JURNAL BIOLOGI UDAYANA
P-ISSN: 1410-5292 E-ISSN: 2599-2856
Volume 29 | Nomor 2 | Desember 2025
DOI: https://doi.org/10.24843/JBIOUNUD.2025.v29.i02.p07

Water-soluble nanomaterials self-assembly for improving the stability of natural food preservatives: A Review

Perakitan spontan nanomaterial larut air untuk meningkatkan stabilitas pengawet makanan alami: Suatu Kajian Pustaka

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Diterima
13 Desember 2025

Disetujui
25 Januari 2026

ABSTRACT
Food spoilage is still a global problem, contributing to foodborne illness, economic losses, and environmental burdens associated with food waste. Conventional chemical preservatives, while effective, face increasing regulatory restrictions and consumer concern regarding potential health risks, driving demand for safer and more natural alternatives. Natural preservatives such as essential oils, phenolic compounds, and antimicrobial peptides offer broad-spectrum antimicrobial and antioxidant activities but are limited by poor water solubility, volatility, degradation during processing, and inconsistent efficacy in complex food matrices. This narrative review examines recent advances in water-soluble self-assembled nanomaterials as stabilization and delivery systems for natural food preservatives. Emphasis is placed on supramolecular self-assembly principles, key non-covalent interactions in aqueous environments, common nanostructures including cyclodextrin inclusion complexes, polymer micelles, nanoemulsions, hydrogels, and vesicles, as well as assembly and characterization methods relevant to food applications. The review further discusses major food spoilage mechanisms and bacterial pathogens, highlighting synergistic effects achieved by combining nanomaterials with natural preservatives to enhance antimicrobial efficacy, prolong shelf life, and reduce sensory impacts. While these systems demonstrate significant promise for clean-label food preservation, challenges related to scalability, cost, sensory optimization, safety, migration, and regulatory acceptance remain. Addressing these issues through green synthesis, mechanistic studies, and robust safety assessments will be essential to support the responsible translation of self-assembled nanomaterials into practical and sustainable food preservation strategies.

Keywords: food spoilage, water-soluble, self-assembly, nanomaterials, natural food preservatives

INTISARI
Kerusakan pangan masih menjadi permasalahan global karena berdampak pada kesehatan masyarakat melalui penyakit bawaan makanan, menimbulkan kerugian ekonomi, serta meningkatkan beban lingkungan akibat limbah pangan. Pengawet kimia konvensional selama ini banyak digunakan karena efektivitasnya, namun penerapannya semakin dibatasi oleh regulasi dan kekhawatiran konsumen terhadap potensi risiko kesehatan. Hal ini mendorong meningkatnya minat terhadap pengawet berbahan alami yang dinilai lebih aman. Pengawet alami, seperti minyak esensial, senyawa fenolik, dan peptida antimikroba, memiliki aktivitas antimikroba dan antioksidan yang luas. Namun, penggunaannya dalam sistem pangan masih terkendala oleh kelarutan air yang rendah, sifat volatil, degradasi selama proses pengolahan, serta efektivitas yang tidak selalu konsisten dalam matriks pangan yang kompleks. Tinjauan ini membahas perkembangan terkini nanomaterial larut air yang tersusun secara spontan sebagai sistem stabilisasi dan penghantaran pengawet pangan alami. Pembahasan mencakup prinsip

perakitan supramolekul, interaksi non-kovalen utama dalam lingkungan berair, serta berbagai nanostruktur yang umum digunakan, seperti kompleks inklusi siklodekstrin, misel polimer, nanoemulsi, hidrogel, dan vesikel. Selain itu, diuraikan pula potensi efek sinergis antara nanomaterial dan pengawet alami dalam meningkatkan efektivitas antimikroba, memperpanjang umur simpan, dan mengurangi dampak sensori. Meskipun menjanjikan untuk pengawetan pangan, penerapan teknologi ini masih menghadapi tantangan terkait skalabilitas, biaya, keamanan, dan penerimaan regulasi, sehingga memerlukan pengembangan lebih lanjut sebelum dapat diterapkan secara luas.

Kata Kunci: kerusakan pangan, larut dalam air, perakitan spontan, nanomaterial, pengawet makanan alami

INTRODUCTION

Global Challenge of Food Spoilage and Danger of Preservatives

Food spoilage remains a pervasive global challenge, with significant implications for public health, food security, and economic sustainability. Around 600 million people become sick and 420,000 die annually due to unsafe food consumption, with children under five years old being more vulnerable (World Health Organization, 2024). Foodborne diseases are among the most common causes of sickness around the world. The burden is exacerbated by the increasing prevalence of antibiotic-resistant pathogens and limitations in traditional antimicrobial interventions (World Health Organization, 2023). The Food and Agriculture Organization (FAO) estimates that 13% of food is lost post-harvest and before retail, with an additional 19% wasted at retail and consumer levels, representing a substantial economic and environmental cost of food spoilage. Food loss and waste even generate 8-10% global greenhouse gases (UN Climate Change, 2024).

