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Plant-Derived Natural Antimicrobials as Sustainable Alternatives to Synthetic Preservatives in the Food Supply Chain

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ABSTRACT: Synthetic preservatives—sodium benzoate, potassium sorbate, sodium nitrite and the phenolic antioxidants BHA and BHT—underpin the safety and shelf life of the modern food supply, yet mounting toxicological scrutiny, tightening regulation and consumer rejection of chemical additives are eroding their acceptability; in 2026 regulators including the US FDA opened formal reassessments of BHA and BHT. Plant-derived antimicrobials offer a scientifically credible and sustainable alternative, combining broad-spectrum activity with renewable sourcing, biodegradability and high consumer acceptance. This review evaluates plant-derived antimicrobials as sustainable substitutes for synthetic preservatives across the entire farm-to-fork supply chain. Six compound classes—phenolics, terpenoid essential oils, organosulfur compounds, alkaloids, saponins and antimicrobial peptides—are examined with respect to chemistry, structure–activity relationships, antimicrobial spectrum and mechanism. Compiled minimum inhibitory concentrations (MICs) show that the principal actives carvacrol, thymol and cinnamaldehyde inhibit major foodborne pathogens (Escherichia coli, Salmonella, Listeria monocytogenes, Staphylococcus aureus) at roughly 128–400 µg/mL, with Gram-positive organisms generally more susceptible than Gram-negative.

Their multi-target mode of action—membrane disruption, proton-motive-force collapse, reactive-oxygen-species induction, efflux-pump and quorum-sensing inhibition, and DNA binding—confers a low propensity for resistance, and binary combinations exhibit marked synergy, lowering effective doses by up to 75–94% and mitigating sensory impact.

Supply-chain applications spanning pre-harvest treatment, processing, active packaging and storage are reviewed, with documented shelf-life extensions of two- to threefold. A sustainability assessment contrasts the renewable, low-ecotoxicity profile of plant antimicrobials with the cost, stability and regulatory advantages that still favour synthetics, and identifies the principal translational barriers—dose–sensory trade-offs, formulation stability, matrix effects, cost and regulatory harmonisation. The review concludes that plant-derived antimicrobials are best deployed not as one-for-one replacements but as engineered components of hurdle-based, clean-label preservation systems.

1. INTRODUCTION

Chemical preservation is one of the foundations of the industrialised food system. Antimicrobial additives such as sodium benzoate, potassium sorbate, calcium propionate and sodium nitrite, together with the antioxidant preservatives butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), protect an enormous share of processed foods against microbial spoilage and oxidative rancidity, and they do so cheaply, consistently and with excellent thermal stability. [1,2] Synthetic preservatives accordingly still hold roughly 60–63% of the global food-preservatives market, and a majority of mass-market products in many regions rely on at least one of them. [1] Their value is real: sodium nitrite, for example, simultaneously fixes the colour of cured meats and inhibits *Clostridium botulinum*, the agent of botulism. [2]

Yet the position of synthetic preservatives is increasingly contested. A growing toxicological literature associates several of them—benzoates, nitrites, sulphites and the phenolic antioxidants BHA and BHT—with adverse effects ranging from hypersensitivity and childhood hyperactivity to modulation of apoptotic and pro-inflammatory pathways, with the nitrite–nitrosamine link and the debated carcinogenicity of BHA/BHT attracting particular attention. [2,3] Regulatory momentum has followed: in 2026 the US Food and Drug Administration opened a formal reassessment of BHA and signalled that BHT would be reviewed next, while a substantial share of food-importing countries have already imposed stricter limits or bans on specific synthetic additives. [1,4] In parallel, consumer sentiment has shifted decisively—around 46% of consumers report active caution toward chemical preservatives such as sodium nitrite and BHA—fuelling the clean-label movement and rapid growth in demand for natural alternatives. [1,5]

Plant-derived antimicrobials are the most promising response to this convergence of pressures. Aromatic and medicinal plants elaborate a rich chemistry of secondary metabolites—phenolics, terpenoids, organosulfur compounds, alkaloids and peptides—that evolved in part as chemical defences against microbial attack and that retain potent, broad-spectrum antimicrobial activity in food systems. [5,6] Beyond efficacy, they align with sustainability goals: they are renewable, biodegradable, of low mammalian toxicity, frequently obtainable from agri-food by-products, and highly acceptable to consumers. [6,7] This review assesses their potential as sustainable substitutes for synthetic preservatives, using the food supply chain as its organising framework. Figure 1 maps the points at which plant antimicrobials can intervene from farm to fork.

