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Natural Preservatives for Postharvest Spoilage Control: Efficacy, Mechanisms, and Industrial Scalability

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ABSTRACT: Postharvest losses consume a substantial fraction of global fruit and vegetable production—commonly cited in the range of 20–40% for disease-driven decay and up to 28–55% overall—with microbial spoilage by fungi such as Botrytis cinerea, Penicillium spp., Rhizopus stolonifer and Monilinia spp. as the dominant biological driver, and an estimated global economic burden of the order of US$150 billion annually. Reliance on synthetic fungicides is increasingly constrained by pathogen resistance, regulatory withdrawal and consumer resistance to chemical residues, motivating a shift toward natural preservatives. This review provides an integrated, critical assessment of natural preservatives for postharvest spoilage control across three linked dimensions: efficacy, mechanisms and industrial scalability. Five principal classes—essential oils, polyphenol-rich plant extracts, microbial biocontrol agents, generally-recognised-as-safe (GRAS) compounds, and edible coatings—are compared with respect to their activity against the major postharvest pathogens. Reported decay reductions frequently reach 60–93%: for example, thyme and oregano essential-oil dips can lower grey-mould lesions in strawberries by roughly 70–90%, antagonistic yeasts and bacteria reduce disease incidence by 60–85% through competition and volatile organic compounds, and natamycin achieves up to ~93% control of citrus green mould.

Mechanisms are shown to be multi-target—membrane disruption, enzyme and ATPase inhibition, reactive-oxygen-species induction, quorum-sensing and biofilm interference,

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nutrient and space competition, and elicitation of host defence—which underlies both broad-spectrum activity and a low propensity for resistance. Industrial translation is examined through registered commercial products (Bio-Save, Shemer, Nexy, BoniProtect, natamycin) and the barriers of cost, formulation stability, regulatory approval and supply-chain integration. Shelf-life extensions of two- to fourfold are documented across diverse commodities. The review concludes that natural preservatives are technically mature for several applications but require standardised efficacy testing, robust formulation, and clearer regulatory pathways to achieve wide commercial adoption.

1. INTRODUCTION

Fruits and vegetables are indispensable to human nutrition, yet their high moisture content, active metabolism and physical fragility make them among the most perishable of all agricultural commodities. A large share of what is grown never reaches the consumer: estimates of postharvest loss for fresh produce range from roughly 28% to 55% of production annually, with the heaviest burden falling on low- and middle-income countries where cold-chain and storage infrastructure are limited. [1,2] Disease-driven decay alone is generally held responsible for losses of the order of 20–40% of production, and the aggregate economic cost of postharvest constraints has been estimated at around US$150 billion per year. [3,4] Beyond the direct economic and food-security consequences, spoiled produce represents a waste of the water, land, energy and labour embodied in its production and contributes to greenhouse-gas emissions during decomposition.

The proximate cause of most postharvest loss is microbial—principally a small set of aggressive filamentous fungi. *Botrytis cinerea*, the agent of grey mould, attacks more than 200 plant species and is responsible for grape-crop losses estimated at 20–25% in some regions; *Penicillium expansum* (blue mould) and *P. digitatum*/*P. italicum* (green and blue moulds of citrus) cause multimillion-dollar losses and, in the case of *P. expansum*, contaminate processed products with the mycotoxin patulin. [3,5,6] *Rhizopus stolonifer*, *Monilinia* spp., *Colletotrichum* spp. and *Aspergillus* spp. round out the principal fungal spoilers, while psychrotrophic bacteria such as *Pseudomonas* spp. dominate soft-rot and slime defects in refrigerated chains. [7] Several of these pathogens establish quiescent (latent) infections before harvest that only develop during storage, complicating control. [6]

For decades these diseases have been managed chiefly with synthetic fungicides. That approach is now under sustained pressure from three directions: the widespread emergence of fungicide-resistant strains (for example quinone-outside-inhibitor resistance in *Colletotrichum*), the progressive regulatory withdrawal of active ingredients over toxicological and environmental concerns, and consumer rejection of chemical residues on fresh produce. [2,8] Natural preservatives—bioactive compounds and organisms of plant, microbial, algal or animal origin, most of which hold GRAS or Qualified-Presumption-of-Safety status—have therefore emerged as the most credible sustainable alternative. [7,9] They combine antimicrobial and often antioxidant activity with biodegradability, low mammalian toxicity and high consumer acceptability.

