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Recent overview of nanotechnology based approaches for targeted delivery of nutraceuticals

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Nutraceuticals and dietary supplements have experienced a remarkable surge in demand over the past decade, driven by growing emphasis on preventive healthcare and heightened consumer preference for bioactive products. Nutraceuticals serve as an interface between pharmaceuticals and bioactives, offering therapeutic potential with minimal adverse effects. However, their clinical applications are often hindered by their inherent physicochemical characteristics, including low bioavailability, susceptibility to environmental degradation, poor aqueous solubility, instability, and post-delivery structural degradation. To address these challenges, nanotechnology has emerged as a promising avenue for enhancing the therapeutic efficacy and bioavailability of nutraceuticals. Nano-sized cargos such as liposomes, nanoparticles, nano-emulsions, and nanogels enable improved encapsulation, stability, bioavailability, cellular internalization, and targeted delivery of nutraceuticals. Furthermore, the sustainable manufacturing of nutraceuticals has undergone substantial technological advancements to enhance the bioavailability, therapeutic effect, and long-term stability. This review provides a comprehensive overview of recently published literature addressing different nano-enabled approaches employed for nutraceuticals, highlighting their targeted applications in disease prevention and management. Additionally, it critically examines the regulatory challenges associated with their production scalability, safety concerns, and environmental impact, while offering insights into existing regulatory frameworks and future considerations for the pervasive use of nanotechnology in the nutraceutical industry.

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Sustainability spotlight

Nutraceuticals are bioactive compounds derived from food sources with purported health benefits and offer great potential for promoting wellness and preventing diseases. However, they face certain limitations including poor bioavailability, high sensitivity to light and oxygen, low water solubility, limited stability, and probable chemical changes after delivery that restrict their applications and health benefits. The integration of advancements in nanotechnology into sustainable nutraceutical manufacturing is driving impactful innovation in industry. Nanotechnology offers a promising avenue for delivery of nutraceuticals to improve bioavailability and targeted delivery. Natural and biodegradable polymers like chitosan, alginate, lignin, zein, casein, *etc.* are being employed for the development of nanocarriers. These biopolymers are non-toxic, non-irritant, easily available, and biodegradable, making them excellent candidates for the delivery of nutraceutical and dietary supplements. Nanotechnology in the food and pharmaceutical industry holds great potential to transform food and agricultural practices as it presents enormous benefits and sustainable production methods to shape the future of nutraceuticals. This review provides a comprehensive overview of the latest advancements in nanotechnological approaches aimed at improving the encapsulation of bioactive compounds emphasizing their targeted applications in disease management.

1 Introduction

Nutraceuticals are bioactive compounds that provide therapeutic benefits beyond basic nutrition, contributing to disease prevention and overall health maintenance. The term is a combination of 'nutrition' and 'pharmaceutical', reflecting their dual role in nourishment and therapeutic efficacy.¹ These compounds encompass a wide range of bioactive substances, including vitamins, minerals, antioxidants, prebiotics, probiotics, herbal products, and spices, as well as a range of

polyunsaturated fatty acids (PUFA).² They are commonly incorporated into functional foods, dietary supplements, and fortified food products such as cereals, soups, and beverages.³

Dietary supplements, a subset of nutraceuticals, are formulated to augment dietary intake and may contain a combination of essential nutrients, herbs, botanicals, amino acids, metabolites, or bioactive extracts. Regulatory authorities such as the United States Food and Drug Administration (USFDA) mandate that dietary supplements must be appropriately labeled and are permitted to bear specific health claims only when supported by robust scientific evidence.^{4,5} They provide various benefits, including anti-aging properties, antioxidant properties, promoting good health and preventing diseases, fewer side

