

Natural and Multifunctional Preservation Strategies for Cosmetic Formulations: A Review of Antimicrobial, Biofilm-Control and Self-Preserving Approaches

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Abstract- Microbial contamination is a critical quality and safety concern in cosmetic formulations, particularly in products containing water and other nutrients that can support microbial proliferation. Conventional preservation systems have historically relied on antimicrobial agents such as parabens, phenoxyethanol, isothiazolinones and formaldehyde-releasing preservatives. At the same time, increasing interest in naturally derived, multifunctional and label-compatible ingredients has stimulated research into preservation systems that combine antimicrobial activity with other formulation functions. This review examines the scientific basis of multifunctional preservation systems incorporating glyceryl caprylate, glyceryl undecylenate, caprylyl glycol and propanediol, together with botanical antimicrobial agents including clove oil, tea tree oil, rosemary-derived materials, citronella oil and nutmeg oil. Emphasis is placed on proposed antimicrobial mechanisms, including perturbation of microbial membranes, modification of the physicochemical environment and enhancement of antimicrobial efficacy through ingredient combinations. The review further discusses the concept of self-preserving cosmetic systems and the relevance of microbial biofilms to preservation performance. Approaches for in-vitro evaluation, including minimum inhibitory concentration (MIC) testing, biofilm biomass assays, mature-biofilm disruption studies, scanning electron microscopy (SEM), formulation stability assessment and preservative efficacy testing, are considered as complementary tools for development and characterization. Overall, the literature and formulation concepts reviewed support a multi-hurdle approach in which antimicrobial activity is not attributed to a single ingredient but is evaluated as a function of ingredient interactions, formulation environment and microbial target.

Keywords— cosmetic preservation; multifunctional ingredients; natural antimicrobial agents; essential oils; glyceryl caprylate; glyceryl undecylenate; biofilm; self-preserving systems; MIC

I. INTRODUCTION

Cosmetic formulations are susceptible to microbial contamination during manufacturing, filling, storage and consumer use. Microbial growth can compromise product quality and may present a consumer-safety concern. Consequently, an effective preservation strategy must provide adequate control of relevant bacteria, yeasts and moulds throughout the intended shelf life and use conditions. Preservation performance is influenced not only by the intrinsic antimicrobial activity of an ingredient but also by formulation composition, pH, water availability, packaging, processing conditions and interactions among raw materials.

Traditional cosmetic preservation has commonly employed established antimicrobial preservatives because of their predictable efficacy, formulation compatibility and regulatory history. However, formulation development has increasingly explored alternative or complementary approaches based on multifunctional ingredients and botanical materials. The objective is not necessarily to replace a conventional preservative molecule with a single natural material, but to develop a preservation system based on multiple antimicrobial hurdles while maintaining acceptable sensory, physicochemical and stability characteristics.

This review therefore focuses on the transition from single-agent preservation toward multifunctional

and self-preserving concepts, with particular attention to glyceryl caprylate, glyceryl undecylenate, caprylyl glycol, propanediol and selected essential oils or botanical materials. It also outlines analytical approaches that can be used to establish antimicrobial efficacy and investigate biofilm-related performance.

II. CONVENTIONAL COSMETIC PRESERVATION SYSTEMS

1. Parabens

Parabens are ester derivatives of p-hydroxybenzoic acid and have been widely used because of their antimicrobial activity and formulation utility. Their activity is associated with interaction with microbial cellular structures and disruption of essential cellular processes. Their historical use demonstrates the importance of efficacy, stability and cost-effectiveness in cosmetic preservation. Nevertheless, consumer perception and the demand for alternative preservative systems have encouraged formulation research beyond conventional paraben-based approaches.

2. Phenoxyethanol

Phenoxyethanol is a widely used cosmetic preservative with applicability across a broad range of personal-care formulations. Its established use reflects useful antimicrobial performance and formulation compatibility. In formulations positioned around naturality or reduced use of conventional preservatives, however, alternative preservation strategies or synergistic systems may be investigated.

3. Isothiazolinones

Isothiazolinone preservatives are potent antimicrobial agents and have been used at low concentrations. Their history in cosmetic preservation also illustrates the importance of sensitization and regulatory considerations when selecting antimicrobial systems. Such considerations have contributed to interest in alternative preservation approaches.

4. Formaldehyde-Releasing Preservatives

Formaldehyde-releasing preservatives have historically been used because of their antimicrobial efficacy. Safety and consumer-acceptance considerations have reduced their desirability in many contemporary formulation contexts, contributing to continued interest in preservation systems based on other antimicrobial mechanisms.