To mitigate spoilage, the food industry has historically relied on chemical preservatives such as benzoates, sorbates, and sulfites (Quansah & Kwesi Saalia, 2024). While these compounds are effective in extending shelf life and preventing microbial growth, they are associated with consumer-perceived health risks and regulatory scrutiny, particularly regarding allergenicity and long-term exposure (Gyawali & Ibrahim, 2014). Consumer awareness of these risks has driven demand for safer and more natural alternatives. Regulatory agencies have responded by tightening permissible limits and encouraging the development of “clean-label” products (Aschemann-Witzel et al., 2019).

Alternative Natural Preservatives and Their Instability

Natural preservatives, including essential oils (EOs), antimicrobial peptides (AMPs), and phenolic compounds have emerged as potential alternatives due to their broad antimicrobial and antioxidant activities (Ganosi et al., 2023; Mohammed et al., 2025; Parada Fabián et al., 2025; Xu et al., 2025). Plant-derived EOs such as clove, oregano, cinnamon, and thyme, as well as phenolics like catechins and flavonoids, are recognized for their Generally Recognized as Safe (GRAS) status and efficacy against foodborne pathogens (Božik et al., 2017; Khan et al., 2025). AMPs, including nisin and pediocin, are also widely used in dairy and meat preservation (Parada Fabián et al., 2025).

Animal-derived natural preservatives also contribute to food preservation and safety. Proteins and peptides such as lysozyme (from egg white), lactoferrin and lactoperoxidase (from milk), and chitosan derived from crustacean shells exhibit antimicrobial activity through cell wall hydrolysis, iron sequestration, membrane destabilization, and inhibition of microbial metabolism. These animal-derived preservatives are commonly applied in dairy products, seafood, meat, and edible coatings (Lee & Paik, 2016).

However, the practical application of these natural compounds is hampered by several instability issues. EOs are highly volatile, hydrophobic, and prone to degradation by light, heat, and oxygen which limits their direct incorporation into food matrices (Ganosi et al., 2023; Khan et al., 2025). Phenolics, peptides, and AMPs are prone to enzymatic degradation, poor water solubility, and rapid loss of bioactivity during processing and storage (Adaro et al., 2023; Parada Fabián et al., 2025; Xu et al., 2025). These limitations result in reduced antimicrobial efficacy, inconsistent sensory properties, and challenges in achieving controlled release and sustained activity (El Alami El Hassani et al., 2025; Ganosi et al., 2023).

Emergence of Nanotechnology in Food Preservation

Nanotechnology has revolutionized food preservation by enabling the design of nanomaterials with tailored physicochemical properties for enhanced stability, bioavailability, and controlled release of bioactive compounds (Han et al., 2025; Mahajan et al., 2025). Nanomaterials such as cyclodextrins, polymer micelles, nanoemulsions, and lipid nanoparticles have demonstrated superior encapsulation efficiency, protection against environmental stressors, and improved antimicrobial performance compared to conventional methods (e.g. direct addition) (Alloush & Demiralp, 2025; Sruthi, 2025; Han et al., 2025; Mahajan et al., 2025).

The integration of nanotechnology into food packaging and preservation has led to the development of active and intelligent packaging systems capable of inhibiting microbial growth and monitor food freshness and quality (Ahari & Soufiani, 2021; Muthu et al., 2025). The food industry has increasingly explored nanotechnology to enhance shelf life and safety of their products. For example, silver nanoparticles (AgNPs) were combined into food packaging films to give antimicrobial activity and thereby extend the shelf life of perishable foods like fresh fruits, meat, and seafood (Pattnaik et al., 2024). Despite these advances, concerns regarding cost-effectiveness, scalability, and safety persist, necessitating further research and regulatory oversight (Mahajan et al., 2025; Muthu et al., 2025; Pattnaik et al., 2024; Prakash & São José, 2026). FDA nano guidance updated 2021, emphasizing phys-chem characterization (Food and Drug Administration, 2022).

