppermint oil achieved complete antibacterial activity against the tested pathogenic bacteria, extending egg shelf life from approximately 7 days to at least 14 days under room temperature. The study further proposed spray application as a practical industrial approach because it provided uniform antimicrobial coverage while minimizing mechanical damage to the eggshell.

Pomegranate peel represents an abundant source of ellagic acid, tannins, and other phenolic antioxidants capable of suppressing microbial growth while simultaneously delaying oxidative deterioration. Thiangtae et al. (2026) developed gelatin-based coatings containing 1.0% and 1.5% pomegranate peel extract, demonstrating effective preservation of washed eggs during 28 days of tropical storage. The improved preservation resulted from complementary mechanisms whereby the gelatin matrix reduced moisture transfer while ellagic acid-rich extract minimized oxidative degradation and inhibited microbial proliferation. This dual protective mechanism illustrates how fruit-derived polyphenols can simultaneously improve microbial safety and physicochemical stability.

Garlic (*Allium sativum*) has long been recognized for its antimicrobial properties owing primarily to sulfur-containing compounds such as allicin and ajoene (Razavi Rohani et al., 2011). Incorporation of garlic extract into polyvinyl alcohol/chitosan/montmorillonite nanocomposite coatings significantly improved egg preservation during four weeks of storage. The formulation containing 4% garlic extract exhibited superior maintenance of shell strength and internal egg quality while displaying concentration-dependent antimicrobial activity, particularly against Gram-positive bacteria (Yousefi Zirabi & khademi shurmasti, 2024). Recent studies have increasingly explored novel botanical materials possessing both antimicrobial and antioxidant activities. Bioactive coatings enriched with *Cordia verbenacea* aqueous extract, for example, were recently shown to preserve eggs under non-refrigerated conditions for 25 days. Remarkably, the coating containing 100% plant extract completely eliminated detectable microbial contamination on eggshells, reducing microbial counts from 70.0 ± 5.8 CFU/egg in untreated controls to zero, highlighting the substantial potential of plant-derived coatings for long-term microbial control (Soares et al., 2026). Cinnamon hydrosol, a by-product of EOs extraction, has been successfully incorporated into pectin coatings to improve coating homogeneity and prolong egg shelf life despite containing relatively low EOs concentrations (< 1 g/L) (Didar, 2019).

Application methods on eggshells

Current application strategies include immersion (dipping), spraying, edible coatings, fumigation, vapor-phase treatments, nanoemulsion-based delivery, and incorporation into active packaging materials, each possessing distinct advantages and limitations (**Table 1**) depending on the processing environment and intended storage period (Moradi et al., 2021; Oliveira et al., 2022).

Immersion and washing treatments

Immersion is one of the simplest and most widely investigated approaches for applying natural antimicrobial compounds to eggshells. In this technique, eggs are submerged in antimicrobial solutions for a predetermined period, allowing direct contact between the antimicrobial agent and bacterial cells attached to the shell surface. Because immersion is compatible with existing commercial egg-washing equipment, it represents one of the most practical strategies for industrial implementation. Upadhyaya et al. (2013) evaluated postharvest washing solutions containing carvacrol, eugenol, β-resorcylic acid, and trans-cinnamaldehyde against *S.* Enteritidis artificially inoculated onto shell eggs. Washing with 0.5% and 0.75% carvacrol or eugenol completely eliminated detectable *S.* Enteritidis, even when eggs were contaminated with 3% chicken fecal material, demonstrating excellent efficacy under conditions simulating commercial contamination. Similar reductions were obtained using trans-cinnamaldehyde, indicating that immersion can rapidly inactivate surface-associated bacteria when suitable phytochemicals are employed. Subsequent investigations further demonstrated the rapid antimicrobial kinetics achievable through immersion. Immersion treatments present several operational challenges. Improper wash-water temperature may facilitate bacterial penetration through eggshell pores owing to pressure differentials generated during cooling. Furthermore, repeated use of washing solutions may increase the risk of cross-contamination if antimicrobial concentrations decline below effective levels (El-

Sabrout et al., 2026; Oliveira et al., 2022). Consequently, strict control of solution composition, temperature, and replacement frequency remains essential for maintaining microbiological safety.

Table 1. Comparison of delivery systems for natural antimicrobials applied to shell eggs