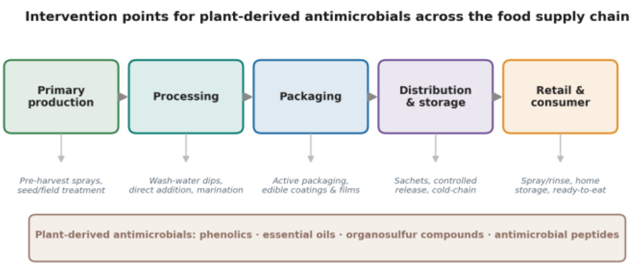

Figure 1. Intervention points for plant-derived antimicrobials across the food supply chain. The same compound classes can be deployed as pre-harvest treatments, processing aids, active-packaging and coating components, storage sachets, and retail/consumer-level rinses, allowing a coordinated farm-to-fork preservation strategy.

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2. THE CASE AGAINST SYNTHETIC PRESERVATIVES

A clear-eyed appraisal of the alternatives must begin with the incumbents. Table 1 summarises the principal synthetic preservatives, their functions, acceptable daily intakes (ADIs) and the health or regulatory concerns that motivate their replacement. Two points deserve emphasis. First, at permitted levels these additives are considered safe by the Joint FAO/WHO Expert Committee on Food Additives and by regional authorities; the concerns arise chiefly from high-dose or long-term exposure and from specific mechanisms such as nitrosamine formation. [2,3] Second, the pressure to replace them is driven as much by consumer perception and regulatory precaution as by settled toxicology—a distinction that matters for how natural alternatives should be positioned and communicated. [1,4] Figure 2 places this shift in market context.

Synthetic preservative	Primary function	ADI (mg/kg bw)	Principal concern
Sodium benzoate	Antimicrobial (acidic foods)	0–5	Hypersensitivity; childhood hyperactivity; benzene formation with ascorbate
Potassium sorbate	Antifungal / antimicrobial	0–25	Generally low concern; migration & sensitivity reports
Sodium nitrite	Antimicrobial (C. botulinum); colour	0–0.07	Nitrosamine formation in cured meats
Sulphites (SO_2)	Antimicrobial, antioxidant	0–0.7	Asthma / hypersensitivity reactions
BHA	Antioxidant (fats, oils)	0–0.5	Possible carcinogen; under FDA reassessment (2026)
BHT	Antioxidant (cereals, fats)	0–0.3	Carcinogenicity debated; endocrine concerns
Calcium propionate	Antifungal (bakery)	not limited	Behavioural reports; generally low concern

Table 1. Principal synthetic preservatives, their functions, acceptable daily intakes (indicative JECFA/EFSA values) and the concerns driving the search for alternatives. At permitted levels these additives are regulated as safe; concerns arise chiefly from long-term or high-dose exposure.

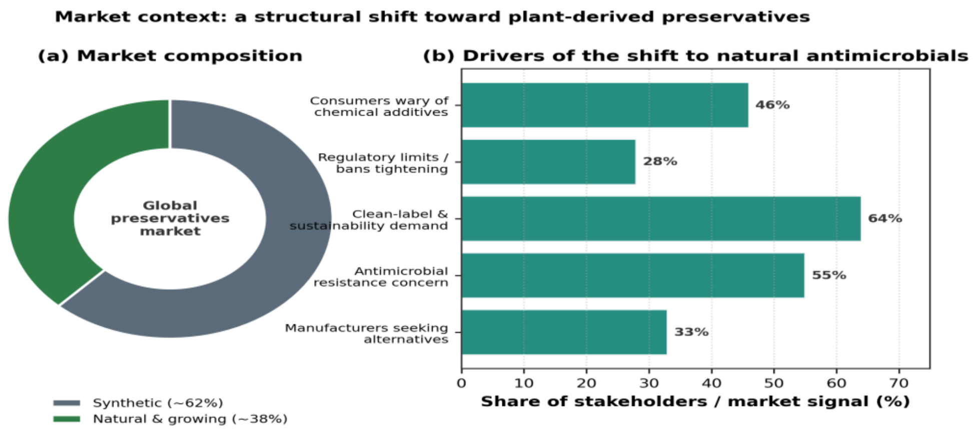

Figure 2. Market context for the transition to plant-derived preservatives. (a) Synthetic preservatives retain the majority (~62%) of the global market, but the natural segment is the fastest growing. (b) The principal demand- and supply-side drivers of the shift. Values are indicative figures compiled from market analyses and cited literature.