This review synthesises the evidence on natural preservatives for postharvest spoilage control across three tightly connected themes: how well they work (efficacy), why they work (mechanisms), and whether they can be deployed at commercial scale (industrial scalability). Figure 1 sets out the classification framework used throughout, organising natural preservatives into five principal classes and their common application formats.

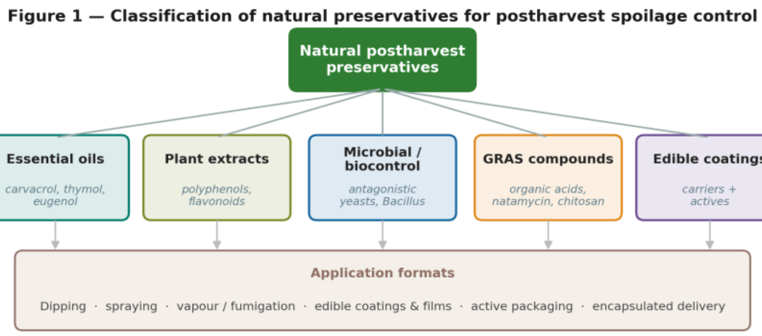

Figure 1. Classification of natural preservatives for postharvest spoilage control. Five principal classes—essential oils, plant extracts, microbial/biocontrol agents, GRAS compounds and edible coatings—are delivered through a common set of application formats and frequently combined to exploit complementary modes of action.

2. THE POSTHARVEST SPOILAGE PROBLEM

2.1 Magnitude and drivers of loss

The scale of postharvest loss varies widely with commodity, region and supply-chain quality, but the pattern is consistent: perishable horticultural produce loses far more between farm and fork than staple grains, and losses concentrate wherever the cold chain is weakest. [1,2] Figure 2 summarises the reported ranges and the relative contribution of the main deterioration pathways. Microbial decay is the single largest cause, but it acts in concert with physiological senescence, mechanical injury and water loss, each of which can predispose tissue to infection—wounds from harvesting and handling are a primary route of entry for wound pathogens. [6]

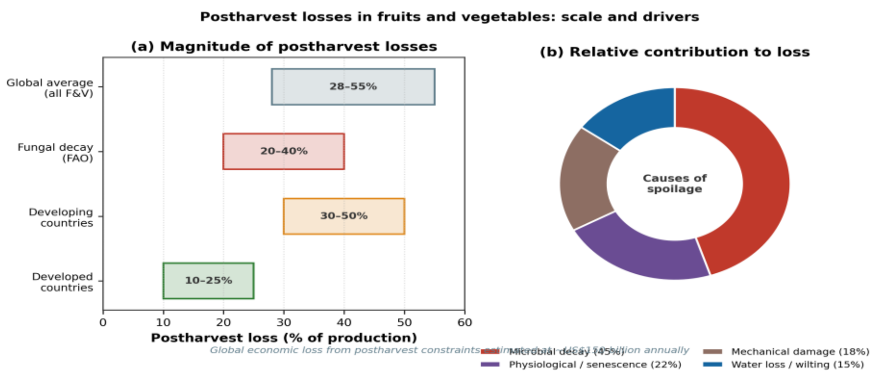

Figure 2. Scale and drivers of postharvest loss. (a) Reported loss ranges across contexts, with disease-driven decay at 20–40% and overall losses up to 28–55%. (b) Indicative relative contribution of the principal deterioration pathways, with microbial decay dominant. Values are compiled from the cited literature to illustrate magnitude.

2.2 The principal postharvest pathogens

Effective preservation begins with knowing the target. Table 1 summarises the dominant postharvest pathogens, their host commodities, characteristic symptoms and, where relevant, the mycotoxins they produce—an important food-safety dimension because contamination of processed products with patulin or ochratoxin A can exceed regulatory limits (for example the 2 μg/kg ceiling commonly applied to ochratoxin A). [5,6] Susceptibility differs by pathogen and by the physiological state of the host, and the mix of quiescent and wound infections dictates whether a preservative must act protectively at the surface or curatively within established lesions.