Potential Combination of Nanotechnology to Stabilize Natural Preservatives

The synergistic combination of nanotechnology and natural preservatives offers a promising strategy to overcome the instability and efficacy challenges of bioactive compounds (Mahajan et al., 2025; McClements et al., 2021; Pattnaik et al., 2024). Water-soluble self-assembled nanomaterials, such as cyclodextrin inclusion complexes, polymer micelles, and nanoemulsions, provide protective matrices that enhance solubility, shield against degradation, and enable controlled release of essential oils (EOs), phenolics, and antimicrobial peptides (AMPs) (Mahajan et al., 2025; McClements et al., 2021; Muthu et al., 2025). For example, cyclodextrin-based encapsulation has improved the stability and antimicrobial ability of EOs against pathogens like *Staphylococcus aureus* and *Escherichia coli* (Alabrahim et al., 2025), while polymer micelles and nanoemulsions have introduced the sustained release and enhanced bioavailability of phenolic antioxidants and peptides. These approaches successfully extend shelf life, minimize sensory alterations, reduce the required dosage of preservatives (Alloush & Demiralp, 2025; McClements et al., 2021).

This aligns well with consumer preferences for minimally processed and natural foods (El Alami El Hassani et al., 2025; Muthu et al., 2025).

Rationale for Water-Soluble Self-Assembled Nanomaterials

Water-soluble self-assembled nanomaterials are particularly attractive for food applications due to their biodegradability, biocompatibility, and ability to form stable dispersions in aqueous environments (Mahajan et al., 2025; Muthu et al., 2025). Cyclodextrins, for instance, possess hydrophilic exteriors and hydrophobic cavities, enabling the encapsulation of hydrophobic essential oils (EOs) and phenolics while maintaining water solubility (Cengiz et al., 2023). Polymer micelles, formed from amphiphilic block copolymers, create core–shell structures that protect and deliver bioactives in aqueous systems (Vaskan et al., 2025). Meanwhile nanoemulsions offer enhanced stability, solubility, and controlled release profiles for a variety of natural preservatives (McClements et al., 2021).

These self-assembled systems leverage non-covalent interactions such as hydrophobic forces, electrostatic interactions, hydrogen bonding, and π–π stacking to achieve robust encapsulation and functional performance in complex food matrices (Alloush & Demiralp, 2025; Buaksuntear et al., 2022). Their modularity and tunability allow for customization to specific food applications, addressing the diverse challenges of spoilage, sensory quality, and regulatory compliance (El Alami El Hassani et al., 2025; Mahajan et al., 2025).

Objectives and Scope of this Narrative Review

This narrative literature review aims to synthesize recent advances in the self-assembly of water-soluble nanomaterials for stabilizing natural food preservatives. The review focuses on the principles of supramolecular self-organization, driving forces in aqueous environments, common self-assembled nanostructures, assembly methods, and characterization techniques. It further explores the mechanisms of food spoilage, key bacterial pathogens, and synergy between nanomaterials with natural preservatives.

FUNDAMENTALS OF WATER-SOLUBLE SELF-ASSEMBLY IN NANOMATERIALS

Principles of Supramolecular Self-Organization

Supramolecular self-organization refers to the spontaneous assembly of molecules into ordered structures through non-covalent interactions, resulting in functional nanomaterials with tailored properties (Buaksuntear et al., 2022; Jarak et al., 2024). In biological systems, self-assembly underpins the formation of cell membranes, protein folding, and nucleic acid structures (Habibi et al., 2016). Synthetic analogs, including amphiphilic polymers, peptides, and cyclodextrins, mimic these processes to create nanostructures such as micelles, vesicles, hydrogels, and inclusion complexes (Cengiz et al., 2023; McClements et al., 2021).

The design of self-assembled systems relies on the careful selection of building blocks with complementary functional groups and geometries. For instance, amphiphilic molecules with distinct hydrophilic and hydrophobic domains can organize into micelles or vesicles in aqueous environments, while cyclic oligosaccharides like cyclodextrins form host–guest inclusion complexes with hydrophobic bioactives (McClements et al., 2021; Vaskan et al., 2025). Supramolecular capsules and cages, assembled via hydrogen bonding, metal coordination, or π–π stacking, offer encapsulation and stabilization of reactive species (Bhattacharyya et al., 2025; Buaksuntear et al., 2022).

Recent advances in computational chemistry and molecular engineering have enabled the rational design of supramolecular architectures with precise control over size, shape, and functionality, facilitating their application in food preservation, drug delivery, and biosensing (Borówko & Staszewski, 2024; Jarak et al., 2024; Mahajan et al., 2025).

