

Nano-Enabled Preservation Technology for Extending Shelf Life of Fresh Fruits

Amar Jensi Solanki

SBN Govt P G College

Barwani MP 451551

Abstract : Fresh-fruit preservation requires simultaneous control of moisture loss, softening, microbial deterioration and nutritional degradation. Nano-enabled edible coatings offer a promising approach by combining film-forming biopolymers with nanoscale delivery systems or functional particles. This paper critically examines published research on chitosan nanoparticles, essential-oil nanoemulsions, phytochemical nanocarriers and nanocomposite coatings for fresh-fruit preservation. A focused narrative review was undertaken using peer-reviewed publications verified through publisher websites, institutional repositories and bibliographic databases. Experimental findings were compared within their original fruit, treatment and storage conditions; heterogeneous results were not pooled into a single effectiveness estimate. Published evidence indicates that nano-enabled formulations can improve selected preservation outcomes, although their advantages depend on formulation composition and the endpoint evaluated. In a mango experiment, coated fruit maintained firmness of 7.30 N compared with 3.42 N in uncoated fruit after 28 days at 9°C, with a reported significant treatment difference. Weight loss was numerically lower, at 3.75% compared with 4.96%, but the difference was not statistically significant. Strawberry and fresh-cut apple studies provide additional evidence for antimicrobial delivery and quality retention. The analysis concludes that nano-enabled preservation should be developed as a fruit-specific complement to established postharvest management. Reliable commercialization requires standardized characterization, appropriate controls, sensory evaluation, exposure assessment and validation under realistic distribution conditions.

Keywords: nanotechnology; edible coatings; fresh fruits; shelf life; chitosan nanoparticles; nanoemulsions; postharvest preservation.

Introduction

Fresh fruits retain biological activity after harvest, making preservation a continuing process rather than a single treatment. Their commercial quality depends on maintaining an acceptable combination of appearance, texture, flavor and freedom from decay. A preservation intervention that improves one characteristic may provide limited practical benefit if another characteristic becomes unacceptable earlier.

Edible coatings provide a platform for modifying the fruit surface and delivering active ingredients. Nano-

enabled approaches extend this platform through smaller dispersed droplets, particulate carriers or reinforcing materials. These systems are intended to improve the distribution, stability or functionality of coating components. Reviews identify potential benefits for moisture management, gas exchange and delivery of antimicrobial or antioxidant compounds. These benefits remain formulation-dependent and should not be interpreted as universal properties of every nanocoating. [ars.usda.gov](https://www.ars.usda.gov)

The expression “nano-enabled preservation” covers substantially different technologies. Chitosan nanoparticles, essential-oil nanoemulsions and zinc-oxide nanocomposites do not have identical structures, mechanisms or exposure considerations. Their evaluation therefore requires clear descriptions of the material, its role and the conditions under which it was tested.

This paper examines the scientific basis and published effectiveness of these approaches. Particular attention is given to distinguishing quality retention from demonstrated shelf-life extension and statistically significant effects from favorable numerical trends.

Research Problem

Research frequently presents nano-enabled coatings as promising preservation technologies, but comparisons across studies are difficult. Fruits differ in maturity, surface structure and susceptibility to deterioration.

Coating matrices, active ingredients, application procedures and storage temperatures also vary.

Consequently, a treatment successful on refrigerated strawberries cannot automatically be recommended for mangoes or fresh-cut apples. Similarly, reduced microbial growth in a laboratory assay does not independently demonstrate longer consumer-acceptable storage.

The central research problem is identifying what the existing evidence actually establishes and which experimental requirements are necessary to translate promising laboratory findings into dependable preservation systems.

Objectives

The study aims to examine major nano-enabled preservation platforms, evaluate their proposed functions, compare selected published findings and identify methodological requirements for reliable assessment. It also considers the limitations affecting practical implementation, particularly sensory acceptability, material characterization and the interpretation of statistical results.



Literature Review

Conventional Coatings as a Necessary Baseline

Gol, Patel and Rao (2013) investigated strawberry coatings based on carboxymethyl cellulose, hydroxypropyl methylcellulose and combinations with chitosan. This research establishes an important baseline: conventional biopolymer coatings themselves can influence preservation. A nanotechnology study should therefore compare its formulation with a suitable polymer-only treatment, rather than relying exclusively on an uncoated control. [ScienceDirect](#)

Cazón and Vázquez (2020) reviewed the mechanical and barrier properties of chitosan combined with other food-packaging components. Their work supports attention to the entire formulation. Polymer blending, plasticization and incorporation of other components can influence film performance, making it inappropriate to attribute every improvement solely to nanoscale size.

