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Nanotechnology in Food Matrices: Optimizing Stability, Nutrient Bioavailability, and Product Longevity

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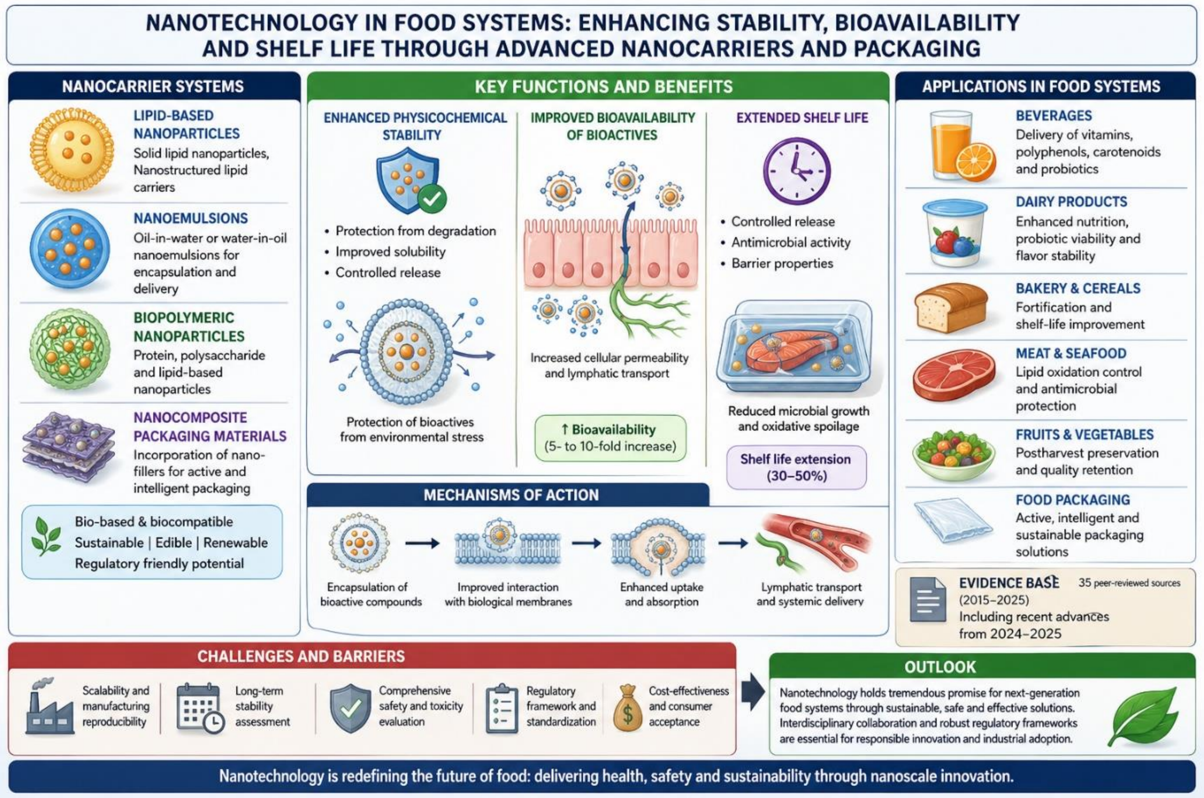
Abstract

Incorporation of nanotechnology in food systems has become a revolution strategy in solving the severe issues of food quality, nutrition, and preservation. This review offers an in-depth discussion of the recent developments in nanoscale interventions that aim at enhancing the stability, bioavailability and shelf life of food products. Nanocarriers such as nanoemulsions, liposomes, solid lipid nanoparticles, and polymeric nanoparticles have distinct benefits in entrapment of bioactive substances such as vitamins, antioxidants, antimicrobials, and flavors. These systems enhance the dispersion and physicochemical stability of labile ingredients through reduction of particle size and increase in the ratio of surface area to volume during the processing and storage environment. Moreover, nanoencapsulation also allows controlled release and targeted delivery, which greatly improves the oral bioavailability of poorly soluble nutraceuticals and functional additives. Nanomaterials with inherent antimicrobial or oxygen-scavenging properties (e.g. nano-silver, nano-zinc oxide and nanoclay compounds) are also utilized in active and intelligent packaging systems in the context of preservation. Such innovations do not only increase microbial and oxidative shelf life, but also allow the real time monitoring of food freshness. Critical safety, regulatory and consumer acceptance concerns related to the application of nanotechnology in food are also covered in the review. Altogether, nanotechnological approaches provide a possible avenue towards more resilient, nutritional, and sustainable food systems, although additional studies on the potential long-term toxicological outcomes as well as standard risk assessment platforms are necessary.