Driving Forces and Interactions in Aqueous Environments

The self-assembly of nanomaterials in water is governed by a complex interplay of non-covalent interactions, including:

- **Hydrophobic interactions**: Drive the aggregation of nonpolar domains, leading to micelle and bilayer formation. In water, hydrophobic collapse is a key mechanism for the assembly of amphiphilic molecules and π-conjugated systems (Buaksuntear et al., 2022; Mahajan et al., 2025; Muthu et al., 2025).
- **Hydrogen bonding**: Provides stability and directionality, enabling the formation of hydrogels, capsules, and host–guest complexes (Buaksuntear et al., 2022; Jain et al., 2022).
- **Electrostatic interactions**: Occur between charged groups, influencing the assembly of polyelectrolytes, peptides, and cyclodextrin derivatives (Buaksuntear et al., 2022; Jarak et al., 2024).
- **π–π stacking**: Facilitates the organization of aromatic molecules, such as porphyrins and phenolics, into ordered nanostructures with enhanced photophysical properties (Bhattacharyya et al., 2025; Buaksuntear et al., 2022).
- **Van der Waals forces**: Contribute to the overall stability of assemblies, particularly in the formation of capsules and cages (Buaksuntear et al., 2022).

Environmental factors such as pH, temperature, ionic strength, and solvent composition modulate these interactions, enabling the dynamic tuning of assembly pathways and morphologies (Buaksuntear et al., 2022; Muthu et al., 2025; Vaskan et al., 2025). For example, the incorporation of hydrophilic side chains into conjugated molecules enhances water solubility and enables kinetic control over aggregation states (Bhattacharyya et al., 2025; Neu et al., 2025).

Common Self-Assembled Nanostructures for Bioactive Delivery

Common self-assembled nanostructures in water ranging from cyclodextrin complexes and polymer micelles to nanoemulsions, hydrogels, liposomes, and co-assembled systems, summarized in Table 1.

Table 1. Representative Self-Assembled Nanostructures for Bioactive Delivery

Nanostructure	Building Blocks	Encapsulated Bioactives	Key Features	Ref
Cyclodextrin Complex	α-, β-, γ-CD, derivatives	EOs, phenolics	Water-soluble, host-guest chemistry	(BenchChem Technical Support Team, 2025; Janik et al., 2023; Nicolaescu et al., 2025)
Polymer Micelle	PEG-PCL, PEG-PLA, etc.	Hydrophobic drugs, EOs	Core-shell, controlled release	(Ansarinik et al., 2022; Luo et al., 2022)
Nanoemulsion	Oil, water, surfactants	EOs, phenolics	Fine droplets, high stability	(Joy et al., 2022; Movahedi et al., 2024)

Nanostructure	Building Blocks	Encapsulated Bioactives	Key Features	Ref
Hydrogel	Proteins, peptides, polysaccharides	Hydrophilic drugs, cells	3D network, stimuli-responsive	(Jain et al., 2022; Joy et al., 2022)
Liposome/ Niosome	Phospholipids, surfactants	Hydrophilic/hydrophobic drugs	Bilayer, dual encapsulation	(Janik et al., 2023; Joy et al., 2022)
Peptide Self-assembly	Antimicrobial peptides	Hydrophobic drugs	Complex noncovalent interactions and folding	(Gao et al., 2023; Ma et al., 2024)
Polyphenol–biopolymer Co-assembly	Polyphenol, metal ion, polysaccharide	Phenolics	Water soluble, antioxidant activity	(Li et al., 2025; Zhang et al., 2021)

The table shows that different nanostructures exploit distinct assembly principles such as host–guest inclusion, core–shell micellization, droplet stabilization, 3D hydrogel networks, bilayer vesicles, peptide folding, and polyphenol co-assembly. Each structure tailored to encapsulate specific classes of bioactives with unique release and stability advantages.