Essential-Oil Nanoemulsions

Hasan, Ferrentino and Scampicchio (2020) reviewed nanoemulsion-based coatings for fresh-cut produce. Their analysis identifies antimicrobial, antioxidant and texture-related applications, while emphasizing sensory and safety questions. This contribution connects formulation design with the multiple quality attributes that determine preservation performance. [Oxford Academic](#)

Oliveira Filho and colleagues (2021) examined nanoemulsions as fruit and vegetable coatings. They describe their potential as carriers for active compounds and discuss improvements in coating characteristics relative to conventional emulsions. Their review also highlights the need for research extending beyond laboratory demonstrations. [ars.usda.gov](#)

Panwar and colleagues (2024) reviewed fabrication methods, matrices and characterization of nanoemulsion coatings. Their emphasis on biological fate, safety and economical production shows that preservation effectiveness is only one component of technology evaluation. Commercial suitability also requires reproducible manufacturing and an acceptable exposure profile. [PubMed](#)

Direct Fruit-Preservation Studies

Salvia-Trujillo and colleagues (2015) evaluated lemongrass-essential-oil nanoemulsions on fresh-cut Fuji apples using concentrations of 0.1%, 0.5% and 1% v/v. The study compared safety and quality attributes and demonstrated that treatment effects were endpoint-specific. Firmness remained practically constant during storage regardless of the coating applied, cautioning against claims that every quality parameter improves. [ScienceDirect](#)

Chu and colleagues (2020) investigated pullulan coatings incorporating cinnamon-essential-oil nanoemulsion for strawberries. This work provides a directly relevant fruit application of an active nanoemulsion within a film-forming matrix. It also illustrates why the matrix and active delivery system must be evaluated together. [ScienceDirect](#)

Fattahi and colleagues (2020) compared macroemulsions and nanoemulsions of cinnamon essential oil in carboxymethyl-cellulose films. Their experiments addressed film properties and in-vitro antifungal performance. Such material studies help explain formulation behavior but should not be treated as independent proof of shelf-life extension on fruit.

[Wiley Online Library](#)

Nanoparticles and Multifunctional Coatings

Abu Salha and Gedanken (2021) developed sonochemically produced chitosan nanoparticles deposited on strawberries. Their comparison with the same amount of non-sonicated chitosan is methodologically valuable because it addresses the added contribution of the nano-enabled process. Characterization included dynamic light scattering and scanning electron microscopy. [Bar-Ilan University](#)

García-García and colleagues (2023) examined chitosan coatings containing nanostructured zinc oxide. They characterized the hybrid material and evaluated strawberry color, texture, acidity, moisture and microbiological characteristics. The authors reported maintenance of fresh appearance after eight days, providing a condition-specific preservation observation rather than a universal shelf-life value. [PubMed](#)

Hu and colleagues (2023) incorporated trans-resveratrol-loaded nanoparticles into chitosan coatings for strawberries. Preservation was investigated at 22°C and 4°C. The study combines active-compound delivery with fruit protection, demonstrating a multifunctional approach in which carrier performance and coating performance require separate interpretation. [Arizona State University](#)

Parente and colleagues (2026) evaluated an active chitosan coating containing zinc-oxide nanoparticles and eucalyptus essential oil for mango preservation. Their findings provide an informative quantitative comparison because firmness improved significantly, whereas lower weight loss was reported as a nonsignificant trend. [Wiley Online Library](#)

Research Gap

The reviewed literature supports continued investigation of nano-enabled coatings but does not establish a single optimal formulation for fresh fruits. Important gaps concern matched comparisons between nanoscale and conventional systems, consistent reporting of formulation concentrations and realistic definitions of commercial shelf life.

A further gap concerns the relationship between material performance and consumer outcomes. Improved film properties do not necessarily guarantee acceptable flavor, appearance or eating quality. Likewise, short-term fruit preservation does not settle questions about long-term storage, distribution variability or material exposure.