Introduction



The food industry is facing a great challenge: the need to deliver adequate volumes of safe, nutritious, and acceptable food with reduced waste and environmental impacts. Two of the biggest technological challenges are the instability of many bioactives, their low bioavailability after ingestion, and the short shelf lives of perishable food products (Liu *et al*., 2024). Traditional methods like thermal treatment, chemical additives, and modified atmosphere packaging have been successful but often at the expense of nutritional value or sensory properties (Jagtiani, 2022).

The challenges posed by these issues can be addressed by innovative nanotechnology approaches, which involve the manipulation of materials at the scale of 1-100 nanometers. Nanoscale materials display different physicochemical properties - higher surface area-to-volume ratios, increased reactivity, modified optical properties and enhanced solubility - that can be exploited to enhance the stability of sensitive compounds, modulate the release of active ingredients and increase the absorption of nutrients and nutraceuticals (Saini *et al*., 2025).

Nanotechnology can be applied for food systems in three main areas: (i) nanoencapsulation/coencapsulation of bioactive compounds for protection and delivery, (ii) nanostructured delivery systems for increased bioavailability, and (iii) nanocomposite packaging materials with active and smart packaging properties (Zhu *et al*., 2024). This review will explore how these applications help to enhance food component stability, increase the bioavailability of nutrients and nutraceuticals, and prolong the shelf life of food products.

The development of bio-based nanomaterials derived from food-grade lipids, proteins, and polysaccharides has overcome initial concerns regarding the application of inorganic nanoparticles in food products (Mishra *et al*., 2024). These safe, environmentally friendly carriers present an eco-friendly approach to incorporating nanotechnology into food processing. However, scaling up and commercializing research findings into viable products must account for processing challenges, regulatory approval, consumer acceptance, and safety (Akuma *et al*., 2019).

This review consolidates information from 35 peer-reviewed publications, including recent literature (2024-2025) to critically evaluate the application of nanotechnology in improving the performance of food systems. The review aims to:

(1) describe the key types of nanocarriers and how they enhance stability and bioavailability (2) assess the impact of nanocomposite packaging to extend product shelf-life

(3) critically examine issues related to safety, regulatory and scalability

(4) discuss emerging opportunities and research directions.

Fundamentals of Nanotechnology in Food Systems

Principles of Nano structuring

The benefits of nanomaterials in food formulations stem from basic principles of colloid and interfacial science. Reducing the material size to below 100 nm increases the number of molecules at the surface to the same or greater than the number in the bulk phase, resulting in a dramatic increase in surface free energy and reactivity (Siegrist & Hartmann, 2020). In food systems, this has a number of practical implications.

First, there are improved solubility and dissolution rates due to increased contact with the solvent. Nanonization of poorly soluble bioactives (e.g. curcumin, quercetin and beta-carotene) can enhance apparent solubility by several orders of magnitude (Onyeaka *et al*., 2022). Second, nanoscale particles are able to bypass biological barriers that are impenetrable to larger particles, such as the mucus lining of the gastrointestinal tract and, in some cases, tight junctions between epithelial cells. Third, the large surface-to-volume ratio allows for efficient loading and release of molecules of interest (Mehta *et al*., 2023).

Top-Down vs Bottom-Up

Nanocarrier preparation can be achieved using two approaches. Top-down strategies involve breaking down bulk materials into nanoscale particles by mechanical processes including high-pressure homogenization, milling or microfluidization. These processes are commercially scalable and can be used to produce nanoemulsions or solid lipid nanoparticles but can cause temperature fluctuations and wide size distributions (Duong *et al*., 2020).

Bottom-up methods involve building nanoscale materials from molecular building blocks via precipitation, self-assembly, or complexation. These allow for greater control of particle size, shape and surface chemistry but often require precise control over processing conditions such as pH, temperature and mixing rates (Gomaa *et al*., 2022). Combination approaches (such as solvent injection, antisolvent precipitation followed by homogenization) offer the benefits of both approaches and are increasingly used for manufacturing food-grade nanocarriers (Liu *et al*., 2022).

Bio-Based Nanomaterials

There has also been a recent surge in bio-based nanocarriers made from food components. Lipids, proteins and polysaccharides provide intrinsic biocompatibility, Generally Recognized as Safe (GRAS) status and functionality that inorganic nanoparticles lack (Salvia-Trujillo *et al*., 2019).