- **Cyclodextrin Inclusion Complexes**: Cyclodextrins (CDs) are cyclic oligosaccharides with hydrophilic exteriors and hydrophobic cavities, enabling the encapsulation of hydrophobic guest molecules such as essential oils and phenolics (BenchChem Technical Support Team, 2025; Janik et al., 2023; Nicolaescu et al., 2025). Inclusion complex formation stabilizes bioactives, improves solubility, photo- and thermostability, also protect against degradation (Nicolaescu et al., 2025). Modified CDs, such as hydroxypropyl-β-cyclodextrin (HPβCD) and sulfobutylether-β-cyclodextrin (SBE-β-CD), offer enhanced water solubility and safety profiles, making them suitable for food and pharmaceutical applications (BenchChem Technical Support Team, 2025; Patwekar Shailesh, 2025).
- **Polymer Micelles**: Polymer micelles are formed from amphiphilic block copolymers, creating core–shell structures with hydrophobic interiors for encapsulating bioactives and hydrophilic exteriors for water solubility. Examples include PEG-PLA and PEG-PCL micelles, which have demonstrated high encapsulation efficiency and controlled release of hydrophobic drugs and natural preservatives (Ansarinik et al., 2022; Luo et al., 2022).
- **Nanoemulsions**: Nanoemulsions are stable dispersions of oil and water kinetically, with droplet sizes ranging from 10 to 1000 nm and stabilized by surfactants and cosurfactants. They enable the solubilization and sustained release of essential oils (EOs) and phenolics, enhancing antimicrobial efficacy and shelf life in food matrices (Joy et al., 2022; Movahedi et al., 2024).
- **Hydrogels and Vesicles**: Hydrogels, formed via self-assembly of proteins, peptides, and amphiphilic polymers, provide three-dimensional networks for encapsulating hydrophilic molecules and cells (Jain et al., 2022). Vesicles, including liposomes and niosomes, offer bilayer structures for dual encapsulation of hydrophilic and hydrophobic bioactives (Janik et al., 2023; Nicolaescu et al., 2025).
- **Peptide-based Self-assembly**: Self-assembling antimicrobial peptides (AMP), amphiphilic peptides, surfactant-like peptides have emerged as promising food-compatible nanomaterials. AMP for example, achieves a dynamic transformation from nanoparticles to nanofibers when bacteria are present. Though not particularly in food, this system exhibits a broad

spectrum antibacterial ability versus multidrug-resistant (MDR) gram-positive negative bacteria (Gao et al., 2023; Ma et al., 2024).

- **Polyphenol–biopolymer Co-assembly**: Emerging self-assembled nanomaterials leverage polyphenol-based scaffolds (e.g., tannic acid coordination networks) to encapsulate separate cargos. For example, curcumin has been encapsulated as the cargo within tannic acid–Fe^{3+} polyphenol networks, where tannic acid functions as the structural building block forming a supramolecular shell via metal coordination and non-covalent interactions (with enhanced stability and controlled release). Meanwhile, polyphenolic shell formed by tannic acid and pectin stabilizes curcumin loaded micelles against degradation and improves delivery profiles (Li et al., 2025; Zhang et al., 2021).

Assembly Methods

Self-assembly methods are broadly categorized into top-down and bottom-up approaches. Top-down methods involve the mechanical breakdown of bulk materials into nanoscale structures using techniques such as homogenization, milling, and ultrasonication (Naman, 2023). These methods are advantageous for their scalability but may lack precision in controlling particle morphology and surface chemistry.

In contrast, bottom-up methods rely on the spontaneous organization of molecules through chemical or biological processes, offering better control over nanostructure formation (Biswas et al., 2012). Common bottom-up techniques include:

- **Coacervation**: This process forms polymer-rich droplets (coacervates) around bioactive molecules through electrostatic, hydrophobic, and hydrogen-bonding interactions between biopolymers such as gelatin, gum arabic, and chitosan. These droplets can be solidified by cooling, drying, or cross-linking, resulting in stable nanoparticles or microcapsules that protect and control the release of the encapsulated compound (Janik et al., 2023).
- **Nanoprecipitation**: A polymer dissolved in a solvent precipitates upon contact with an antisolvent in which the polymer is insoluble. This rapid precipitation traps the bioactive molecule within polymeric nanoparticles, typically in the 50–500 nm range. The process is mild and does not require high temperatures, making it suitable for thermolabile and hydrophobic compounds such as essential oils and polyphenols (Janik et al., 2023).
- **Spray Drying and Freeze Drying**: These dehydration-based techniques convert emulsions or suspensions into dry powders, facilitating handling, storage, and industrial-scale production. Spray drying involves atomizing a liquid into hot air to evaporate the solvent, while freeze drying removes water through sublimation under low temperature and pressure, both preserving the bioactive compound (Janik et al., 2023).
- **Electrospinning and Electrospraying**: These methods use high-voltage electric fields to manipulate polymer solutions containing bioactives. In electrospinning, a viscous polymer solution forms a continuous jet that stretches into nanofibers as the solvent evaporates, producing high-surface-area fibers ideal for controlled release. In electrospraying, a less viscous solution breaks into droplets under the electric field, which solidify into nanoparticles or microparticles. Both methods are suitable for heat-sensitive compounds and allow precise control over particle size and morphology (Janik et al., 2023).