Pathogen	Disease / symptom	Principal commodities	Mycotoxin / note
Botrytis cinerea	Grey mould; soft watery rot	Grapes, strawberry, tomato, kiwi	Broad host range (>200 spp.)
Penicillium expansum	Blue mould	Apple, pear, pome fruit	Patulin
P. digitatum / P. italicum	Green / blue mould	Citrus	Rapid sporulation
Rhizopus stolonifer	Rhizopus soft rot	Stone fruit, strawberry, tomato	Fast-spreading
Monilinia spp.	Brown rot	Stone fruit (peach, apricot)	Field–store continuum
Colletotrichum spp.	Anthracnose	Mango, papaya, avocado	Quiescent infection; QoI resistance
Aspergillus spp.	Black mould / rot	Grapes, figs, nuts	Ochratoxin A, aflatoxins
Pseudomonas spp.	Bacterial soft rot, slime	Leafy & refrigerated produce	Psychrotrophic; biofilms

Table 1. Major postharvest spoilage pathogens of fruits and vegetables, their characteristic diseases, host commodities and food-safety notes. Fungi dominate, but psychrotrophic bacteria are significant in refrigerated supply chains.

3. CLASSES OF NATURAL PRESERVATIVES

Natural preservatives for postharvest use fall into five overlapping classes, summarised with representative examples and sources in Table 2. In practice these are frequently combined—an essential oil carried within an edible coating, or a biocontrol yeast co-applied with a GRAS salt—to exploit complementary modes of action and to compensate for the limitations of any single agent. [9,10]

Class	Representative agents	Typical source	Principal activity
Essential oils	Thyme, oregano (carvacrol, thymol), clove (eugenol), cinnamon (cinnamaldehyde)	Aromatic plants (steam distillation)	Broad antifungal / antibacterial; volatile
Plant extracts	Polyphenols, flavonoids, tannins (grape, pomegranate, green tea)	Fruit/vegetable tissues & by-products	Antioxidant + antimicrobial
Microbial / biocontrol agents	Metschnikowia fructicola , Candida oleophila , Bacillus , Pseudomonas	Phyllosphere / fruit surface isolates	Competition, VOCs, mycoparasitism, induced resistance
GRAS compounds	Natamycin, chitosan, organic acids (acetic, sorbic), bicarbonate	Fermentation, crustacean shells, fruits	Direct antimicrobial; film-forming
Edible coatings	Chitosan, alginate, starch, protein/lipid composites	Polysaccharides, proteins, lipids	Barrier + carrier for actives

Table 2. The five principal classes of natural postharvest preservatives, with representative agents, sources and dominant activities. Combinations are common and often synergistic.

3.1 Essential oils

Essential oils (EOs) are the most extensively studied natural antifungals for postharvest use. Their activity resides chiefly in phenolic and terpenoid constituents—carvacrol and thymol (oregano, thyme), eugenol (clove) and cinnamaldehyde (cinnamon)—whose lipophilicity allows them to partition into and destabilise microbial membranes. [7,9] They are effective at low concentrations: dips of 0.5% thyme or oregano EO have reduced *B. cinerea* lesions in strawberry by roughly 70–90%. [7] Their principal drawbacks—volatility, strong odour and poor water solubility—are increasingly addressed by encapsulation and by incorporation into coatings, which reduce volatilisation and provide sustained release at the produce surface. [9,10]

3.2 Plant extracts

Polyphenol-rich extracts from fruits, vegetables and their processing by-products (grape pomace, pomegranate peel, green tea) combine antimicrobial action with strong antioxidant activity, the latter delaying oxidative browning and senescence. [9] Using agri-food by-products as the extract source aligns postharvest preservation with circular-economy objectives. Extracts are generally milder and less volatile than EOs, and are well suited to incorporation into coatings, though their efficacy is more variable and matrix-dependent.

3.3 Microbial biocontrol agents

Antagonistic yeasts and bacteria applied to the fruit surface represent the most commercially advanced class. Yeasts such as *Metschnikowia fructicola*, *Candida oleophila* and *Aureobasidium pullulans*, and bacteria such as *Bacillus amyloliquefaciens* and *Pseudomonas fluorescens*, suppress pathogens through competition for nutrients and space, secretion of volatile organic compounds and cell-wall-degrading enzymes, and elicitation of host defences—reducing disease incidence by 60–85% in many trials. [8,11,12] Because they act through multiple non-toxic mechanisms rather than a single biochemical target, resistance development is unlikely. Their limitations are biological: sensitivity to storage stress, a need for viable cells, and generally protective rather than curative action.