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effects, easy availability, and a holistic approach to wellness.⁵ The consumption of nutraceuticals and dietary supplements has increased substantially due to growing consumer interest in naturally derived compounds and preventive healthcare strategies.⁶ Extensive research highlights their therapeutic potential in mitigating oxidative stress-related disorders, including cardiovascular diseases^{7,8} and cancer,^{9,10} neurodegenerative conditions such as Alzheimer's disease¹¹ and Parkinson's disease,^{12,13} metabolic disorders like diabetes mellitus,^{14,15} and obesity,^{16,17} as well as immunological^{18,19} and inflammatory disorders.^{20,21} The global nutraceutical market is experiencing significant expansion, driven by increasing consumer awareness and advancements in functional food development.²² As of 2022, the market was valued at approximately \$317.22 billion and is projected to grow at a compound annual growth rate (CAGR) of 9.6%, reaching nearly \$600 billion by 2030²³ (see Fig. 1). While India accounted for only 2% of the global nutraceutical market in 2017,²⁴ recent estimates suggest it is anticipated to expand at a CAGR of 15% between 2023 and 2028, with the preventive healthcare segment anticipated to reach \$195 billion by 2025 at a CAGR of 22%.²⁵ This illustrates both the economic potential and the increasing significance of nutraceuticals in the global health sector.

Despite their promising therapeutic applications, the efficacy of many nutraceuticals is hindered by inherent physicochemical limitations, including poor bioavailability, low aqueous solubility, high sensitivity to light and oxygen, limited stability, and probable chemical changes after their delivery.²⁷ These challenges necessitate innovative delivery strategies to enhance their absorption, protect them from environmental degradation, and ensure targeted delivery to specific physiological sites.²⁸ Thus, nanotechnology has been seen as a breakthrough invention for the efficient delivery of nutraceuticals and dietary supplements and in activating the positive characteristics of human health, hence improving their efficacy in a variety of ailments.²⁹

This literature review intends to provide a comprehensive analysis of nanotechnology-based delivery systems for nutritional supplements, highlighting their targeted applications in disease prevention and management. It further examines how

various nanocarriers address the physicochemical limitations of conventional nutraceutical formulations, thereby advancing their clinical and commercial viability. Additionally, it discusses the limitations of existing regulatory frameworks and provides a comparative analysis of different nanoformulations based on their production costs, scalability, regulatory challenges, and environmental concerns.

2 Strategies to improve the nutritional properties of foods using nanotechnology

Nutraceuticals exhibit several physicochemical limitations that hinder their therapeutic efficacy, including poor bioavailability, low aqueous solubility as a result of their hydrophobic nature, sensitivity to temperature, light, pH, free radicals, or oxygen, limited stability, and potential structural degradation during their delivery.^{27,28} Many bioactive compounds derived from natural sources, such as curcumin and quercetin, face significant challenges in achieving their full therapeutic potential due to inefficient absorption, short systemic circulation time, and rapid metabolic degradation.^{30–32} To overcome these limitations, nanotechnology has emerged as a promising approach for effectively delivering nutritional supplements.^{33,34} Nano-encapsulation offers several advantages, including the ability to protect bioactive compounds from environmental degradation (*e.g.*, pH fluctuations, photodegradation, temperature variations, and oxidative stress), enhance bioavailability, facilitate targeted delivery, and permit controlled and sustained release of the encapsulated compound^{35,36} (Fig. 2).

The encapsulation process must be carefully designed to ensure precise regulation of release kinetics, allowing for controlled dosage at the intended site of action.³⁷ An optimal delivery system should protect against external destabilizing factors such as enzymatic degradation, moisture, and temperature fluctuations, thereby preserving the structural and functional integrity of the encapsulated compound.³⁸ Additionally, once encapsulated within nanocarriers, the physicochemical properties of nutraceuticals are largely influenced by the characteristics of the carrier system rather than the entrapped bioactive compound, thereby enhancing solubility and stability. Moreover, nanocarrier-based systems enable the co-delivery of hydrophilic and lipophilic bioactives, facilitating their synergistic therapeutic effects and improved bioavailability.^{39,40}

It is imperative to ensure that nanotechnology-based delivery systems utilize biocompatible, non-toxic, and non-immunogenic materials that pose no threat to human health.⁴¹ The materials commonly employed in nanocarrier fabrication include lipid, polymer, and protein-based systems, all of which must comply with regulatory standards and be categorized as Generally Recognized as Safe (GRAS).⁴¹ The selection of an appropriate nanocarrier system is determined by the physicochemical properties of the encapsulated nutraceutical, the intended site of action, and the specific therapeutic application.^{42,43} Among the key nanocarriers explored in recent research are nanogels, nanoemulsions, nanoparticles (lipidic,