The selection of an encapsulation method is closely linked to the physicochemical properties of the bioactive compound and its intended food application. For example, essential oils and other hydrophobic phenolics are frequently encapsulated by nanoprecipitation or coacervation. It efficiently entraps nonpolar molecules within polymeric matrices while avoiding thermal degradation. Heat-sensitive compounds, including volatile essential oils and antimicrobial peptides, are better suited to electrospinning or electrospraying. It enables nanoscale encapsulation and controlled release without exposure to high temperatures. In contrast, spray drying and freeze drying are commonly applied to emulsified phenolics, flavors, and antioxidants to produce stable powders for large-scale food applications, with freeze drying preferred for thermolabile compounds. These examples illustrate how matching compound properties with appropriate encapsulation strategies is essential to maximize stability, functionality, and practical applicability in food systems.

Characterization Techniques

Characterizing self-assembled nanomaterials involves evaluating their size, morphology, surface charge, chemical composition, thermal behavior, encapsulation efficiency, and release kinetics. All of which influence their behavior in food matrices and biological systems.

Table 2. Key Characterization Techniques

Technique	Purpose	Reference
Dynamic Light Scattering (DLS)	Measures hydrodynamic diameter and polydispersity index to assess size distribution and colloidal stability.	(Jagadeesh et al., 2024)
Transmission/Scanning Electron Microscopy (TEM/SEM)	Visualizes morphology, structure, and aggregation of nanoparticles and nanofibers.	(Jagadeesh et al., 2024)
Atomic Force Microscopy (AFM)	Provides surface topology and nanosheet thickness at nanometer resolution.	(Jagadeesh et al., 2024)
Zeta Potential Analysis	Evaluates surface charge, indicating electrostatic stability and interaction potential.	(Jagadeesh et al., 2024)
Fourier Transform Infrared Spectroscopy (FTIR)	Identifies chemical bonds and molecular interactions within nanostructures.	(Jagadeesh et al., 2024)
X-ray Diffraction (XRD)	Assesses crystallinity and phase composition of encapsulated systems.	(Jagadeesh et al., 2024)
Encapsulation Efficiency & Loading Capacity	Quantified via UV-Vis, HPLC, or mass spectrometry to determine bioactive entrapment.	(Jagadeesh et al., 2024)
Release Kinetics	Evaluated using in vitro digestion models, dialysis, or simulated food matrices to assess sustained release.	(Carmona-Almazán et al., 2024; Jagadeesh et al., 2024)

The characterization of nanoparticles and nanofibers involves complementary techniques targeting size, morphology, surface properties, chemical composition, structural order, and functional performance. DLS quantifies particle size distribution and colloidal stability, while TEM/SEM and AFM provide nanoscale visualization of shape, aggregation, and surface topology. Zeta potential assesses electrostatic stability and interaction potential. Chemical identity and interactions are probed by FTIR, whereas XRD evaluates crystallinity and phase composition. Functional performance is measured through encapsulation efficiency, loading capacity, and release kinetics, enabling evaluation of bioactive entrapment and controlled delivery.

UNDERSTANDING FOOD SPOILAGE AND ITS INHIBITION

Key Bacterial Pathogens in Food Spoilage

Food spoilage is primarily driven by the growth and metabolic activity of bacterial pathogens, which vary according to food type, storage conditions, and intrinsic properties.

Gram-Positive Pathogens

- ***Staphylococcus aureus****: S. aureus* is a major cause of foodborne spoilage and sickness. It produces heat-stable enterotoxins and forms biofilms that resist cleaning and disinfection. It is prevalent in protein-rich foods such as meat, dairy, and bakery products, with reported prevalence in some ready-to-eat foods up to 23.2% (Mekhloufi et al., 2021; Parvin et al., 2023; Sun et al., 2025).
- ***Bacillus cereus***: Known for its spore-forming ability and survival in hostile environments, *B. cereus* contaminates dairy and processed foods, causing spoilage and food poisoning (Zhou et al., 2024).
- ***Listeria monocytogenes***: Associated with dairy, meat, seafood, and ready-to-eat products, *L. monocytogenes* is notable for its ability to grow at refrigeration temperatures and cause severe illness, particularly in vulnerable populations (Chu et al., 2025; EFSA Panel on Biological Hazards (BIOHAZ), 2018).
- ***Brochothrix thermosphacta***: This spoilage bacterium affects meat and seafood by producing off-flavors and odors. It thrives in vacuum-sealed and modified atmosphere packaging, making it a concern for extended-shelf-life products (Gribble et al., 2014; Wang et al., 2024).