3.4 GRAS compounds

Several individually defined natural or nature-identical compounds hold GRAS status and are used directly. Natamycin, a polyene macrolide produced by *Streptomyces* fermentation, is a registered postharvest biofungicide for citrus and stone fruit and—notably—no resistance has been described despite decades of use as a food preservative. [13,14] Chitosan, from crustacean shells, is simultaneously antimicrobial and film-forming; organic acids and bicarbonate salts provide inexpensive, broadly active options. These compounds offer the clearest regulatory path to market.

3.5 Edible coatings as delivery systems

Edible coatings are less a separate class than an enabling delivery platform: thin biopolymer layers of polysaccharide, protein or lipid that both modify the produce microenvironment—slowing respiration and water loss by modulating $O_2/CO_2/H_2O$ exchange—and serve as carriers for EOs, extracts or GRAS actives, releasing them in a controlled manner at the surface where infection begins. [9,10] This dual barrier-plus-carrier function is why coatings frequently outperform the free active applied alone.

4. EFFICACY AGAINST POSTHARVEST PATHOGENS

The practical test of any preservative is the reduction of decay and the extension of marketable life. Figure 3 compiles representative decay-reduction values from the literature across the five classes, and Table 3 details the corresponding treatments, targets and outcomes. Two patterns stand out. First, several natural treatments achieve control comparable to synthetic standards—decay reductions of 80–93% are reported for optimised EO dips, selenium–chitosan nanoparticles and natamycin. Second, efficacy is strongly context-dependent: the same natamycin concentration that reduced green-mould decay by ~93% on grapefruit gave only ~58% control on orange, reflecting differences in cuticle, wound response and pathogen load. [14]

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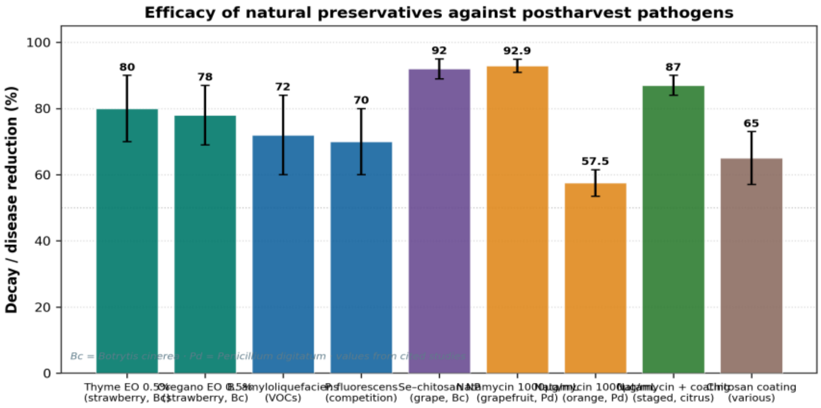

Figure 3. Decay/disease reduction achieved by representative natural-preservative treatments against major postharvest pathogens. Error bars indicate the approximate reported spread. Efficacy varies markedly with commodity and pathogen, underscoring the need for application-specific optimisation. (Bc = Botrytis cinerea; Pd = Penicillium digitatum.)

A recurring and important finding is that staged or combined applications outperform single treatments. Natamycin applied as an aqueous treatment followed by a fruit coating reduced citrus decay to ≤10.7% versus 81.9% in untreated controls—substantially better than either component alone. [14] Similarly, combining a biocontrol yeast with a GRAS salt or mild heat consistently improves and stabilises performance. [11,12] This hurdle-technology logic—stacking several partial barriers—is central to compensating for the more modest and variable efficacy of individual natural agents relative to broad-spectrum synthetic fungicides.

Treatment	Target pathogen / commodity	Dose	Outcome	Ref.
Thyme / oregano EO dip	B. cinerea / strawberry	0.5%	70–90% lesion reduction	7
Selenium–chitosan NPs	B. cinerea / grape	—	~92% inhibition (ROS, wall damage)	8
Bacillus amyloliquefaciens	Broad / various	Cell suspension	60–85% disease reduction (VOCs)	8
Natamycin (aqueous spray)	P. digitatum / grapefruit	1000 µg/mL	~93% decay reduction	14
Natamycin (aqueous spray)	P. digitatum / orange	1000 µg/mL	~58% decay reduction	14
Natamycin + fruit coating	Green mould / citrus	staged	Decay ≤10.7% vs 81.9% control	14
Chitosan coating	Various / multiple fruit	1–2%	Reduced decay; delayed senescence	9
EO-loaded biopolymer film	Fungal / F&V	variable	Sustained release; extended shelf life	10

Table 3. Representative efficacy data for natural postharvest treatments. Values are drawn from the cited studies; "—" indicates a parameter not reported in comparable form. Staged/combined treatments consistently outperform single applications.