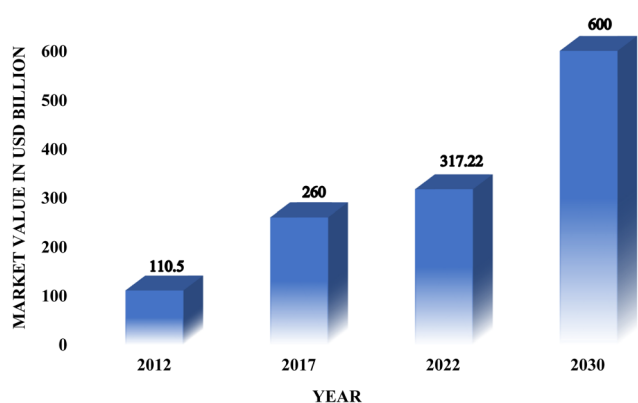


Fig. 1 The global market value of nutraceuticals in USD Billion from the year 2012 to 2027.^{24,26}



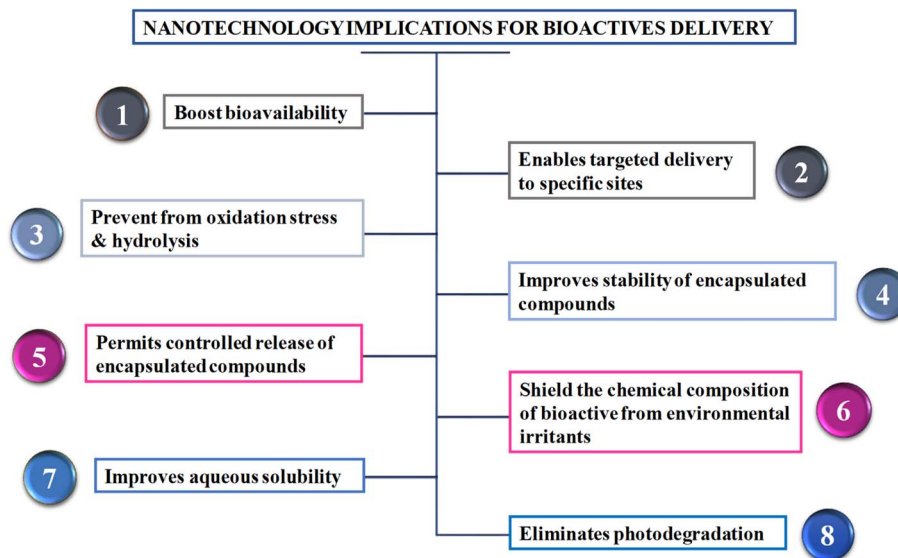


Fig. 2 Nanotechnology implications to nutraceuticals and dietary supplements delivery.

polymeric, or protein-based), niosomes (non-ionic surfactant vesicles), liposomes, nanocrystals, and polymeric nanocapsules (Fig. 3). The following sections provide a comprehensive discussion of these nanocarrier systems and their applications in enhancing nutraceutical delivery.

2.1 Nanogels

Nanogels are hydrogel particles with remarkable versatility in nutraceutical delivery due to their nanoscale size (typically <1000 nm), high loading capacity, stability, and ability to protect and control the release of bioactive compounds.⁴⁴ They are predominantly synthesized through self-assembly, chemical modifications, ionic gelation, and ultrasonication techniques, often incorporating proteins and polysaccharides as core materials. Recent advancements in nanogel formulation have demonstrated significant improvements in the encapsulation efficiency, bioavailability, and functional properties of encapsulated nutraceuticals.

He M. *et al.* developed soy protein isolate (SPI)-based nanogels modified with dextran and succinic acid anhydride to

encapsulate curcumin. The Maillard reaction and succinic acid anhydride modification enhanced the functional properties of SPI, such as hydrophobicity and charge distribution, facilitating self-assembly into nanogels. This resulted in nanogels with a particle size of 143 nm, a dispersion index of 0.20, an encapsulation efficiency of 93%, and a loading capacity of 54%.⁴⁵ These nanogels exhibited excellent stability and antioxidant activity, making them suitable for addressing oxidative stress-related diseases. Similarly, Wang *et al.* formulated self-assembled nanogels using acylated rapeseed protein isolate (ARPI) through a process of chemical acylation and heat-induced protein denaturation.⁴⁶ This approach endowed the nanogels with unique secondary and tertiary structures, reduced sulfhydryl groups, and increased hydrophobic surfaces, resulting in spherical particles with a hydro-diameter of 170 nm and a light core-dark shell morphology. ARPI nanogels were effective in enclosing curcumin with an exceptional encapsulation efficiency of 95% which significantly boosted its potential to fight cancer in different cell lines. However, the study lacks data on pH stability and performance in complex food matrices and *in vivo* studies to prove their safety and efficacy.⁴⁶ In another approach, Yu *et al.* formulated acylated kidney bean protein isolate (AcKPI) nanogels *via* the self-assembly method, achieving uniform particles with particle size of 137 nm and PDI of 0.3. They exhibited excellent encapsulation efficiency of 92%, significant antioxidant properties, and pH and temperature tolerance. The study provides the application scope of AcKPI-nanogels for potential use as an innovative and ideal delivery system for bioactive compounds for controlled release.⁴⁷