Gram-Negative Pathogens

- ***Pseudomonas* spp:** Pseudomonas species are the predominant spoilage bacteria under aerobic conditions, especially in meat, dairy, and seafood. *P. fluorescens* and *P. aeruginosa* secrete proteases and lipases, leading to rancidity, off-odors, and slime formation. These bacteria are highly adaptable, capable of biofilm formation and often exhibit antibiotic resistance (Bloomfield et al., 2024; Mat Saad et al., 2025).
- ***Escherichia coli*:** *E. coli* is a common contaminant in meat, dairy, and fresh produce. While many strains are harmless, pathogenic variants such as *E. coli O157:H7* can cause serious foodborne illness. It also contributes to spoilage through metabolic activity and toxin production (Kim & Song, 2023).
- ***Salmonella* spp:** Salmonella is a major cause of foodborne illness and spoilage in poultry and eggs. It is resilient to environmental stressors and forms biofilms that enhance survival in food processing environments (Mkangara, 2023).
- **Enterobacteriaceae:** This diverse family of facultative anaerobes includes spoilage organisms that affect a wide range of food production facilities. Their presence often reflects poor hygiene during production and transport (Altieri et al., 2025).

General Mechanisms of Food Spoilage

Food spoilage results from a combination of microbial activity, enzymatic reactions, chemical changes, and physical alterations that compromise food safety, sensory quality, and shelf life. Spoilage indicators include increased colony-forming units (CFU), increasing concentration of biogenic amines, production of volatile organic compounds (VOCs), and sensory changes such as off-odors, discoloration, and texture loss. General mechanism of food spoilage is listed below:

- **Microbial Activity**: Bacteria, molds, and yeasts metabolize food components, producing enzymes such as proteases, lipases, and amylases that degrade proteins, lipids, and carbohydrates. These reactions generate biogenic amines, free fatty acids, aldehydes, and exopolysaccharides, leading to off-flavors, odors, slime formation, and textural degradation (Janik et al., 2023; Mat Saad et al., 2025; Zhou et al., 2024).
- **Biofilm Formation**: Pathogens like *Staphylococcus aureus* and *Pseudomonas spp.* form biofilms on food surfaces and processing equipment, enhancing resistance to cleaning, disinfection, and antimicrobial agents (Mat Saad et al., 2025; Parvin et al., 2023).
- **Redox Reactions**: Lipid oxidation and protein oxidation generate rancid flavors, discoloration, and toxic byproducts. Lipid peroxidation and Maillard reactions are key contributors to sensory deterioration and nutrient loss (Geng et al., 2023; Khan et al., 2022).
- **Enzymatic Browning**: Polyphenol oxidase catalyzes the oxidation of phenolic compounds in fruits and vegetables, leading to browning, flavor changes, and reduced consumer appeal (Tilley et al., 2023).

Synergistic Approaches Combining Nanomaterials and Natural Food Preservatives

The integration of self-assembled nanomaterials with natural preservatives has demonstrated synergistic effects in inhibiting food spoilage and extending shelf life (Mbonambi et al., 2025).

- **Cyclodextrin-based Systems**: Cyclodextrin inclusion complexes have been used to encapsulate EOs and phenolics, enhancing their stability, solubility, and antimicrobial activity (Alabrahim et al., 2024; Dai et al., 2024). For example, HPβCD-encapsulated *Boswellia sacra* EO improved antibacterial efficacy against *S. aureus* and *E. coli*, with Minimum Inhibitory Concentration (MIC) values reduced by up to 4-fold compared to free EO (Alabrahim et al., 2024). SBE-β-CD inclusion complexes with quercetin achieved encapsulation efficiencies of 86% and enhanced antioxidant and antimicrobial activity, with MIC against S. aureus at 21.25 mg/mL (Dai et al., 2024).
- **Polymer Micelles and Nanoemulsions**: Polymer micelles formed from PEG-PLA and PEG-PCL have been used to encapsulate hydrophobic EOs and drugs, providing controlled release and improved antimicrobial performance (Ansarinik et al., 2022; Luo et al., 2022). Nanoemulsions of lemongrass EO and chitosan nanoparticles extended the shelf life of fresh strawberries up to 15 days and increased antioxidant capacity 1.2–2.6 times than pure EO. It also significantly improved antibacterial effects compared to empty chitosan. The improvements observed at combined state signal synergistic effects of EO and chitosan components (Do et al., 2025).

- **Chitosan-based Nanocomposites**: Chitosan nanoparticles loaded with nisin (an antimicrobial peptide) have demonstrated enhanced antimicrobial activity against *S. aureus* and *L. monocytogenes*, reducing populations by 5- to 7-fold compared to free nisin (Phan et al., 2025). Chitosan/graphene oxide composites delayed mango ripening by slowing ethylene synthesis and minimized anthracnose incidence during storage (Vilvert et al., 2022).
- **Phenolic-loaded Nanoparticles**: Phenolic compounds from Amazon palm fruits encapsulated in acCGP/CS nanoparticles achieved 40% encapsulation efficiency and increased antioxidant activity by 45-fold. The MIC against *S. aureus* was reduced to 4.48 mg/mL (Ferreira et al., 2024).