5. MECHANISMS OF ACTION

The durability and breadth of natural preservatives derive from the fact that they act on multiple cellular targets simultaneously, rather than inhibiting a single enzyme as most synthetic fungicides do. Figure 4 depicts the principal mechanisms, which are summarised by class in Table 4. This multi-target action explains both the broad-spectrum activity typical of these agents and their low propensity to select for resistant strains—a decisive advantage given the resistance crisis affecting single-site synthetic fungicides. [8,13]

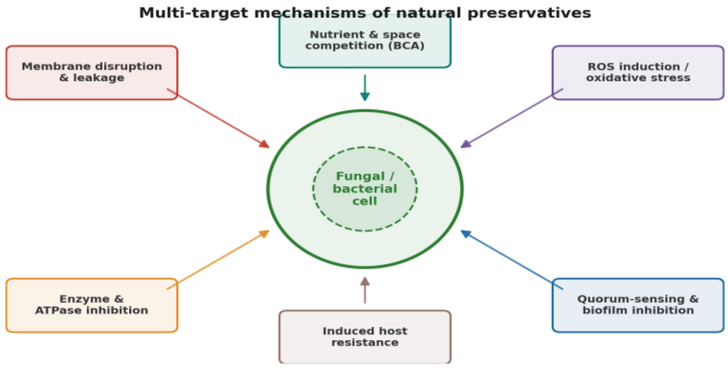

Figure 4. Multi-target mechanisms of natural preservatives. Direct antimicrobials (essential oils, GRAS compounds) disrupt membranes, inhibit enzymes and ATPases, induce reactive oxygen species and interfere with quorum sensing and biofilms; biocontrol agents add nutrient and space competition and elicit host defence responses. Simultaneous action on several targets underlies broad-spectrum efficacy and low resistance risk.

5.1 Direct antimicrobial mechanisms

For EOs and GRAS antimicrobials the primary event is disruption of the microbial cytoplasmic membrane. Lipophilic terpenoids and polyenes such as natamycin insert into or bind membrane components (natamycin binds ergosterol), increasing permeability, dissipating ion and pH gradients, and causing leakage of intracellular contents. [7,13] Secondary effects follow: inhibition of membrane-bound ATPases and metabolic enzymes, interference with nucleic-acid synthesis, and—for several agents—induction of intracellular reactive oxygen species that overwhelm fungal antioxidant defences, a mechanism explicitly demonstrated for selenium–chitosan nanoparticles against *B. cinerea*. [8] Many phenolics additionally suppress quorum sensing and biofilm formation, which is particularly relevant to bacterial soft-rot control. [7]

5.2 Biocontrol mechanisms

Antagonistic microorganisms operate through a different, largely indirect repertoire. Rapid colonisation of wounds allows them to outcompete pathogens for limiting nutrients (notably iron, sequestered by yeast siderophores) and physical space. Many secrete volatile organic compounds and hydrolytic cell-wall-degrading enzymes (chitinases, glucanases) that inhibit or lyse pathogen hyphae, and several—including *M. fructicola*—elicit host defence signalling and the accumulation of reactive oxygen species at the wound site. [11,12] Because effective control usually requires the coincidence of several of these mechanisms, biocontrol agents are robust to resistance but sensitive to anything that impairs their viability or establishment.

5.3 Physical and physiological mechanisms of coatings

Edible coatings contribute a non-biocidal layer of protection by modifying gas exchange and surface humidity: restricting oxygen availability and water loss slows respiration, delays senescence and reduces the physiological stress that predisposes tissue to infection, while the coating itself presents a physical barrier to pathogen ingress and a reservoir for controlled release of incorporated actives. [9,10]

Mechanism	Predominant class	Molecular / biological effect
Membrane disruption & leakage	Essential oils, natamycin	Loss of integrity; ion/pH gradient collapse
Enzyme & ATPase inhibition	EOs, polyphenols	Impaired energy metabolism
ROS induction	Metal/Se nanoparticles, some EOs	Oxidative damage to lipids, proteins, DNA
Quorum-sensing / biofilm interference	Polyphenols, EOs	Reduced virulence & bacterial soft rot
Nutrient & space competition	Biocontrol yeasts/bacteria	Pathogen starvation at wound sites
Mycoparasitism / lytic enzymes	Biocontrol agents	Hyphal lysis (chitinase, glucanase)
Induced host resistance	Biocontrol agents, chitosan	Activation of plant defence pathways
Modified atmosphere / barrier	Edible coatings	Slowed respiration & water loss

Table 4. Mechanisms of action of natural postharvest preservatives mapped to the class in which each predominates. Most agents act through several of these simultaneously.