III. DRIVERS FOR MULTIFUNCTIONAL AND NATURALLY DERIVED PRESERVATION

The development of multifunctional preservation systems is influenced by several formulation and market factors. These include demand for naturally derived ingredients, clean-label positioning, sustainability considerations, multifunctionality and the need to maintain antimicrobial performance without compromising product aesthetics or stability. Importantly, the term 'natural' does not by itself establish antimicrobial efficacy or safety; performance must be demonstrated experimentally under relevant formulation conditions.

A scientifically defensible natural-preservation strategy therefore requires characterization of antimicrobial potency, compatibility with the formulation matrix, stability of the active components and preservation efficacy in the finished product. Where botanical ingredients are used, variability arising from botanical source, chemotype, extraction method and storage conditions should also be considered.

IV. MULTIFUNCTIONAL PRESERVATION INGREDIENTS

1. Glyceryl Caprylate

Glyceryl caprylate is a multifunctional lipid-derived ingredient with reported antimicrobial activity. Its antimicrobial contribution is generally associated with interaction with microbial membranes. In cosmetic formulations it can also contribute emollient or sensory functionality, making it relevant to multi-functional preservation design. Because its activity may be insufficient as a sole preservation

strategy in many aqueous systems, combination with other antimicrobial hurdles is of particular interest.

2. Glyceryl Undecylenate

Glyceryl undecylenate is another multifunctional ingredient investigated for antimicrobial performance, including activity against microorganisms relevant to cosmetic preservation. Its longer-chain fatty-acid-derived structure provides a basis for interaction with microbial membranes. Combination with other multifunctional ingredients may broaden or strengthen preservation performance.

3. Caprylyl Glycol

Caprylyl glycol is a multifunctional diol used in personal-care formulations for humectant, emollient and antimicrobial-boosting functions. Its contribution to preservation can depend strongly on the formulation environment and the presence of complementary antimicrobial components. It is therefore better considered as a component of a preservation system rather than automatically treated as a complete preservative on its own.

4. Propanediol

Propanediol is widely used as a multifunctional cosmetic ingredient, including as a humectant and solvent. It may also contribute to microbial control through changes in the formulation environment and by modifying the performance of other antimicrobial ingredients. At concentrations selected for preservation purposes, the overall antimicrobial effect should be demonstrated experimentally because solvent and humectant functionality alone does not establish adequate preservation.

5. Essential Oils and Botanical Antimicrobials

Essential oils contain complex mixtures of volatile compounds, including terpenes, terpenoids and phenolic constituents. Their antimicrobial activity can arise through multiple mechanisms, particularly interaction with microbial membranes and changes in membrane permeability. However, antimicrobial activity is highly dependent on chemical composition, concentration, microorganism and formulation environment. Odour, oxidation, colour,

solubility and batch variability are important formulation considerations.

V. BOTANICAL ANTIMICROBIAL AGENTS AND THEIR POTENTIAL ROLES

1. Clove Oil

Clove oil, obtained from *Syzygium aromaticum* flower buds, is characterized by a high proportion of eugenol together with other volatile constituents such as eugenyl acetate and β -caryophyllene. The draft literature reviewed identifies antibacterial and antifungal activity against microorganisms including *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Candida albicans*. Eugenol has been associated with membrane perturbation, leakage of intracellular components and interference with cellular functions. Potential inhibition of biofilm formation has also been reported. Important formulation limitations include strong odour, possible irritation at elevated concentrations and compositional variability.

2. Tea Tree Oil

Tea tree oil is derived from *Melaleuca alternifolia* leaves and contains terpinen-4-ol, γ -terpinene, α -terpinene and other volatile constituents. Its antimicrobial activity has been reported against Gram-positive and Gram-negative bacteria as well as yeasts and fungi. Membrane perturbation and increased membrane permeability are commonly proposed mechanisms. Tea tree oil has also been investigated for effects on microbial biofilms. Oxidative instability, characteristic odour and sensitization considerations should be addressed during formulation and storage.

3. Rosemary-Derived Materials

Rosemary-derived materials contain bioactive constituents such as carnosic acid, carnosol, rosmarinic acid and ursolic acid. Although rosemary materials are particularly recognized for antioxidant activity, antimicrobial effects have also been described. Within a preservation system, their potential value may therefore arise from complementary antioxidant and antimicrobial functions. Activity can vary according to botanical source and extraction process, and combinations

with other antimicrobial components may be required.