Beyond protein-based nanogels, Xu *et al.* designed an innovative nanogel encapsulating lutein in an ovomucin and chitosan oligosaccharide blend through the self-assembly technique.⁴⁸ The encapsulated lutein showed remarkable stability across a wide pH range and ionic concentrations, retained its amorphous state, and achieved controlled release



Fig. 3 Schematic representation of liposomes and niosomes.



with significant antioxidant activity. The nanogels demonstrated no cytotoxicity toward L929 fibroblast cells at higher concentrations. The study presents the potential application of lutein-loaded ovomucin and chitosan oligosaccharide blend nanogels as the promising and effective oral carrier of lutein. However, the absence of *in vivo* studies left uncertainties regarding their oral bioavailability and long-term safety.⁴⁸ Another study encapsulated folic acid (vitamin B₉) in soy proteins and polysaccharides using a self-assembling technique to prevent deterioration due to pH, temperature, and light.⁴⁹ The folic acid-encapsulated nanogels could be used for intestinal release, as folic acid was gradually released under neutral pH. Furthermore, the nano-encapsulated substance remained stable at high temperatures, high light exposure, and high oxygen pressures, making it a feasible option for employing the nanogels in a variety of food and drink formulations without worrying about the risk of deterioration.⁴⁹ Additionally, Sun *et al.* utilized a Maillard reaction and self-assembly to fortify orange juice with curcumin.⁵⁰ The encapsulated curcumin demonstrated superior stability and antioxidant activity, expanding its potential for acidic beverage applications. Despite their advantages, they may pose allergenicity risks and limit their applicability in certain populations. Nevertheless, self-assembled nanogels can effectively encapsulate a variety of nutraceuticals and drugs, improving their stability and bioavailability. The process avoids the use of toxic solvents, aligning with green chemistry principles.

The ultrasonication technique is another widely employed method for nanogel synthesis, offering advantages such as controlled particle size tuning (30–200 nm), crosslink density modulation, and adjustable drug release profiles by varying ultrasonication time, amplitude, and polymer concentration.⁵¹ Jin *et al.* encapsulated vitamin B₂ in nanogels made with dextran and thermally denatured soy protein using an ultrasonication technique, having a diameter of 40 nm and maintaining their spherical shape at pH 6.52 Encapsulation efficiency was 65.9%, with gradual intestinal release, making them suitable for specific gastrointestinal applications. The study demonstrated that nanogels made with dextran and thermally denatured soy protein had low dispersion, nanoscale sizes, and fair encapsulation efficiency when riboflavin was delivered in an intact form, supporting their potential as functional nutraceutical carriers.⁵²

Another promising approach in nanogel synthesis is ionic gelation, a simple and mild technique that enables the fabrication of nanogels under physiological pH and ambient temperatures, making it particularly suitable for encapsulating sensitive bioactive compounds.⁵³ Buosi *et al.* developed a resveratrol-loaded chitosan-sodium tripolyphosphate nanogel targeted for ophthalmic delivery.⁵⁴ The nanogel demonstrated remarkable protection of the encapsulated bioactive compound from UV light. It exhibited biocompatibility with a human retinal pigment epithelial cell line (ARPE-19). These findings underscore the ability of ionic gelation-derived nanogels to serve as protective carriers for bioactives while maintaining cellular compatibility.