6. INDUSTRIAL SCALABILITY AND COMMERCIALISATION

Laboratory efficacy is necessary but not sufficient for commercial adoption. Industrial deployment depends on cost, formulation stability, regulatory approval, compatibility with existing packing-line operations and consistent field performance. Figure 5 shows the shelf-life extensions achievable across major commodities, and Figure 6 profiles the five classes against the criteria that govern scalability.

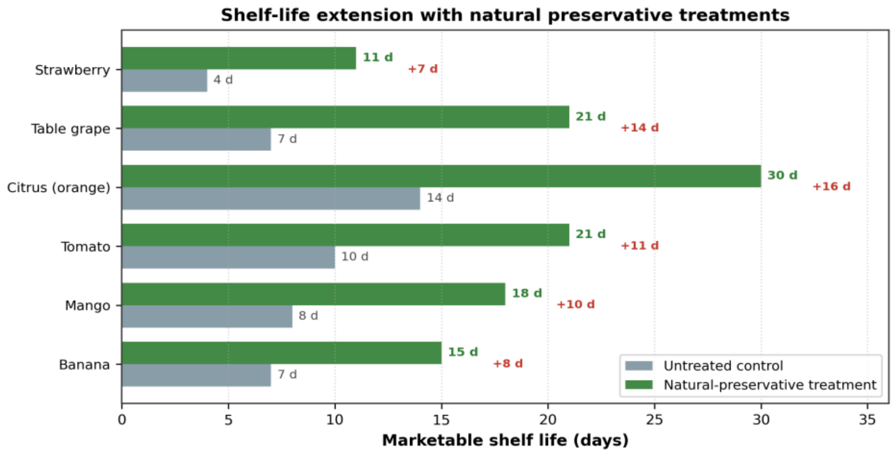

Figure 5. Marketable shelf-life extension achieved with natural-preservative treatments across representative commodities. Extensions of roughly two- to fourfold are typical, though absolute values depend on cultivar, initial quality and storage conditions. Bars synthesise values reported across the cited literature.

6.1 Registered commercial products

A number of natural postharvest products have already achieved registration and commercial use, demonstrating that the regulatory and manufacturing hurdles are surmountable (Table 5). The bacterial biofungicides Bio-Save 100/110 (*Pseudomonas syringae*) were registered in the United States in 1995 for pome and citrus rots; the yeast-based Shemer (*Metschnikowia fructicola*) was registered in Israel in 2007 and subsequently acquired by Bayer and sublicensed through Koppert; Nexy (*Candida oleophila*) was approved across the European Union in 2013; and BoniProtect (*Aureobasidium pullulans*) and Candifruit (*Candida sake*) serve the pome-fruit market in Europe. [11,12] Among GRAS compounds, natamycin (marketed for postharvest use and, as Zivion, for field application) is registered for citrus and stone fruit, and low-cost fermentation routes using agro-industrial by-products are being developed to improve its economics. [13,14,15]

Product	Active agent	Target / commodity	Status / region
Bio-Save 100/110	Pseudomonas syringae	Pome & citrus rots	Registered, USA (1995)
Shemer	Metschnikowia fructicola	Broad F&V (Botrytis, Penicillium, Rhizopus)	Israel (2007); Bayer/Koppert
Nexy	Candida oleophila	Pome fruit	EU approval (2013)
BoniProtect	Aureobasidium pullulans	Pome fruit (pre-harvest)	Germany / EU
Candifruit	Candida sake	Pome fruit	Spain
Natamycin / Zivion	Streptomyces fermentation product	Citrus, stone fruit	Registered (USA & others)
Chitosan coatings	Chitosan (± actives)	Multiple fruit	Widely used; GRAS

Table 5. Selected commercial natural-preservative products for postharvest use, illustrating that microbial and GRAS-based technologies have achieved registration and market deployment in multiple regions.