Table 1 summarizes the major classes of bio-based nanocarriers and their key characteristics.

Table 1: Classification and Characteristics of Bio-Based Nanocarriers for Food Applications

Nanocarrier Type	Primary Materials	Size Range (nm)	Encapsulation Efficiency (%)	Key Advantages	Main Limitations
Nanoemulsions	Vegetable oils, surfactants	20-200	85-98	Thermodynamic stability, clear appearance, easy scale-up	Surfactant dependence, limited payload for hydrophobic actives
Solid Lipid Nanoparticles (SLNs)	Solid fats, emulsifiers	50-500	70-95	Controlled release, physical stability, low toxicity	Low loading capacity, potential gelation, polymorphic transitions
Nanostructured Lipid Carriers (NLCs)	Mixed solid/liquid lipids	50-300	75-95	Higher loading than SLNs, reduced expulsion	Complex formulation, multiple processing steps
Liposomes	Phospholipids, cholesterol	50-1,000	40-80	Dual hydrophilic/hydrophobic loading, biocompatibility	Low stability, high production cost, leakage issues
Protein Nanoparticles	Whey, zein, gelatin, soy	50-300	60-90	GRAS status, functional versatility, pH-responsive release	Heat sensitivity, denaturation risks, batch variability
Polysaccharide Nanoparticles	Chitosan, alginate, pectin, starch	100-500	50-85	Mucoadhesive properties, pH-responsive, abundant sources	Variable molecular weight, potential viscosity issues
Bio-derived Vesicles	Exosomes, plant vesicles	30-150	50-75	Naturally occurring, immune evasion, targeted delivery	Low yield, complex isolation, purity concerns

Source: Compiled from Liu *et al*., 2024; Subroto *et al*., 2023; Rashidi, 2021

Enhancing Stability of Food Components

Protection Against Degradation

Food bioactives, such as vitamins, polyphenols, carotenoids and polyunsaturated fatty acids, are prone to degradation during processing and storage, as well as during gastrointestinal digestion. Oxidation, photo-degradation, thermal degradation and pH-dependent reactions are all responsible for the loss of function (Sadati Behbahani *et al*., 2019). Nanocarriers offer physical protection by shielding sensitive compounds in a protective capsule against environmental factors.

Lipid nanocarriers such as nanoemulsions and solid lipid nanoparticles generate a lipophilic core that shields lipophilic bioactives from water-phase prooxidants (Subroto *et al*., 2023). In the case of beta-carotene, nanostructured lipid carriers (NLCs) protected the carotenoid against degradation with 60% less degradation under accelerated storage conditions than free beta-carotene (Gao *et al*., 2021). Likewise, NLC-encapsulated curcumin retained 85% of its activity after six months of refrigerated storage, but free curcumin was completely degraded within 60 days (Taha *et al*., 2019). Protein-based nanoparticles provide protection in other ways. The protein matrix restricts oxygen diffusion, and can include metal-chelating amino acid residues that prevent transition metal-catalyzed oxidative degradation (Zhang *et al*., 2022). Antisolvent-prepared zein nanoparticles protected quercetin from UV degradation, with 92% activity remaining after UV exposure that destroyed 70% of the free quercetin (Li *et al*., 2017).

Suppression of Phase Separation and Aggregation

Colloidal food formulations are often thermodynamically unstable systems that phase separate, cream, sediment or aggregate. Nanostructuring can provide kinetic stability to these systems by lowering the size of the droplets or particles below the critical size for gravitational separation. According to Stokes' law, creaming rate is proportional to the square of the particle radius, so reducing particle radius from 1 μm to 100 nm reduces creaming rate 100-fold. Nanoemulsions (droplet size 20-200 nm) are highly resistant to creaming and coalescence. Nanoemulsions of cinnamaldehyde were stable without phase separation for more than 90 days, compared to conventional emulsions, which creamed after 7 days (Yan *et al*., 2024). This stability allows for the preparation of clear and low-viscosity beverages containing lipophilic flavorants or nutraceuticals that were previously stabilized using clouding agents or homogenization just before serving. Polysaccharide nanoparticles can also enhance the stability of food systems via thickening and gelling at low levels. Chitosan nanoparticles have a positively charged surface that enables electrostatic interaction with negatively charged food components, with the formation of electrostatic complexes that are less susceptible to aggregate over pH ranges where uncomplexed components are prone to precipitation (Rodríguez-Félix *et al*., 2019).