Collectively, these studies showcase innovative methods to prepare nanogels with tailored properties for nutraceutical delivery. The techniques employed, such as chemical modification, self-assembly, ionic gelation, and the Maillard reaction, enhance the functional capabilities of protein-based carriers. However, a significant limitation across most studies is the absence of *in vivo* validation, which remains crucial for assessing the clinical efficacy, safety, and scalability of these systems. Future research should focus on optimizing nanogel formulations to address allergenicity concerns, improving stability in complex biological environments, and conducting comprehensive *in vivo* evaluations to establish their commercial viability. Other recent studies related to the entrapment of bioactives into polymeric nanogels are summarised in Table 1.

2.2 Nano-emulsions

Nano-emulsions (NEs) are small-sized colloidal particulate systems utilized for the transportation of numerous drug molecules.⁶¹ They differ from traditional emulsions due to their smaller droplet size, typically in the nanometre range. They typically consist of water, oil, and an emulsifier, which plays a crucial role in reducing the interfacial surface tension between water and oil phases, stabilizing the NEs, and preventing coalescence.⁶² Surfactants, proteins, and lipids are commonly used emulsifiers.^{63,64} NEs offer multiple advantages such as shielding active ingredients, enhancing their effectiveness, and serving as delivery systems for nutraceuticals and food components.^{65,66}

Recent studies have extensively investigated the potential of NEs as advanced nutraceutical delivery systems, focusing on their ability to enhance bioavailability, stability, and functional properties. In one such study, researchers encapsulated co-enzyme Q10 into chitosan-based NEs, demonstrating excellent stability, reducing oxidative stress and inflammation in cardiomyoblast cells and hepatocytes against the damaging effects of the potent anticancer drug doxorubicin.⁶⁷ They also increased cell viability by 35–40% in hepatocytes and cardiomyocytes and decreased the production of nitric oxide, interleukins, and TNF- α . The chitosan surface provided biocompatibility and enhanced bio-adhesion, improving cellular uptake.⁶⁷ Similarly, another study encapsulated clove oil in whey-protein NEs utilizing the ultrasonication method, achieving a droplet size of 280 nm, a PDI of <2, and a zeta potential (ZP) of –35 mV.⁶⁸ These properties contributed to stability across various pH levels, temperatures, and ionic concentrations. These NEs exhibited potent antimicrobial efficacy against *E.coli* and *B. subtilis* strains with a minimum inhibitory concentration and minimum bactericidal concentration of 50 and 90 $\mu\text{g mL}^{-1}$, respectively, suggesting their potential for food safety applications. The small droplet size and negative zeta potential likely enhanced the interaction with microbial membranes, improving efficacy. This study heralds a promising avenue for leveraging clove oil's antimicrobial properties in practical applications within food systems.⁶⁸ Another study utilizing a NE mixture of whey protein isolate (WPI) and gardenia fruit oil encapsulated three different bioactive compounds, named β -carotene, hesperetin, and naringenin, achieving remarkable encapsulation efficiencies of





Table 1 Polymers employed for the encapsulation of bioactive compounds into nanogels