3. CLASSES AND CHEMISTRY OF PLANT-DERIVED ANTIMICROBIALS

Plant antimicrobials are chemically diverse, and their activity is a direct function of molecular structure. Table 2 organises the six principal classes with representative compounds and sources. The most food-relevant—and by far the most studied—are the phenolics and the terpenoid-rich essential oils, whose activity is dominated by a small number of highly active constituents: the monoterpenoid phenols carvacrol and thymol, and the phenylpropanoids eugenol and cinnamaldehyde. [5,6]

Class	Representative compounds	Typical plant source	Chemical nature
Simple phenolics & phenolic acids	Gallic, ferulic, rosmarinic acids	Fruits, herbs, by-products	Hydroxylated aromatic acids
Flavonoids & polyphenols	Quercetin, catechins, tannins	Tea, grape, pomegranate	Polyphenolic
Terpenoid essential oils	Carvacrol, thymol, cinnamaldehyde, eugenol	Oregano, thyme, cinnamon, clove	Monoterpenoids / phenylpropanoids
Organosulfur compounds	Allicin, diallyl sulphides, isothiocyanates	Garlic, onion, brassicas	Sulphur-containing
Alkaloids	Berberine, piperine	Berberis, black pepper	Nitrogenous heterocycles
Antimicrobial peptides & lectins	Defensins, thionins	Seeds, legumes	Cationic peptides / proteins

Table 2. The six principal classes of plant-derived antimicrobials, with representative compounds, sources and chemical nature. Terpenoid essential-oil constituents and phenolics dominate current food applications.

3.1 Structure–activity relationships

The potency of the leading actives is not accidental. For the monoterpenoid phenols, a free aromatic hydroxyl group and a delocalised electron system are critical: they permit both partitioning into microbial membranes and proton release across them, which is why carvacrol and its isomer thymol are consistently among the most active constituents. [6] The reactive α,β-unsaturated aldehyde group of cinnamaldehyde underlies its distinct, highly bactericidal behaviour, and the allyl and disulphide chemistry of garlic-derived organosulfur compounds gives them thiol-directed reactivity. [5,6] Understanding these relationships allows rational selection and combination of actives and rationalises the observed differences in spectrum and potency.

4. ANTIMICROBIAL SPECTRUM AND EFFICACY

The quantitative benchmark of antimicrobial efficacy is the minimum inhibitory concentration (MIC). Figure 3 compiles representative MIC values for the four leading actives against the major foodborne pathogens, and Table 3 details the corresponding data with sources. Three patterns are consistent across the literature. First, the monoterpenoid phenols and cinnamaldehyde are potent, inhibiting most target organisms at roughly 128–400 µg/mL, whereas eugenol is generally several-fold less active. [8,9,10] Second, Gram-positive bacteria (*L. monocytogenes*, *S. aureus*) tend to be more susceptible than Gram-negative organisms, whose outer membrane impedes the ingress of hydrophobic actives; the psychrotroph *Pseudomonas fluorescens* is frequently the most resistant target. [10] Third, efficacy is markedly matrix-dependent—MICs determined in broth routinely underestimate the doses needed in real foods, where fat, protein and starch sequester lipophilic actives. [5]

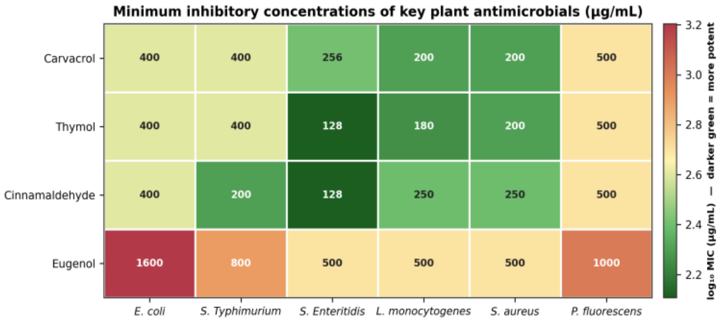

Figure 3. Minimum inhibitory concentrations (μg/mL) of the four principal plant antimicrobials against major foodborne pathogens. Darker green indicates greater potency (lower MIC). Carvacrol, thymol and cinnamaldehyde are broadly potent; eugenol is weaker; Gram-negative and psychrotrophic organisms are generally more resistant. Values are representative figures compiled from the cited studies.