Preservation of Bioactives

Heat is the most widely used preservation technique in the food industry but can cause degradation of heat-sensitive bioactives. protective effects of nanocarrier encapsulation may be due to: (i) glass transition of the carrier matrix at lower temperatures than bioactives, (ii) replacement of water with carrier material to reduce the rate of hydrolysis, and (iii) a reduction in the mobility of molecules in the glassy matrix, thereby reducing reaction rates (Liu *et al*., 2020).

Li *et al*. (2017) showed that curcumin degradation during pasteurization (72°C, 15 seconds) was prevented by zein-caseinate nanoparticles, with 95% retention compared to 65% for free curcumin. Likewise, probiotic bacteria encapsulated in alginate-chitosan nanoparticles showed improved survival during spray drying from 1% (free) to 45% (encapsulated) (McClements & Gumus, 2016).

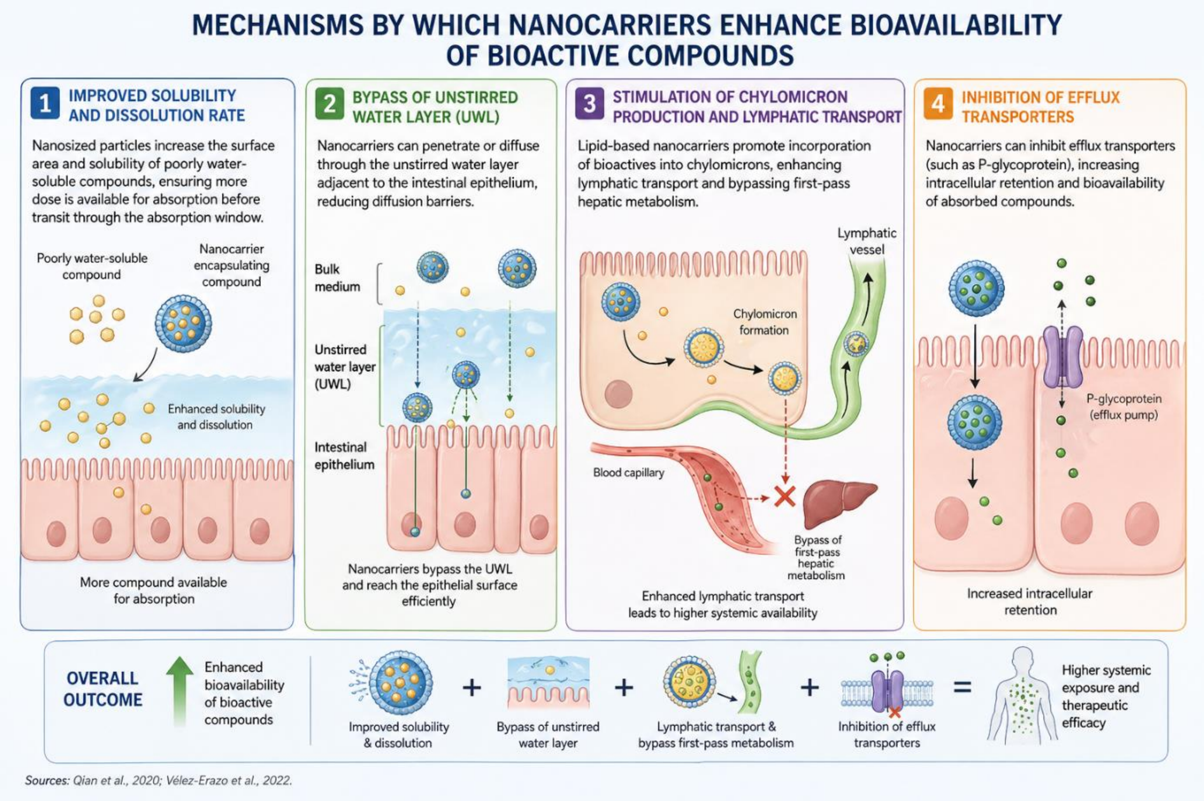
Enhancing Bioavailability of Nutrients and Nutraceuticals

The Bioavailability Challenge

Bioavailability, the proportion of an orally consumed nutrient that enters the systemic circulation in its active form, is frequently very poor for many nutrients and other food elements. There are four main reasons for low bioavailability: (1) poor solubility in gastrointestinal fluids, (2) low permeation in the intestinal space, (3) high first-pass metabolism, and (4) active efflux into the intestine (Tie *et al*., 2024). For example, curcumin, with strong anti-inflammatory effects, has low oral bioavailability (less than 1%) due to all four of these limitations (Wang *et al*., 2025).