Delivery system	Representative antimicrobial	Main advantages	Main limitations	Industrial potential	References
Washing/Immersion	Carvacrol, Eugenol, Cinnamaldehyde	Rapid microbial reduction; simple process	Possible cross-contamination; limited residual activity	High	(Upadhyaya et al., 2014; Upadhyaya et al., 2013)
Spray application	Green tea extract + peppermint oil	Uniform coverage; low solution consumption; easy automation	Coverage depends on nozzle design	Very high	(Songsamoe et al., 2022)
Edible coating	Chitosan, alginate, pectin, whey protein	Sustained antimicrobial release; improved egg quality	Additional drying step required	Very high	(Jin et al., 2013; Supaphol, 2026)
Nanoemulsion	Trans-cinnamaldehyde; limonene	Enhanced stability; improved solubility; lower effective concentration	Higher production cost	High	(Allen et al., 2023; Matan & Khunjan, 2026)
Vapor fumigation	Trans-cinnamaldehyde	Uniform shell coverage; suitable for hatching eggs	Specialized equipment required	Moderate–High	(Upadhyaya et al., 2015)
Active packaging	Orange oil; clove oil; *Litsea cubeba* oil	Continuous antimicrobial release during storage	Packaging development costs	Very high	(Kabploy et al., 2023; Phothisuwan et al., 2020)
Nanocomposite coating	Garlic extract; dill oil	Improved mechanical strength and controlled release	More complex formulation	Emerging	(Yousefi Zirabi & khademi shurmasti, 2024)
Hurdle technology	EOs + bacteriophage/UV/pulse electric field	Synergistic antimicrobial effect; lower antimicrobial doses	Process optimization required	Future commercial application	(Han et al., 2024; Matan & Khunjan, 2026).

Spray application

Recent studies indicate that spray application may achieve antimicrobial efficacy comparable to immersion while improving process sustainability. Songsamoe et al. (2022) proposed spray application of a formulation containing 10% green tea extract and 0.15% peppermint EO, which successfully extended shelf life from approximately 7 to 14 days under ambient storage. The authors emphasized that spraying ensured homogeneous surface coverage while minimizing mechanical abrasion of the eggshell cuticle, an important advantage for preserving the egg's natural protective barrier. Compared with immersion, spray application also allows easier adjustment of antimicrobial dosage according to contamination level and production speed. Spraying minimizes the accumulation of contaminated wash water and significantly reduces opportunities for cross-contamination between eggs. Nevertheless, adequate nozzle design, droplet size optimization, and uniform spray distribution remain critical engineering parameters influencing antimicrobial performance in industrial environments.

Edible coating application

Edible coatings represent one of the most sophisticated antimicrobial delivery systems currently available for shell eggs. Rather than providing only transient microbial reduction immediately after treatment, coating technologies establish a semipermeable protective layer that remains attached to the eggshell throughout storage.

This layer gradually releases antimicrobial compounds while simultaneously reducing moisture loss, limiting gas exchange, and preserving internal egg quality (Ezazi et al., 2021). Numerous studies have demonstrated that coating systems substantially outperform direct antimicrobial application during prolonged storage. Chitosan coatings incorporating 1.0% lauric arginate ester reduced *Salmonella* populations by approximately 5.2 $\log_{10}$ CFU/cm^2(Jin et al., 2013), whereas pectin-based coatings containing carvacrol, eugenol, and 0.75% β-resorcylic acid completely eliminated detectable *S.* Enteritidis after only three days of refrigerated storage (Upadhyaya et al., 2016). These findings indicate that sustained antimicrobial release rather than immediate bacterial killing is largely responsible for the superior long-term performance of coating technologies. An additional advantage of edible coatings is their multifunctionality. Besides serving as antimicrobial reservoirs, coatings improve Haugh unit values, reduce albumen thinning, minimize weight loss, and maintain eggshell strength during storage. Consequently, edible coatings simultaneously enhance microbial safety and commercial egg quality, providing significant advantages over conventional disinfectants that primarily target microorganisms alone (Avramescu et al., 2020; Supaphol, 2026).

Nanoemulsion-based delivery systems

The hydrophobic nature of most EOs considerably limits their direct application in aqueous sanitizing solutions. Nanoemulsion technology addresses this challenge by dispersing EOs droplets into nanoscale particles, thereby improving water dispersibility, physical stability, surface contact area, and controlled antimicrobial release (Ghodsi Sheykhjan et al., 2025). Allen et al. (2023) demonstrated that nanoemulsions containing only 0.06–0.48% trans-cinnamaldehyde achieved approximately 2–2.5 $\log_{10}$ CFU/egg reductions after merely one minute of washing, without causing measurable alterations in eggshell color. Compared with conventional emulsions, the nano-scale droplets exhibited improved interaction with bacterial membranes, leading to more efficient microbial inactivation despite substantially lower active ingredient concentrations. Nanoemulsion technology has also proven highly effective for vapor-based treatments. Matan and Khunjan (2026) reported that cold limonene nanoemulsion vapor at 0.08%, combined with ultraviolet treatment, reduced *S.* Enteritidis and *S. aureus* populations by approximately 6–7 $\log_{10}$, while preserving egg quality. Similarly, citronella nanoemulsion vapor applied at 80 μL/mL for 10 min generated a uniform antimicrobial coating that effectively extended quail egg shelf life (Kabploy et al., 2025; Matan & Khunjan, 2026).