CURRENT CHALLENGES AND DIRECTION

Despite significant progress, several challenges hinder the widespread adoption of water-soluble self-assembled nanomaterials in food preservation.

- **Stability and Scalability:** Achieving consistent size, morphology, and encapsulation efficiency at industrial scale remains difficult. Batch-to-batch variability and nanoparticle aggregation can compromise performance and reproducibility. This challenge can be overcome by implementing tightly controlled, continuous manufacturing processes (e.g., microfluidics or in-line high-shear homogenization) combined with real-time process monitoring and standardized formulation parameters to minimize batch-to-batch variability and prevent nanoparticle aggregation (Gorantla et al., 2020; Osouli-Bostanabad et al., 2022; Shen et al., 2024).
- **Cost and Complexity:** Advanced self-assembly techniques often require high-purity reagents, specialized equipment, and multistep synthesis, which increase production costs and limit commercial viability for low-margin food products. Future work should therefore emphasize cost-conscious green synthesis strategies, such as the use of plant extracts, microbial enzymes, or food-grade biopolymers. It can reduce reliance on expensive solvents, lower energy input, simplify processing steps, and enable integration with existing food-processing infrastructure (Herrera-Rivera et al., 2024; Pattnaik et al., 2024).
- **Sensory Impact:** Essential oils (EOs) and phenolic compounds possess strong aromas and flavors that may alter the sensory profile of foods. This necessitates careful formulation and the use of controlled-release systems to minimize off-flavors while maintaining efficacy (Do et al., 2025). Public perception of nanotechnology in food remains cautious. Reduction of sensory impact will help to reduce resistance to adoption. Transparent communication about benefits, risks, and regulatory safeguards is essential to build trust. Educational campaigns, labeling initiatives, and stakeholder engagement can foster informed decision-making and broader acceptance (Aschemann-Witzel et al., 2019; EFSA Panel on Biological Hazards (BIOHAZ), 2018; Pattnaik et al., 2024).
- **Migration and Toxicity:** Nanomaterials may migrate from packaging into food, raising concerns about human exposure, bioaccumulation, and long-term health effects. Migration is influenced by nanoparticle size, surface chemistry, food composition, and storage conditions (Pattnaik et al., 2024; Singh et al., 2017). In response, high-throughput screening approaches, together with functional genomics and metabolomics, are emerging as powerful tools for evaluating nanomaterial safety and performance. These techniques enable the identification of toxicity biomarkers, elucidation of metabolic pathways, and assessment of encapsulated bioactive stability

under realistic food storage conditions (Singh et al., 2017; Wang et al., 2025).

- **Mechanistic Understanding:** The antimicrobial mechanisms of nanomaterial-bioactive systems are not fully elucidated. Additionally, interactions with complex food matrices may attenuate their efficacy, highlighting the need for more mechanistic and in situ studies (Muthu et al., 2025; Wang et al., 2017). Studies using in situ imaging and molecular modeling are needed to unravel these mechanisms and optimize nanocarrier design.

CONCLUSIONS

This narrative review highlights the strong potential of water-soluble self-assembled nanomaterials as enabling technologies to stabilize natural food preservatives and address the persistent global challenge of food spoilage. By leveraging supramolecular self-assembly driven by non-covalent interactions in aqueous environments, nanostructures such as cyclodextrin inclusion complexes, polymer micelles, nanoemulsions, hydrogels, and vesicles effectively enhance the solubility, stability, and controlled release of essential oils, phenolics, and antimicrobial peptides. The reviewed evidence demonstrates that these systems can significantly improve antimicrobial and antioxidant efficacy against key spoilage and pathogenic microorganisms, reduce required preservative dosages, and mitigate undesirable sensory impacts, thereby aligning with clean-label trends and consumer demand for safer, natural food products. Despite these advantages, critical challenges remain, including scalability, cost-effectiveness, sensory optimization, regulatory acceptance, and comprehensive safety assessment related to migration and long-term exposure. While in vitro and food-matrix studies are encouraging, in vivo animal validation is increasingly necessary to bridge the gap between laboratory performance and real-world safety. Addressing these limitations will require interdisciplinary efforts integrating green synthesis, advanced characterization, mechanistic studies, and high-throughput toxicological evaluation under realistic food conditions. Overall, water-soluble self-assembled nanomaterials represent a promising and versatile platform for next-generation food preservation, with the potential to improve food safety, extend shelf life, and reduce food waste when supported by robust scientific validation and responsible regulatory frameworks.

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