How Nanocarriers Improve Bioavailability

Nanocarriers improve bioavailability via several mechanisms. First, nanocarriers enhance dissolution and solubility, allowing more drug to be available for absorption prior to entering the absorption window. Second, nanocarriers can penetrate the unstirred water layer near the intestinal epithelium, overcoming diffusion barriers. Third, some nanocarriers, such as lipid-based nanocarriers, induce chylomicron formation and the lymphatic transport pathway, bypassing some hepatic first-pass metabolism (Qian *et al*., 2020). Fourth, nanocarriers may block efflux transporters (e.g., P-glycoprotein) and enhance intracellular retention (Vélez-Erazo *et al*., 2022).



MECHANISMS BY WHICH NANOCARRIERS ENHANCE BIOAVAILABILITY OF BIOACTIVE COMPOUNDS

1 IMPROVED SOLUBILITY AND DISSOLUTION RATE

Nanosized particles increase the surface area and solubility of poorly water-soluble compounds, ensuring more dose is available for absorption before transit through the absorption window.

2 BYPASS OF UNSTIRRED WATER LAYER (UWL)

Nanocarriers can penetrate or diffuse through the unstirred water layer adjacent to the intestinal epithelium, reducing diffusion barriers.

3 STIMULATION OF CHYLOMICRON PRODUCTION AND LYMPHATIC TRANSPORT

Lipid-based nanocarriers promote incorporation of bioactives into chylomicrons, enhancing lymphatic transport and bypassing first-pass hepatic metabolism.

4 INHIBITION OF EFFLUX TRANSPORTERS

Nanocarriers can inhibit efflux transporters (such as P-glycoprotein), increasing intracellular retention and bioavailability of absorbed compounds.

Sources: Qian et al., 2020; Vélez-Erazo et al., 2022.

Table 2: Comparative Bioavailability Enhancement by Nanocarrier Type

Bioactive Compound	Nanocarrier Type	Bioavailability Ratio (Nano/Free)	Enhancement Mechanism	Reference
Curcumin	Solid Lipid Nanoparticles	8.5x	Lymphatic transport, P-gp inhibition	Ban *et al.*, 2020
Curcumin	NLCs	9.2x	Enhanced solubility, sustained release	Sadati Behbahani *et al.*, 2019
Quercetin	Zein Nanoparticles	5.8x	Mucus penetration, cellular uptake	Rodríguez-Félix *et al.*, 2019

Beta-carotene	Nanoemulsions	3.7x	Micellar solubilization	Salvia-Trujillo *et al*., 2019
Coenzyme Q10	Liposomes	4.2x	Epithelial permeability	Rashidi, 2021
Epigallocatechin gallate	Chitosan Nanoparticles	6.1x	P-gp inhibition, mucoadhesion	Yang *et al*., 2020
Resveratrol	Protein Nanoparticles	7.0x	Metabolic protection, transcytosis	Zhang *et al*., 2022

Data compiled from indicated sources

Lipid-Based Nanocarriers for Lipophilic Bioactives

Nanocarriers based on lipids are especially useful for enhancing the bioavailability of lipophilic substances (log P > 3). This is achieved by solubilising the bioactive in mixed micelles after lipolysis of the carrier lipid, keeping the compound solubilized at the absorption site (Karim *et al*., 2022). In the case of beta-carotene, nanoemulsion encapsulation led to 3.7-fold higher area under the plasma concentration-time curve (AUC) than crystalline suspension (Salvia-Trujillo *et al*., 2019).

Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) can be used in place of nanoemulsions for improving bioavailability. The solid structure retards cargo release, extending the absorption period and minimising fluctuations. Also, SLNs can incorporate lipid excipients that facilitate lymphatic transport. SLNs containing curcumin were reported to have 8.5-fold increased oral bioavailability in animal studies over free curcumin with around 40% of the dose being transported to lymphatics (Yang *et al*., 2020).

Polysaccharides and Proteins for Hydrophilic and Amphiphilic Compounds

Hydrophilic bioactives (such as many phenolic glycosides, vitamins B and C and peptides) are best delivered by protein and polysaccharide nanocarriers. They may form hydrogels that can entrap water-soluble compounds and protect them against stomach degradation. Co-encapsulation of hydrophilic and hydrophobic bioactives in zein nanoparticles has been shown to deliver multiple bioactive types (Gowthami & Angayarkanny, 2019). Mucoadhesive polysaccharide nanoparticles, such as those derived from chitosan, increase the residence time of compounds in the gastrointestinal tract by sticking to the mucus. This prolonged interaction with the absorptive epithelium increases the chances of absorption before the gut contents move further along the gastrointestinal tract. Kotenkova *et al*. (2025) found chitosan-alginate nanoparticles containing curcumin remained in the stomach for 8 hours compared to 2 hours for curcumin alone, resulting in improved bioavailability.