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Curcumin	Soy protein isolate (SPI)	Heat-induction	<ul style="list-style-type: none"> Reported particle size, PDI, and EE% of 143 nm, 0.2 and 93%, respectively Revealed sustained release of curcumin (approx. 80%) Showed enhanced stability and antioxidant nature Reported a hydro-diameter of 170 nm and encapsulation efficiency of 95% Had significantly different spatial secondary and tertiary structures Demonstrated enhanced hydrophobic surfaces and reduced levels of free sulphydryl groups Exhibited remarkable anti-inflammatory activity <i>in vitro</i> as well as <i>in vivo</i> Macrophages incorporated curcumin-loaded nanogels to release it under acidic conditions Reported EE% and DL% of 89% and 17%, respectively Exhibited remarkable bioavailability of 55%, enhanced stability, and excellent antioxidant activity Reported a spherical shape of 40 nm and EE% of 66% Exhibited low dispersion, nanoscale sizes, and fair encapsulation efficiency The stability of vitamin B₉ was independent of the presence of a singlet oxygen atom Stable at high temperatures, light exposure, and oxygen pressures Crystallinity was inversely proportional to gelatin concentration Exhibited excellent sensitivity to both pH and temperature Reported particle size, ZP, and EE% of 140 nm, 32 mV, and 59%, respectively Demonstrated biocompatibility with human pigment epithelial cell line (ARPE-19) and remarkable protection from UV light Reported an encapsulation effectiveness of 94.5% and a spherical shape with a particle size of 220 nm <i>In vitro</i> results showed high protective activity of resveratrol against oxidative stress in fibroblast and neuroblastoma cells Nanogel particle size, PDI, and zeta-potential were reported to be 370 nm, 0.528, and -24.8 mV, respectively Reported an entrapment efficiency of 98% Exhibited sustained release of the drug up to 48 hours Reported particle size ranges from 44 to 194 nm 	Targeted therapy for numerous ailments like cancer, diabetes, and cardiovascular diseases	45
	Rapeseed protein isolate	Chemical acylation and heat-induced protein denaturation		Anti-cancer therapy for several cell lines	46
	Polyglutamate	Esterification reaction with vitamin B ₆		Targeted anti-inflammatory effect	55
Vitamin B ₂ (riboflavin)	Soy protein isolate and dextran	Maillard reaction and self-assembly technique		Fortification of acidic beverages like orange juice	50
Vitamin B ₉ (folic acid)	Soy protein isolate	Self-assembly		Targeted delivery system for vitamin B ₂	52
Capsaicin	Poly(vinyl alcohol) and gelatin	Esterification		Targeted delivery of folic acid	49
Resveratrol	Chitosan and sodium tripolyphosphate	Ionic gelation		Innovative delivery system for capsaicin	56
	Tribasic acid and 1,2,5-pentanetriol	Esterification precipitation reaction		Targeted ophthalmic delivery	54
Quercetin	Chitosan	Ionic-gelation		For the enhancement of protective effects in oxidative stress cells	57
				Targeted transdermal delivery of quercetin as an antioxidant	58
					59

Table 1 (Contd.)

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Lutein	Poly-ε-caprolactone (PCL) and poly ethylene glycol (PEG) Ovomucin and chitosan oligosaccharide	Crosslinking with folic acids Self-assembly method	<ul style="list-style-type: none"> Revealed remarkable drug loading and entrapment efficiencies Nanogels with greater crosslinking densities disintegrated in buffer solution too quickly Demonstrated particle size, PDI, ZP, EE%, and DI% of 210 nm, 0.25, -20.71 mV, 90%, and 6.5%, respectively Exhibited remarkable stability over a wide range of pH values Exhibited significant antioxidant activity and no cytotoxicity toward L929 fibroblast cells Demonstrated excellent protection from UV light and high temperature Exhibited remarkable stability indicated by enhanced retention (56–69%) of encapsulated β-carotene upon one month storage Showed improved bioavailability of encapsulated β-carotene 	Targeted delivery system for a wide range of cancers Novel oral delivery system for lutein and other hydrophobic drugs	48
β-Carotene	Chitosan and carboxymethyl starch	Chemical cross-linking		Targeted oral delivery of β-carotene and other bioactives	60

80%, 51%, and 46%, respectively.⁶⁹ Small droplet sizes (<300 nm) achieved through ultrasound application stabilized the NEs under challenging environments, *i.e.*, lower temperatures, alkaline conditions, and reduced cationic concentrations. They impressively curtailed the generation rate and peroxide value (PoV) and amount of thiobarbituric acid reactive substances (TARS) during the 14 day accelerated oxidation experiment, confirming the improved oxidation stability of gardenia fruit oil.⁶⁹

In terms of functional bioavailability and cellular uptake, albumin-stabilized NEs encapsulating resveratrol exhibited neuroprotective effects by mitigating postoperative cognitive dysfunction in older rats by decreasing hippocampal inflammation.^{70,71} The smooth surface and bioactive encapsulation protected resveratrol from degradation and improved its interaction with cellular targets. The neuroprotective effects were linked to the activation of the SIRT1 signaling pathway, highlighting the role of surface characteristics in influencing biological pathways.⁷¹ Additionally, N. Walia and L. Chen demonstrated that the encapsulation of vitamin D by pea protein-stabilized NEs enhanced its bioavailability and potentially alleviated vitamin insufficiency in older adults. The protein surface enhanced cellular absorption, highlighting the value of protein–emulsifier interactions in optimizing nutrient delivery.⁷² V. Campani *et al.* utilized low-energy techniques to prepare vitamin K₁ (VK₁)-loaded PLGA NEs, which exhibited intriguing droplet size and stability across different storage conditions. The porous surface facilitated skin penetration and transdermal delivery. Nebulization studies confirmed the potential for spray formulations without altering the NE properties, suggesting commercial viability for topical applications.⁷³