These gaps justify an evaluation framework that links formulation characterization, fruit-quality measurements and explicitly defined acceptability criteria.

Materials and Methods

Study Design

This paper employed a focused narrative review with descriptive analysis of selected published results. No new fruit-storage experiment was conducted. The methodology therefore supports evidence synthesis and within-study numerical comparison, rather than claims of original laboratory findings.

Literature Identification and Verification

Searches used combinations of terms including “nanoemulsion edible coating,” “chitosan nanoparticles,” “fruit shelf life,” “strawberry preservation,” “fresh-cut apple” and “nanocomposite mango coating.”

Publication details were checked through journal publishers, PubMed and institutional records. Twelve relevant references were retained for the paper. This was a targeted selection, not an exhaustive systematic review; no comprehensive screening count or formal pooled estimate is claimed.

Evidence Selection

Direct fruit experiments were prioritized for preservation conclusions. Reviews supplied broader context, while film-characterization studies supported interpretation of material properties. Whole fruits and fresh-cut products were kept distinct because their treatment conditions and deterioration pathways are not interchangeable.



Data Extraction

The extraction framework recorded fruit identity, formulation class, storage conditions, measured endpoints and reported statistical interpretation.

Table 1. Evidence-extraction framework

Variable	Information retained	Reason
Fruit and product form	Species, cultivar where available, whole or fresh-cut	Limits inappropriate transfer of findings
Treatment	Matrix, active ingredient and nano-enabled component	Identifies what was evaluated
Comparator	Uncoated, polymer-only or conventional system	Determines the meaning of treatment benefit
Storage	Temperature and observation period	Places findings in their original context
Endpoint	Firmness, weight loss, microbial or visual outcome	Separates different preservation effects
Statistics	Reported significance and available uncertainty	Distinguishes evidence from numerical trends

Numerical comparisons were restricted to values measured within the same experiment and storage condition. Differences between treatment means were calculated descriptively:

$$\left[\frac{\text{Relative difference (\%)}}{\text{Treatment}} - \frac{\text{Control}}{\text{Control}} \right] \times 100$$

For deterioration indicators, a lower treatment value represents a favorable direction. Percentage-point differences were distinguished from relative percentage changes.

No standard deviations, confidence intervals, exact p-values or sample sizes were invented. Published significance statements were retained without generating new inferential tests.

Results

Preservation Platforms

The selected literature identified several distinct technological platforms.

Table 2. Nano-enabled preservation approaches

Platform	Published application	Main evaluation emphasis
Sonochemical chitosan nanoparticles	Strawberries	Nano-enabled process versus non-sonicated chitosan
Essential-oil nanoemulsion coating	Fresh-cut Fuji apples	Microbial and quality outcomes

Quantitative Analysis

Pullulan– cinnamon-oil nanoemulsion	Strawberries	Active coating application
Resveratrol- loaded nanoparticles in chitosan	Strawberries	Delivery functionality and preservation
Chitosan–ZnO hybrid coating	Strawberries	Material characterization and fruit quality
Chitosan–ZnO– eucalyptus-oil coating	Mangoes	Firmness, ripening and decay-related outcomes

Sources: Abu Salha and Gedanken; Salvia-Trujillo et al.; Chu et al.; Hu et al.; García-García et al.; Parente et al.

Quantitative Quality Retention

The mango study supplies an internally comparable dataset for assessing selected endpoints after 28 days at 9°C.

Table 3. Published mango outcomes and descriptive comparisons

Endpoi nt	Uncoat ed fruit	Coat ed fruit	Calcula ted differen ce	Original statistical interpreta tion
Pulp firmness	3.42 N	7.30 N	+3.88 N; 113.45% higher	Significant ; reported ($P \leq 0.05$)
Weight loss	4.96%	3.75 %	–1.21 percenta ge points; 24.40% lower	Not statistically significant
Delta- absorba nce index	1.77	1.91	+0.14	Different treatment groups in source table

Source: Parente et al. (2026), published treatment means. Relative differences are calculations from those means, not additional experimental observations. [Wiley Online Library](#)

This comparison demonstrates why preservation findings require endpoint-specific interpretation. A favorable direction in one variable may lack statistical support, while another variable shows a supported treatment difference. Without underlying replicate data, additional significance calculations would be unjustified.