Nanotechnology to Increase Shelf Life

Active Nanocomposite Packaging

Traditional food packaging offers passive protection barrier against mechanical damage, oxygen and water. Nanotechnology allows active packaging that reacts with the food to improve shelf life by delivering an antimicrobial effect, removing oxygen or ethylene

(Plucinski *et al*., 2021). Table 3 lists the main types of active nanocomposite packaging and their uses.

Table 3: Active Nanocomposite Packaging Systems and Applications

Nanomaterial	Polymer Matrix	Active Function	Target Food Products	Shelf-Life Extension	Reference
Silver nanoparticles	LDPE, PLA	Antimicrobial	Meat, poultry, dairy	40-60%	Mishra *et al*., 2024
Zinc oxide nanoparticles	Chitosan, PVA	Antimicrobial, UV-blocking	Fresh produce, seafood	35-50%	Zhu *et al*., 2024
Titanium dioxide nanoparticles	PP, PET	Ethylene scavenging, antimicrobial	Fruits, vegetables	45-55%	Onyeaka *et al*., 2022
Clay nanoparticles (nanoclays)	Biopolymers	Oxygen/Moisture barrier	Dry foods, snacks	25-35%	Rashidi, 2021
Essential oil nanoemulsions	Starch, alginate	Antimicrobial, antioxidant	Bakery, dairy	30-50%	Gomaa *et al*., 2022
Cellulose nanocrystals	Biodegradable films	Mechanical strength, barrier	General packaging	20-30%	Karim *et al*., 2022

Antimicrobial nanocomposite films embed nanoparticles that have inherent antimicrobial properties, such as silver, zinc oxide, titanium dioxide or nanoemulsions of essential oils, into biopolymers or synthetic polymers (Egbuna *et al*., 2022). These films reduce spoilage bacteria and pathogens either by release of antimicrobial ions (silver, zinc) or compounds (essential oils), or via contact killing. Low-density polyethylene (LDPE) films containing silver nanoparticles decreased the number of *Listeria monocytogenes* by 4 log cycles on meat products and extended the shelf life of refrigerated products from 7 to 14 days (Chauhan *et al*., 2024).

Improved Barrier against Oxygen and Water

Nanomaterial incorporation can drastically enhance packaging film gas barrier characteristics. The use of nanoclays (plate-like silicate nanoparticles) dispersed at 3-5% in polymers creates a tortuous path leading to the effective diffusion length for oxygen and water vapor being 5-10 times larger (Onyeaka *et al*., 2022). Cellulose nanocrystals offer a similar improvement in barrier with transparency - essential for consumer acceptance (Karim *et al*., 2022). Nanoparticle dispersion is key to barrier enhancement. Barrier is best with exfoliated (fully separated) nanoclays, rather than intercalated (layer expanded but not fully separated) or aggregated. Dispersion of exfoliated nanoclays is achieved through compatibilization approaches such as modification of nanoclays and processing parameters (Rashidi, 2021).

Smart Packaging for Monitoring

Nanotechnology can be used to develop smart packaging systems that provide real-time quality monitoring and visual spoilage indicators of foods. Nanoparticle sensors undergo color, fluorescence or electrical property changes in response to spoilage indicators such as pH shift, biogenic amine formation or volatile compounds (Egbuna *et al*., 2022). Gold and silver nanoparticle sensors are based on localized surface plasmon resonance (LSPR) that leads to nanoparticle colour change when they aggregate in response to the analyte of interest. These can detect biogenic amines down to 10 ppm concentrations, much lower than spoilage levels for meat and fish products (Chauhan *et al*., 2024).