4. Citronella Oil

Citronella oil, obtained from *Cymbopogon* species, contains constituents such as citronellal, citronellol and geraniol. Antibacterial and antifungal activity has been reported, with membrane and cellular-metabolism effects proposed as contributing mechanisms. However, its volatile and strongly aromatic nature can restrict formulation flexibility and may influence storage stability.

5. Nutmeg Oil

Nutmeg oil from *Myristica fragrans* contains volatile constituents including sabinene, myristicin, α -pinene and β -pinene. Antimicrobial activity has been reported against selected microorganisms and is associated with interference with membrane integrity and cellular metabolism. Compared with more extensively investigated essential oils, cosmetic preservation literature for nutmeg oil is relatively limited in the present draft. Safety, regulatory and sensory considerations should therefore be evaluated before practical application.

VI. SELF-PRESERVING COSMETIC SYSTEMS

A self-preserving cosmetic system can be defined as a formulation designed to achieve microbiological stability through the combined action of multiple formulation components and physicochemical hurdles, with reduced dependence on a conventional single preservative. The concept should not be interpreted as an assumption that a product is intrinsically protected because it contains natural or multifunctional ingredients. Microbiological performance must be demonstrated in the finished formulation.

A multi-hurdle system may combine multifunctional ingredients such as glyceryl caprylate, glyceryl undecylenate, caprylyl glycol, propanediol or pentyleneglycol with selected botanical antimicrobial agents. The objective is to exploit complementary mechanisms while maintaining

acceptable pH, sensory properties, physical stability and regulatory suitability.

1. Potential Advantages

- Reduced dependence on conventional preservative molecules where adequate preservation can be demonstrated.
- Integration of antimicrobial and formulation functions within the same system.
- Potential compatibility with formulations positioned around naturally derived ingredients.
- Opportunity to investigate complementary antimicrobial mechanisms and synergistic interactions.
- Potential contribution to sensory or emollient properties from multifunctional ingredients.

2. Development Challenges

- Achieving reliable broad-spectrum antimicrobial activity.
- Maintaining physical and chemical stability of the formulation.
- Managing odour, colour and volatility associated with botanical materials.
- Controlling raw-material variability and establishing appropriate specifications.
- Demonstrating preservation efficacy in the finished cosmetic matrix.
- Meeting applicable regulatory and safety requirements in the intended market.

VII. ANTIMICROBIAL AND BIOFILM EVALUATION STRATEGIES

Evaluation of a multifunctional preservation system should progress from simple antimicrobial screening toward formulation-level microbiological validation. No single in-vitro assay is sufficient to establish the preservation performance of a finished cosmetic product. Instead, complementary assays can provide information on antimicrobial potency, biofilm-associated activity, structural effects and formulation robustness.

1. Minimum Inhibitory Concentration (MIC)

MIC is defined as the lowest tested concentration of an antimicrobial system that prevents visible microbial growth under the specified assay

conditions. Broth microdilution provides a quantitative screening approach and allows comparison of individual ingredients, combinations and concentration ranges. MIC results should be interpreted with attention to inoculum, medium, incubation conditions, solvent effects and the physicochemical characteristics of poorly water-soluble materials.

2. Biofilm Formation and Inhibition

Microbial biofilms are structured communities of microorganisms embedded within an extracellular matrix. Because biofilm-associated cells can exhibit increased tolerance to antimicrobial treatment compared with planktonic cells, biofilm evaluation is relevant to advanced preservation research. The crystal violet assay provides a relatively simple approach for quantifying total attached biomass. Useful outputs include percentage inhibition relative to an untreated control and concentration-response relationships.

3. Mature Biofilm Disruption

In a mature-biofilm disruption assay, a biofilm is established before exposure to the test system. Changes in biomass can be quantified by crystal violet staining, while viable-cell enumeration can provide complementary information on microbial survival. Distinguishing reduction in biomass from reduction in viable cells is important because these measurements represent different biological outcomes.

4. Scanning Electron Microscopy

Scanning electron microscopy can provide morphological evidence of microbial attachment, biofilm architecture and structural changes following treatment. Biofilms may be developed on suitable substrata such as glass or stainless-steel coupons. SEM is primarily a structural visualization tool and should be interpreted alongside quantitative microbiological measurements rather than used as a stand-alone efficacy assay.