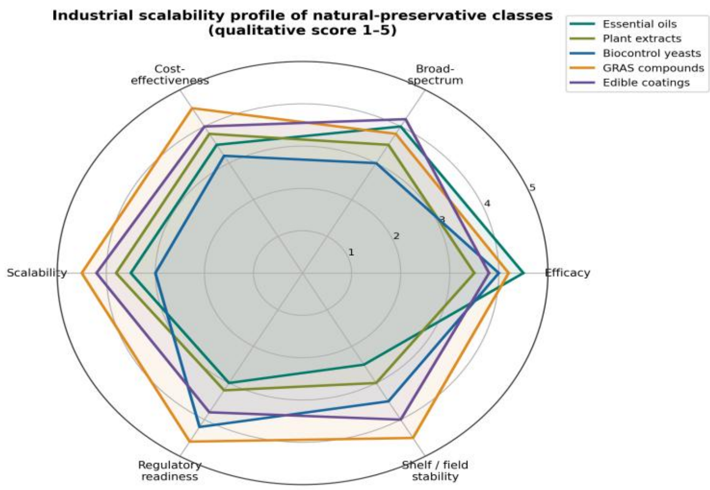

Figure 6. Qualitative industrial-scalability profile of the five natural-preservative classes across six decision criteria (1 = weak, 5 = strong). GRAS compounds and edible coatings score highest on cost, scalability and regulatory readiness; essential oils lead on intrinsic efficacy but lag on stability and regulatory clarity; biocontrol agents offer strong regulatory precedent but require viable-cell logistics

6.2 Barriers to adoption

Four barriers recur. Cost and formulation: many natural actives are more expensive per treated tonne than synthetic fungicides and are chemically or biologically less stable, demanding careful formulation to preserve activity through storage and application. Variable field efficacy: performance that is excellent in inoculated laboratory assays often weakens under commercial loads, mixed pathogen populations and fluctuating conditions, which is why standardised, commercially realistic efficacy testing is essential. Regulatory complexity: although GRAS compounds enjoy a relatively clear path, novel biocontrol strains and nano-formulations face lengthy, jurisdiction-specific approval. Supply-chain integration: treatments must be compatible with existing dip tanks, waxing lines and cold chains, and must not impart off-flavours or visible residues. [2,9,12] Encapsulation and coating technologies address several of these simultaneously by stabilising actives and enabling controlled release, and are consequently a focus of current scale-up research. [10]

7. CHALLENGES AND FUTURE PERSPECTIVES

The field is transitioning from demonstrating efficacy to engineering reliable products. Priorities for the next phase include: standardised, commercially realistic efficacy protocols so that results are comparable across studies and predictive of field performance; robust formulation and encapsulation to overcome the volatility of EOs and the fragility of biocontrol cells; rational design of combination (hurdle) treatments that pair complementary mechanisms—for example a biocontrol yeast within an EO-loaded coating—to reach synthetic-fungicide-level control; clearer and more harmonised regulatory pathways, particularly for novel strains and nanomaterials, including nano-specific safety data; valorisation of agri-food by-products as low-cost sources of both actives and carrier materials, reinforcing circular-economy goals; and integration with the broader postharvest ecosystem of cold chain, modified-atmosphere packaging and non-thermal physical treatments (UV-C, cold plasma), within which natural preservatives function best as one coordinated hurdle rather than a stand-alone replacement. [2,9,10] Advances in "omics"-guided strain selection and in stimulus-responsive coatings that release actives in response to spoilage cues are especially promising directions.

8. CONCLUSION

Natural preservatives have matured into a technically credible response to postharvest spoilage. Across essential oils, plant extracts, microbial biocontrol agents, GRAS compounds and edible coatings, decay reductions of 60–93% and shelf-life extensions of two- to fourfold are achievable, delivered through multi-target mechanisms that confer broad-spectrum activity and a low risk of resistance—a structural advantage over single-site synthetic fungicides. Commercial products such as Bio-Save, Shemer, Nexy and natamycin prove that registration and industrial deployment are attainable. The remaining obstacles are not primarily ones of biological efficacy but of engineering and governance: standardised efficacy testing, stable and cost-effective formulation, harmonised regulation, and seamless integration into existing supply chains. The most effective path forward treats natural preservatives not as drop-in replacements for synthetic fungicides but as coordinated components of a hurdle-based postharvest system, in which their complementary mechanisms are combined with each other and with physical and atmospheric interventions to deliver reliable, residue-free protection at commercial scale.

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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