Vapor-phase fumigation and active packaging

Unlike liquid-based application methods, vapor-phase technologies deliver volatile antimicrobial compounds through the surrounding atmosphere rather than by direct surface contact. This approach provides highly uniform antimicrobial exposure over complex shell geometries while minimizing excessive moisture accumulation. Upadhyaya et al. (2015) demonstrated that fumigation with 1% trans-cinnamaldehyde for 20 min completely eliminated detectable *S.* Enteritidis from embryonated eggshells, with no bacterial recovery observed during incubation. These findings suggest that gaseous antimicrobial delivery may be particularly suitable for hatching eggs where excessive liquid exposure should be avoided. Recent advances have extended this concept to active packaging systems. Antimicrobial paper egg trays containing orange oil, clove oil, or *Litsea cubeba* EOs gradually release volatile antimicrobial compounds throughout storage. Orange oil incorporated at concentrations between 0.001% and 0.004% (w/w) effectively suppressed pathogenic bacteria for up to 14 days, whereas clove oil vapor combined with UV-C irradiation extended egg shelf life approximately five-fold while inhibiting *Salmonella*, *E. coli*, and *S. aureus* (Kabploy et al., 2023; Phothisuwan et al., 2020).

Operational challenges and quality assessment

Sensory impact

One of the principal challenges associated with natural antimicrobial compounds is their potential influence on the sensory characteristics of eggs. EOs possess strong volatile aromas that may alter the odor, flavor, or overall acceptability of eggs when applied at high concentrations. This issue is particularly important because consumer purchasing decisions are strongly influenced by external appearance and perceived freshness, even before the product is consumed (Yazdanbakhsh et al., 2026). The intensity of sensory alterations largely depends on the chemical composition and concentration of the antimicrobial compound. Phenolic-rich EOs such as oregano, thyme, clove, and cinnamon generally exhibit superior antimicrobial activity but also possess stronger characteristic aromas than citrus-derived EOs (Falleh, 2025; Hyldgaard et al., 2012). Consequently, identifying the minimum effective antimicrobial concentration has become a major objective of formulation studies. Several investigations included in this review demonstrated that appropriate formulation strategies can effectively minimize undesirable sensory changes. Allen et al. (2023) reported that washing shell eggs with 0.06–0.48% trans-cinnamaldehyde nanoemulsion produced approximately 2–2.5 $\log_{10}$ CFU/egg reductions of *S.* Enteritidis without causing measurable changes in eggshell color. The nanoemulsion system improved antimicrobial efficiency while permitting substantially lower concentrations of cinnamaldehyde than conventional emulsions, thereby reducing the likelihood of undesirable sensory effects. Similarly, Sharaf Eddin and Tahergorabi (2019) observed that sweet potato starch coatings containing 4% thyme EO provided the best overall balance between antimicrobial efficacy and coating quality. Although the 6% formulation exhibited slightly greater antimicrobial activity, increasing EOs concentration adversely affected coating properties, illustrating the importance of optimizing formulations to simultaneously satisfy microbiological and sensory requirements.

Stability of bioactive compounds during storage

Another important limitation concerns the chemical stability of natural antimicrobial compounds throughout storage and distribution. Many EOs constituents are highly volatile and susceptible to oxidation, photodegradation, and thermal degradation, leading to progressive reductions in antimicrobial activity during prolonged storage. This instability represents one of the principal reasons why direct application of EOs frequently provides only short-term protection (Ganosi et al., 2023; Singh & Pulikkal, 2022). Active packaging systems provide an additional strategy for maintaining antimicrobial activity during commercial distribution. Rather than releasing the entire antimicrobial dose immediately after application, packaging materials containing volatile EOs gradually emit antimicrobial vapors throughout storage. For example, antimicrobial paper trays containing orange oil effectively inhibited pathogenic bacteria for 14 days (Kabploy et al., 2023), whereas clove oil incorporated into paper trays extended egg shelf life by approximately five-fold when combined with UV-C treatment (Phothisuwan et al., 2020). These findings indicate that controlled-release technologies substantially improve the long-term stability and effectiveness of volatile phytochemicals.

Conclusion and future perspectives

Bioactive compounds such as thymol, carvacrol, eugenol, cinnamaldehyde, limonene, and diverse plant phenolics effectively inhibit *Salmonella* by disrupting bacterial membranes, interfering with cellular metabolism, and suppressing biofilm formation. Numerous studies have demonstrated that these natural compounds can significantly reduce bacterial contamination while maintaining egg quality and extending shelf life. Recent advances in nanoemulsion technology and active packaging have further improved the stability and antimicrobial performance of EOs, increasing their suitability for commercial application. Despite remaining challenges related to formulation standardization, regulatory approval, and industrial scalability, the available evidence strongly supports the future integration of EOs and plant extracts into sustainable egg sanitation strategies. Continued research focusing on optimized delivery systems and commercial validation will accelerate their adoption as environmentally friendly alternatives to conventional chemical disinfectants.

Conflicts of interest

The authors declare no conflicts of interest.

Disclaimer

Author hereby declares that NO generative AI technologies, have been used during manuscript preparation.

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