Controlled Release of Preservatives using Nanoencapsulation

Traditional direct additives result in initial high concentrations and sub-optimal concentrations by the end of the shelf life. Nanoencapsulation allows for a controlled release of preservatives, such as organic acids, essential oils and bacteriocins, at a rate that matches the growth of spoilage microorganisms (Kotenkova *et al*., 2025). The main active compound in thyme oil, thymol, is very volatile when used on food products. Nanoparticles based on cyclodextrin reduced losses due to volatilization by 70% and extended the product shelf life from 7 to 21 days against mold growth in bakery products (Plucinski *et al*., 2021). Likewise, nisin-encapsulated solid lipid nanoparticles exhibited prolonged inhibitory effect against *Listeria* in cheese for 60 days, compared to free nisin (14 days) (McClements & Gumus, 2016). –
- ## 6. Safety, Regulatory, and Consumer Considerations 6.1 Nanomaterial Toxicity The unique properties of nanomaterials that make them useful (small size, high surface reactivity, and translocation) also raise safety concerns. Nanoparticles can cross the gut barrier into the bloodstream, accumulate in secondary organs, and potentially cause oxidative stress, inflammation or DNA damage (Onyeaka *et al*., 2022). The safety of inorganic nanoparticles (silver, titanium dioxide, zinc oxide) has attracted the most attention due to their non-degradable nature and potential for bioaccumulation. Long-term oral animal toxicity studies have shown accumulation in Peyer's patches, liver, spleen and kidneys (Mishra *et al*., 2024). But the significance of animal high-dose studies to human dietary exposure is uncertain. In terms of food-grade bio-based nanocarriers (lipids, proteins, polysaccharides), there are few toxicity concerns since these are normally digested and absorbed.

Table 4 summarizes current safety classifications and regulatory status of nanomaterials used in food systems.

Table 4: Safety Assessment and Regulatory Status of Food Nanomaterials

Nanomaterial	**Current EU Status**	**Current US FDA Status**	**Known Toxicological Concerns**	**Key Unresolved Questions**

Silver nanoparticles	Not authorized for food contact	Limited allowances in specific packaging	Accumulation, inflammation, microbiome disruption	Long-term chronic exposure effects
Titanium dioxide (E171)	Banned (eff. 2022)	GRAS (under review)	Genotoxicity potential, accumulation	Relevance of high-dose studies to dietary exposure
Zinc oxide	Food additive allowance	GRAS (limited applications)	Minimal at intended doses	Cumulative effects with dietary zinc
Silica nanoparticles	E551 allowance, nano-specific limits	GRAS	Low acute toxicity	Long-term accumulation in gut-associated tissues
Lipid-based nanocarriers	Generally accepted	GRAS	Minimal	Stability and identity characterization
Protein/polysaccharide nanoparticles	Generally accepted	GRAS	None identified	Allergenicity of novel protein assemblies
Nanoclays	Limited allowances	GRAS for specific polymers	Low concern	Migration under all use conditions

Source: Compiled from Onyeaka *et al*., 2022; EFSA opinions; FDA guidance documents

Regulatory Frameworks and Gaps

There is a wide disparity between technological advancement and regulatory control of nanotechnology in food systems. Nanomaterials introduced into the European Union must be labeled and safety assessed under the Novel Food Regulation as nano-specific, yet the currently available GRAS substances that are reintroduced at nano-scale pose a regulatory dilemma (Siegrist & Hartmann, 2020). The US FDA has taken a case-by-case policy without explicit nanotechnology policies, which relies on the preexisting food additive and GRAS systems, which was not created to consider nanoscale-specific characteristics (Akuma *et al*., 2019).

The main gaps of regulation are: (1) the absence of standardized methods of characterizing nanomaterials in food matrices, (2) the absence of validated methods of analyzing and quantifying nanoparticles in food, (3) the lack of toxicological data on chronic low-dose exposure, and (4) the absence of an environmental impact assessment of nano-packaging at the end of life (Onyeaka *et al*., The acceptance and communication of consumers are to be considered in the 6th stage.

The acceptance of nanotechnology in food is still skeptical by consumers. According to large-scale surveys (n > 10,000) conducted in Europe and North America, it can be concluded that about 30-40% of consumers would shun nano-enabled food products, 40-50% is neutral to uncertain, and only 15-25% are interested (Siegrist & Hartmann, 2020). Perceived benefit is the major force behind acceptance, consumers are more ready to accept nanotechnology in terms of clear health benefits (improved nutrition, reduced allergens) than as a purely industrial benefit (longer shelf life) (Jagtiani, 2022). Clear communication of applications, advantages, and safety evaluation of nanotechnology are critical in developing a consumer confidence. The experience of the industry with genetically modified organisms proved secrecy and defensive communication strategies to be counterproductive (Siegrist and Hartmann, 2020)