Active compound	Target organism	MIC	Note / reference
Eugenol / cinnamaldehyde / thymol / carvacrol	*E. coli*	1600 / 400 / 400 / 400 μg/mL	Broth 649icrodilution [8]
Cinnamaldehyde / thymol / carvacrol	*S. Typhimurium*	200 / 400 / 400 μg/mL	Synergy on combination [8]
Thymol / carvacrol / cinnamaldehyde	*S. Enteritidis*	128 / 256 / 128 μg/mL	In chicken; biofilm inhibited [9]
Thymol / carvacrol	Multiple food/clinical strains	32–64 μg/mL	Efflux-pump inhibition [11]
Oregano / thyme / cinnamon EO	Broad panel	MIC ≥ 0.125 μL/mL	P. fluorescens most resistant [10]
Carvacrol	MRSA (S. aureus)	0.015–0.03% v/v	Active vs resistant strains [6]

Table 3. Representative minimum inhibitory concentration (MIC) data for plant-derived antimicrobials against foodborne pathogens. Note that 1 μg/mL = 1 mg/L; values compiled from the cited primary studies.

5. MECHANISMS OF ACTION

Plant antimicrobials owe their broad spectrum and low resistance risk to the fact that they act on several cellular targets at once, in contrast to the single-site action of many synthetic antimicrobials. Figure 4 depicts the principal molecular targets. The primary and best-characterised event, for the lipophilic terpenoids in particular, is disruption of the cytoplasmic membrane: insertion of the active expands and destabilises the lipid bilayer, increasing permeability, dissipating the proton-motive force and pH gradient, and causing leakage of ions, ATP and other intracellular contents—rapidly compromising the cell's energy status. [5,6,12] Secondary and often simultaneous effects include inhibition of membrane-bound ATPases and efflux pumps (the latter making the actives useful as resistance-reversal agents), generation of intracellular reactive oxygen species that damage lipids, proteins and DNA, direct binding to DNA that impedes replication, and interference with quorum sensing and biofilm formation that lowers virulence and improves control of established contamination. [11,12,13]

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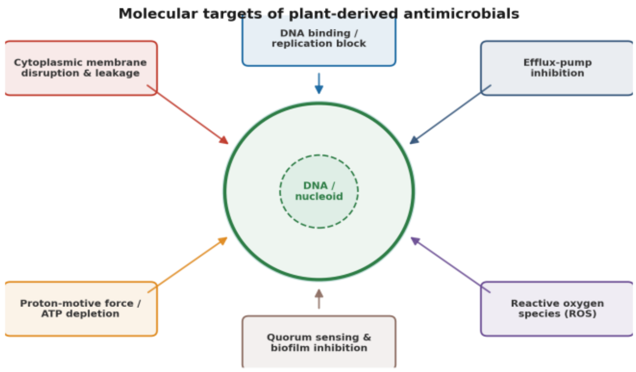

Figure 4. Molecular targets of plant-derived antimicrobials within the microbial cell. Membrane disruption and proton-motive-force collapse are the primary effects for lipophilic terpenoids, complemented by efflux-pump inhibition, reactive-oxygen-species induction, DNA binding and quorum-sensing/biofilm interference. Simultaneous action on multiple targets underlies broad-spectrum activity and a low propensity for resistance.

5.1 Synergy and the hurdle concept

Because these mechanisms are complementary, combinations of plant antimicrobials frequently act synergistically—a property of decisive practical importance, since synergy lowers the effective dose and, with it, both cost and the sensory penalty that limits stand-alone use. Checkerboard assays repeatedly return fractional inhibitory concentration indices ≤ 0.5 (indicating synergy) for binary phenolic/aldehyde pairs. Figure 5 quantifies a representative case: against *E. coli*, combining the actives in pairs reduced the MIC of eugenol from 1600 to 400 μg/mL and those of cinnamaldehyde, thymol and carvacrol from 400 to 100 μg/mL—dose reductions of 75–94%. [8] The same logic underpins hurdle technology, in which plant antimicrobials are combined with each other and with mild physical treatments (for example the pairing of grapefruit essential oil with UV-C, which achieved ~1.9–4.0 log reductions of *E. coli* O157:H7 on fresh produce) to achieve reliable control at concentrations that individually would be sub-lethal or organoleptically unacceptable. [5,6]