From an antioxidant and food system perspective, black rice bran phenolics (ferulic and *p*-coumaric acids) were successfully entrapped in sunflower oil NEs using homogenization and ultrasonication, exhibiting sustained antioxidant activity across varying thermal and ionic conditions (0.2–1 mol L⁻¹), thereby suggesting their utility in food preservation.⁷⁴ Similarly, Li J. *et al.* incorporated lycopene from tomato waste into oil-in-water NEs utilizing isopropyl myristate (oil phase) and Pluronic F-127 (emulsifier) through high-speed homogenization combined with spray-drying technology. The spray-drying technique preserved lycopene's bioactivity, and small droplet sizes enhanced its dispersion and uptake in food systems.⁷⁵

Despite these promising attributes, several challenges remain in the development and commercialization of NE-based nutraceuticals. While NEs demonstrate superior EE%, payload capacity, and protection from degradation, their stability is highly dependent on the selection of appropriate surfactants and emulsifiers. Expanding *in vivo* studies to validate their bioavailability and therapeutic efficacy is essential for their clinical and commercial translation. Future innovations should explore hybrid NE systems integrating multiple encapsulation strategies to achieve synergistic effects. Table 2 summarizes studies on nutraceutical delivery *via* NEs, highlighting natural and synthetic polymers used for encapsulating nutritional supplements and their targeted applications.



Table 2 Polymers used for the entrapment of bioactive compounds into nano-emulsions

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Coenzyme Q10	Chitosan	High-pressure homogenization	<ul style="list-style-type: none"> Cell viability increased by 35–40% in coenzyme Q10-loaded nanoemulsions Decreased the production of nitric oxide, interleukins and TNF-α Reduced oxidative stress and inflammation in cardiomyoblast cells (HCF cell line) and hepatocytes (THLE-2 cell line) Reported droplet size, PDI, and zeta potential of 280 nm, less than 0.2, and -35 mV, respectively Exhibited astonishing resistance to different pH values (3–7), temperatures (60–120 °C), and ionic concentrations (0.1–1 M NaCl) Demonstrated potent antimicrobial efficacy against <i>E. coli</i> and <i>B. subtilis</i> strains after a rigorous contact period of 8 hours 	Protection of cardiomyocytes and hepatocytes against the damaging effects of doxorubicin and trastuzumab	67
Eugenol from clove oil	Whey protein	Ultrasonication	<ul style="list-style-type: none"> Reported small droplet sizes (<300 nm) at 10% v/v concentration of oil Demonstrated excellent stability at low temperature, high pH, and low ionic strength All three NEs exhibited remarkable encapsulation efficiencies 	Antimicrobial agent for various food products	68
β -Carotene, hesperetin, and naringenin	Whey protein isolate (WPI) and gardenia fruit oil	High-speed homogenization and ultrasonication techniques	<ul style="list-style-type: none"> Reduced the cognitive impairment brought on by surgery and associated hippocampus neuroinflammation The concurrent injection of sirtinol decreased the neuroprotective effects of resveratrol's nano-emulsion 	Targeted and controlled delivery of lipid-soluble nutraceuticals	69
Resveratrol	Albumin	Low-energy emulsification	<ul style="list-style-type: none"> Revealed excellent stability, reduced droplet sizes (170–350 nm), and remarkable encapsulation efficiency (94–96%) Exhibited high cellular uptake in the Caco-2 cell line 	Prevention of cognitive dysfunction	71
Vitamin D	Pea protein	High-pressure homogenization	<ul style="list-style-type: none"> Exhibited intriguing droplet size and stability over time at various storage temperatures Had the potential to be used for the commercial production of an aqueous spray formulation for the topical administration of VK₁ 	Alleviation of vitamin insufficiency in elderly people	72
Vitamin K ₁ (Phytonadione)	PLGA (polylactic-co-glycolic acid)	Spontaneous emulsification		Targeted transdermal delivery of VK ₁	73



Table 2 (Contd.)