5. Cosmetic Formulation Evaluation

Following screening of individual components and combinations, selected systems should be evaluated in representative cosmetic formulations such as

lotions or serums. Relevant parameters include pH, viscosity, appearance, odour, phase stability and accelerated stability. Changes in these parameters may indicate incompatibility, oxidation, phase separation or other formulation effects that could alter preservation performance.

6. Preservation Efficacy / Challenge Testing

Preservation efficacy of the finished formulation should ultimately be evaluated using an appropriate preservative efficacy or challenge-test methodology, such as ISO 11930 or an applicable equivalent procedure. The formulation is challenged with specified microorganisms and microbial reduction is monitored over the defined test period. The draft identifies *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Candida albicans* and *Aspergillus brasiliensis* as representative test organisms.

Comparison of Conventional and Emerging Preservation Approaches

System	Primary antimicrobial basis	Potential advantages	Key limitations / considerations
Parabens	Antimicrobial interaction with microbial cells	Established efficacy; economical	Consumer perception and market positioning considerations
Phenoxyethanol	Antimicrobial activity / cellular effects	Broad cosmetic applicability ; established use	May not fit all natural-positioned formulations
Organic acids	Intracellular acidification under suitable pH conditions	Useful in selected natural-oriented systems	Strongly influenced by formulation pH
Glyceryl caprylate	Membrane interaction	Multifunctional; emollient contribution	Often requires combination with

			other hurdles
Glyceryl undecylenate	Antimicrobial activity associated with fatty-acid-derived structure	Multifunctional; natural-origin positioning	May be insufficient alone in some systems
Essential oils	Multiple effects, particularly membrane perturbation	Botanical positioning; multifunctional potential	Odour, volatility, oxidation, variability and solubility

VIII. RESEARCH GAPS AND FUTURE PERSPECTIVE

An important research gap is the systematic evaluation of combinations of multifunctional preservation ingredients with botanical antimicrobial agents. Evidence of activity for individual ingredients does not automatically establish additive or synergistic activity in combination. Accordingly, future studies should distinguish among additive, synergistic and antagonistic interactions using appropriate experimental designs and quantitative analysis.

Biofilm-associated microbial persistence represents a further area for investigation. Conventional antimicrobial screening commonly evaluates planktonic growth, whereas biofilm-associated microorganisms may exhibit different susceptibility profiles. Combining MIC screening with biofilm inhibition, mature-biofilm disruption and structural visualization could therefore provide a more comprehensive understanding of antimicrobial performance.

Another important research requirement is formulation-level validation. A combination that performs well in a simplified laboratory medium may behave differently after incorporation into a cosmetic matrix because of partitioning,

solubilization, adsorption, pH, water activity and interactions with surfactants, oils or polymers. Consequently, promising systems should be evaluated sequentially from screening assays through prototype formulations and, ultimately, preservative efficacy testing.

For the proposed research direction, a rational workflow can therefore be represented as: (1) characterization of individual multifunctional ingredients; (2) MIC screening of individual ingredients and combinations; (3) selection of promising combinations; (4) biofilm inhibition and mature-biofilm disruption studies; (5) SEM-based morphological assessment where appropriate; (6) incorporation into a representative cosmetic formulation; (7) physicochemical and stability evaluation; and (8) preservative efficacy testing of the optimized formulation.

IX. CONCLUSION

Multifunctional and naturally derived preservation systems represent an active area of cosmetic formulation research. Glyceryl caprylate, glyceryl undecylenate, caprylyl glycol and propanediol can contribute to preservation strategies through complementary physicochemical and antimicrobial effects, while selected botanical materials may provide additional antimicrobial activity. However, the use of a natural or multifunctional ingredient should not be equated with adequate preservation without experimental verification.

A scientifically robust self-preserving strategy should therefore be treated as a multi-hurdle system whose performance depends on ingredient concentration, interactions, formulation environment and target microorganism. Integration of MIC testing, biofilm assays, structural characterization, formulation stability assessment and preservative efficacy testing provides a logical framework for evaluating such systems. Future research should focus particularly on quantitative assessment of ingredient interactions, biofilm control and the translation of in-vitro activity into stable, reproducible and microbiologically robust cosmetic formulations.

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The present revision is a scientific language and structure revision of the supplied manuscript. The supplied draft did not contain a formal reference list. Before journal submission, each substantive literature claim—especially antimicrobial mechanisms, microorganism-specific activity, constituent percentages, regulatory statements and challenge-test methodology—should be supported by appropriate primary research papers, standards or authoritative regulatory sources. References should be inserted at the exact claims they support rather than added as a generic bibliography.

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