Difficulties and Prospects

The scalability and cost of manufacturing are 7.1. Production Laboratory-scale production of nanocarriers with a fine size distribution, a high encapsulation efficiency, and batch-to-batch reproducibility is standard. Large scale production, which exhibits the same quality characteristics at the cost that can be afforded in the low-margin food industry, has not been achieved (Mehta *et al*., 2023). Microfluidic production systems are more in control of the size of particles but with low throughput (milliliters to milliliters per hour). High-pressure homogenization can be scaled (liters to kiloliters per hour) with wider size distributions and can cause sensitive cargo to be damaged by high shear and temperature (Duong *et al*., 2020). In the case of bio-based nanocarriers, the variability of the raw materials is another complication. The molecular weight, degree of substitution, and functional properties of proteins and polysaccharides vary in each batch to influence the formation of nanocarriers (Gomaa *et al*., 2022). Designs that consider variability of raw materials and use process analytical technology to provide real-time quality control are required.

In 7.2, regulatory harmonization and risk assessment will be discussed.

Lack of harmonized world standards on nanotechnology in food poses barriers to access and confusion to consumers. Physicochemical characterization approaches have been advanced by the OECD Working Party on Manufactured Nanomaterials, although internationally agreed migration testing procedures, toxicological screening methods and environmental risk assessment models are still being developed (Onyeaka *et al*., 2022). Risk assessment should cover the entire lifecycle of nanomaterials: manufacturing (exposure to workers), formulation (interaction with the matrix), food contact (migration and transformation), consumption (GIT fate), and disposal (environmental release). Conventional risk assessment models presuppose one and well-defined chemical substance, which is not relevant to nanomaterials that can change during processing or digestion (Mishra *et al*., 2024).

Emerging trends and innovations are captured in 7.3.

Synthetic Biology-Enabled Production: With the intersection of nanotechnology and synthetic biology, it becomes possible to generate bio-derived nanocarriers, such as exosomes and plant-derived vesicles, with behavioral characteristics tailored to particular food applications. Genetically engineered microorganisms have the ability to make designer exosomes with targeting ligands and cargo-loading properties (Akuma *et al*., 2019).

Design with Artificial Intelligence-Assisted Design: The machine learning model that is trained on nanocarrier formulation databases can learn optimal compositions and processing environments of novel bioactive compounds in a few days instead of months. AI methods can also be used effectively in multi-component nanocarriers when designing a nanocarrier requires too much time to be explored exhaustively by experiment (Chauhan *et al*., 2024).

Multicomponent Delivery Systems: The shift in favor of personalized nutrition and combination nutraceuticals necessitates nanocarriers that can deliver more than one bioactive compound with varying physicochemical characteristics. This is met by multi-compartment nanoparticles and nanoparticle-in-hydrogel systems, which increase the complexity of formulation (Wang *et al*., 2025). Sustainable and Biodegradable Materials: Green packaging: Nanocarriers and nanocomposites made of renewable materials such as the byproducts of agriculture are in demand by consumers. Circular economy methods include lignin nanoparticles, cellulose nanocrystals derived by crop residues, chitosan derived by fishery waste, and more (Karim *et al*., 2022).

Conclusion

Nanotechnology has a transformational potential to overcome three long-standing problems in food systems: the stability of labile bioactive compounds, bioavailability of nutrients and nutraceuticals and the shelf life of perishable food products. Food-grade lipids, proteins and polysaccharide-derived bio-based nanocarriers offer resistance to degradation during storage and processing, absorption through various biological pathways and the ability to release preservatives in controlled amounts that increase the shelf life of the product by 30-50 percent over the traditional methods.

It has a mature scientific base, established fabrication techniques, mechanistic knowledge of bioavailability enhancement and proven efficacy in a variety of food matrices. Nanoemulsions, solid lipid nanoparticles, and protein-based carriers have become commercially viable and a number of products are already commercially available in the beverage, supplement and packaging industries.

Nevertheless, there are still major obstacles to mass adoption. Scalability in manufacturing should also be enhanced to allow cost structures to be in line with food industry economics. The regulatory frameworks have to be harmonized and revised to incorporate the properties of nanoscale without creating excessive burdens that are not in line with the low toxicity of bio-based carriers. The transparent communication and perceived benefits that far outweigh the perceived risks depend on consumer acceptance, which is essential to commercial success.

The main areas of research focus in the future include (1) continuous manufacturing with real-time quality control, (2) lifecycle safety evaluation of nanomaterials in the presence of realistic exposure conditions, (3) accelerated optimization of formulation using AI, and (4) environmentally friendly, renewable-based production of nanomaterials. Nanotechnology can live up to its hype of safer, healthier, and more sustainable food systems with a concerted effort on the part of researchers, industry, regulators, and consumer advocates.

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