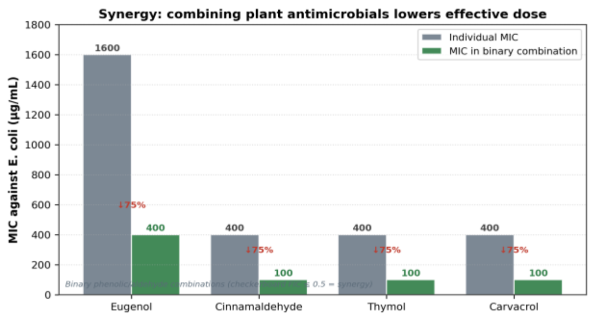

Figure 5. Synergy between plant antimicrobials. Binary combinations markedly reduce the minimum inhibitory concentration against E. coli relative to each compound applied alone, with dose reductions of 75–94%. Lower effective doses reduce both cost and adverse sensory impact, and underpin hurdle-based formulation.

6. APPLICATIONS ACROSS THE FOOD SUPPLY CHAIN

The versatility of plant antimicrobials allows their deployment at every stage of the supply chain (Figure 1), and their performance has been demonstrated across all major food categories (Table 4). The dominant application formats are direct addition and dipping during processing, incorporation into edible coatings and active packaging, and vapour-phase or sachet delivery during storage. Encapsulation is increasingly used as an enabling technology across formats, because it stabilises volatile actives, masks their strong flavour and enables controlled release—directly addressing the two limitations (volatility and sensory impact) that most constrain adoption. [7,14]

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Food category	Representative active / format	Target	Outcome
Meat & poultry	Thymol/carvacrol (128–256 µg/mL); rosemary extract	Salmonella, Listeria, oxidation	Reduced counts; biofilm inhibition; delayed rancidity
Poultry (marinated)	Thyme + eucalyptus EO combination	Spoilage flora	Shelf life 4 → 10–11 days
Fresh produce	Grapefruit EO + UV-C (hurdle)	E. coli O157:H7, norovirus	1.9–4.0 log reductions
Dairy	EO-loaded coatings; phenolic extracts	Spoilage yeasts/moulds	Extended shelf life; antioxidant protection
Bakery	Cinnamon/clove EO; propionate replacers	Moulds	Delayed fungal spoilage
Beverages	Phenolic acids, organic acids	Yeasts, acid-tolerant bacteria	Microbial stabilisation
Active packaging	Phenolic/EO-loaded biopolymer films	Broad	Sustained release; shelf-life extension

Table 4. Applications of plant-derived antimicrobials across food categories and delivery formats, with representative outcomes drawn from the cited literature. Encapsulation and coating formats predominate because they stabilise actives and mitigate sensory impact.

A recurring finding across categories is that combined and delivery-optimised applications outperform simple direct addition. Marinated chicken skewers treated with a thyme–eucalyptus essential-oil combination reached a shelf life of 10–11 days versus 4 days for untreated controls, and coating- or packaging-based delivery consistently improves on the free active by concentrating it at the food surface where spoilage begins. [14] These results confirm that the practical efficacy of plant antimicrobials is governed as much by formulation and delivery as by intrinsic potency.

7. SUSTAINABILITY ASSESSMENT

The central claim of this review—that plant antimicrobials are *sustainable* alternatives—requires explicit justification rather than assertion. On the environmental and social dimensions the case is strong: plant antimicrobials are derived from renewable biological sources, are readily biodegradable, exhibit low ecotoxicity and low mammalian toxicity, and enjoy high consumer acceptance; sourcing them from agri-food processing by-products (grape pomace, citrus and pomegranate peel, herb residues) further valorises waste streams and advances circular-economy objectives. [6,7] The toxicological margins are reassuring—carvacrol, for example, carries an ADI of 0–2.5 mg/kg body weight and the leading actives have NOAEL values of the order of 125–250 mg/kg per day, comfortably above realistic dietary exposures. [6] Figure 6 contrasts the two preservative paradigms across seven sustainability-relevant criteria.