Evidence Across Fruit Systems

The strawberry studies support investigation of several preservation routes, including particulate chitosan, active phytochemical carriers and inorganic–biopolymer hybrids. Their findings cannot be combined into a single number of additional storage days because they differ in treatment composition and evaluation conditions.

Similarly, the apple evidence indicates that antimicrobial performance and texture behavior can differ. This reinforces the need to report individual endpoints rather than describing an entire coating as uniformly superior.

Discussion

Interpretation of Preservation Benefits

Nano-enabled coatings should be understood as formulation systems. Their performance may arise from the polymer matrix, active ingredient, application process and nanoscale organization together. Identifying a “nano effect” requires a comparator that differs mainly in the relevant nanoscale feature.

A polymer-only control establishes whether the active system adds value beyond the matrix. A conventional-emulsion control addresses whether smaller droplets improve performance at comparable active concentrations. Individual-component controls help interpret multicomponent formulations.

The distinction between quality retention and shelf-life extension is equally important. Firmness retention demonstrates an effect on texture. It does not independently establish acceptable flavor, absence of spoilage or a defined extension in marketable days. Commercial shelf life should be determined using predetermined rejection criteria.

Methodological Alignment

A dependable fruit experiment should specify maturity, treatment allocation, independent replication and storage conditions before measurements begin. Destructive measurements require separate fruit samples at successive time points, whereas repeated weighing can follow the same fruit when appropriate.

Table 4. Experimental requirements for future validation

Requirement	Recommended reporting
Formulation identity	Ingredient concentrations, units, pH and preparation conditions
Nanoscale characterization	Size distribution, measurement method and stability
Application	Contact time, deposited amount and drying procedure
Replication	Independent treatment batches and experimental units
Quality assessment	Defined methods, units and sampling schedule
Shelf-life endpoint	Predetermined marketability or rejection criteria
Statistical analysis	Model, uncertainty, effect size and comparison procedure
Practical assessment	Sensory acceptance, exposure and distribution performance

For time-dependent data, an analysis incorporating treatment, storage time and their interaction is more informative than unrelated tests at every sampling date. Batch effects and repeated measurements must be handled according to the actual experimental design.



Practical Implications

A coating suitable for laboratory application may require reformulation for dipping or spraying at commercial scale. Stability during preparation, coating uniformity and compatibility with existing handling steps determine whether a promising material can function consistently.

Sensory evaluation is particularly important for essential-oil systems. Antimicrobial activity must be balanced against the possibility of an unacceptable aroma or flavor. The reviewed literature identifies this as a formulation concern rather than a minor supplementary measurement. [Oxford Academic](#)

Material exposure must also be assessed according to the actual formulation. Evidence for one nanoemulsion cannot establish the suitability of an unrelated inorganic nanoparticle system. Reviews explicitly identify biological fate and potential toxicity as areas requiring further investigation. [PubMed](#)

Limitations

This review used a targeted literature selection and is vulnerable to selection and publication bias. Some publications were accessible primarily through abstracts or institutional summaries, limiting extraction of complete experimental details.

The selected studies differed substantially in fruit type, formulation and storage conditions. No meta-analysis was therefore performed. The numerical table represents one published mango experiment and should not be interpreted as a general effect size for nanotechnology.

The source mango article also contains differing formulation concentrations across parts of its methods and treatment descriptions. Its outcome data are cited

here, but its formulation should not be adopted as a reproducible recipe without clarification.

Conclusion

Nano-enabled preservation technologies offer credible opportunities for improving fresh-fruit quality through active coatings and delivery systems. Published experiments support specific benefits, including texture retention and selected antimicrobial or visual outcomes. They also show that favorable numerical changes are not necessarily statistically significant.

The strongest development strategy is fruit-specific and comparator-driven. Formulation characterization, independent replication, sensory assessment and predefined shelf-life criteria should guide evaluation. Nano-enabled coatings can complement postharvest management, but broad commercial claims require validation under the conditions in which fruit will actually be stored, transported and consumed.

Declarations

Data availability: Numerical values presented in this paper originate from the cited publications. No original experimental dataset was generated.

Ethics: No new human-participant or animal experiment was conducted for this review.

Funding and competing interests: These statements must reflect the submitting authors' actual circumstances.

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Author lists are abbreviated with "et al." for longer publications.

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