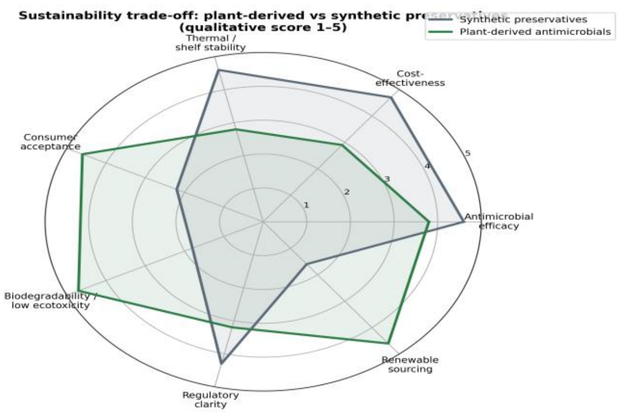

Figure 6. Sustainability trade-off between plant-derived and synthetic preservatives across seven criteria (1 = weak, 5 = strong). Plant antimicrobials lead decisively on consumer acceptance, biodegradability/low ecotoxicity and renewable sourcing; synthetics retain advantages in cost, thermal/shelf stability and, currently, regulatory clarity. The profiles are complementary rather than uniformly superior.

The assessment is not, however, one-sided. On the economic and technical dimensions synthetics still lead: plant antimicrobials are generally more expensive per treated unit, chemically or biologically less stable, and—critically—often require higher and organoleptically detectable doses to match synthetic efficacy in real matrices. [1,5] A rigorous sustainability judgement must also weigh life-cycle factors such as the land, water and energy demands of cultivating and extracting the actives, which are seldom quantified in the current literature. The honest conclusion is that plant antimicrobials are more sustainable on renewability, biodegradability and health-perception grounds, but that closing the cost, stability and dose gaps—largely through formulation, encapsulation and by-product sourcing—is essential before the sustainability advantage can be realised at scale.

8. CHALLENGES AND FUTURE PERSPECTIVES

Five challenges define the translational agenda. Sensory impact and dose: the strong aroma and flavour of the most active terpenoids limit usable concentrations, making encapsulation, controlled release and synergistic combination not optional refinements but prerequisites for adoption. Matrix effects and standardisation: because efficacy varies widely with food composition, broth MICs are poor predictors of in-food performance, and the field needs standardised, matrix-relevant efficacy testing to enable fair comparison and confident formulation. Formulation stability and cost: volatile and oxidation-prone actives must be stabilised, and cost lowered—objectives that by-product sourcing and modern encapsulation address simultaneously. Regulatory harmonisation: although many actives hold GRAS status, approval of novel extracts, combinations and nano-formulations remains jurisdiction-specific and slow, and nano-delivery raises additional safety-data requirements. Systems integration: plant antimicrobials perform best as one hurdle among several, so their future lies in rational combination with mild thermal and non-thermal processing (UV-C, cold plasma, high-pressure processing), modified-atmosphere packaging and the cold chain, rather than as isolated drop-in replacements. [5,6,7,14] Progress in structure-guided active selection, machine-learning-assisted synergy prediction and stimulus-responsive packaging will accelerate this integration.

9. CONCLUSION

Plant-derived antimicrobials constitute a scientifically mature and sustainable response to the mounting pressures on synthetic food preservatives. Their leading actives—carvacrol, thymol and cinnamaldehyde—inhibit the major foodborne pathogens at low micromolar-to-millimolar concentrations, act through multi-target mechanisms that resist adaptation, and combine synergistically to reduce effective doses by up to 75–94%. Deployed across the farm-to-fork chain through dips, coatings, active packaging and encapsulated delivery, they achieve shelf-life extensions of two- to threefold while offering renewable sourcing, biodegradability and the clean-label appeal that consumers increasingly demand. They are not, however, cost- or stability-equivalent to the synthetics they aim to replace, and their sensory impact and matrix sensitivity remain real constraints. The evidence therefore supports a clear strategic conclusion: plant antimicrobials should be engineered into hurdle-based, delivery-optimised, clean-label preservation systems—combined with each other, with encapsulation and with complementary physical technologies—rather than positioned as one-for-one substitutes. Realising their promise now depends on standardised efficacy testing, robust and economical formulation, harmonised regulation, and full life-cycle sustainability assessment.

Declarations

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Author contributions: Conceptualisation, A.O.; investigation and writing—original draft, A.O. and A.T.; visualisation, A.T.; writing—review and editing, A.T.; supervision, A.O. All authors approved the final manuscript.

Data availability: No new primary data were generated; all data discussed are available in the cited references.

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