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Curcumin	Chitosan	Homogenization	<ul style="list-style-type: none"> • Chitosan improved the spreadability, feel, and consistency of the nano-emulsion • Showed improved skin permeability • Increased the solubility and skin permeability of curcumin • Droplet size, PDI, and zeta potential were 10.57 nm, 0.094, and -18.7 mV, respectively • Results showed fast recovery of psoriasis in rat models 	For the transdermal delivery of curcumin	76
	Polyacrylic acid	Low-energy emulsification	<ul style="list-style-type: none"> • All NEs reported droplet sizes within 128–226 nm • Exhibited excellent stability at high temperature (65 °C) over a one-month storage period • Demonstrated remarkable stability and antioxidant activity at different ionic strengths (0.2, 0.5, and 1 mol L⁻¹) 	For the management of psoriasis	77
Ferulic acid and <i>p</i> -coumaric acid	Polysorbate 80 and soy lecithin	Homogenization and ultrasonication	<ul style="list-style-type: none"> • Evaluated the effect of different coating agents, drying temperatures (120–170 °C), and feed flow rates (3–9 ml min⁻¹) on droplet size • Maltodextrin (coating agent) enhanced the stability of NEs 	Targeted drug delivery system for polyphenols	74
Lycopene	Isopropyl myristate and Pluronic F-127	High-speed homogenization and spray-drying techniques		Novel drug delivery system for lycopene and other bioactives	75



2.3 Liposomes and Niosomes

Liposomes and niosomes are advanced vesicular nanocarriers used for the efficient delivery of hydrophilic and lipophilic substances. Unlike nanogels and nanoemulsions, these vesicles can encapsulate a wide range of bioactives due to their unique multilamellar structure.⁷⁸ Both hydrophilic and lipophilic molecules, as well as amphiphilic substances, can be incorporated into their structures (Fig. 3).⁷⁹ Multilamellar liposomes, for instance, offer additional versatility by hosting substances within their multiple bilayers. Liposomes primarily consist of phospholipids and surfactant molecules, while niosomes are synthesized from non-ionic surfactants, making them cost-effective.⁸⁰ Numerous techniques are employed for the preparation of these vesicles, including lipid layer hydration, reversed-phase evaporation, transmembrane pH gradient, micro-fluidization, ether injection, and extrusion techniques.⁸¹ Critical factors influencing their synthesis include the type of vesicle, phospholipid properties, their interactions with the dispersion medium, and the bioactive molecules being encapsulated.⁸²

Liposomes and niosomes have demonstrated remarkable potential in delivering various vitamins (A, C, and E), phytochemicals, and other bioactive substances.⁸³ Encapsulation in liposomes improved all-trans retinoic acid's (ATRA's) photostability and anti-cancer efficacy, enhancing cellular uptake and reducing degradation.^{84,85} The anticancer effects of retinoic acid were enhanced on thyroid carcinoma cell lines (FRO, PTC-1, and B-CPAP) when ATRA was delivered *via* liposomes. The intracellular uptake of the vesicular formulation in the *in vitro* assays on FRO and B-CPAP cell lines demonstrated a more pronounced anticancer effect when compared with the free drug.⁸⁶ Similarly, niosomes synthesized using the film hydration technique demonstrated a narrow size distribution (107–190 nm) and high encapsulation efficiency, enhancing stability and reducing lipid peroxidation.⁸⁷

In a parallel investigation, liposomal formulations of curcumin and α -tocopherol, prepared with the homogenization method, retained the antioxidant activity in fortified cookies without compromising sensory attributes. Their encapsulation efficiencies were reported to be above 90%. DPPH and ferric-reducing antioxidant power assays reported the successful liposomal encapsulation of curcumin and α -tocopherol into the fortified cookies, preserving the antioxidant properties of both.⁸⁸ Another group of researchers explored niosomal formulations for co-delivering nutraceuticals and dietary supplements. They encapsulated gallic acid with curcumin and ascorbic acid with quercetin in niosomes, which significantly boosted solubility and antioxidant efficacy.⁸⁹ This enhanced synergistic antioxidant activity, making it more promising for chronic disease management. A separate investigation highlighted the encapsulation of gallic acid extracted from Indian gooseberry and sappan wood heartwood using the ethanol injection method to produce mucus-penetrating niosomes with potent anti-inflammatory activity. The addition of poloxamer 407 influenced the diffusion mechanisms, enabling efficient intestinal absorption.⁹⁰

Incorporating bioactive lipids into vesicular systems has also demonstrated promising outcomes. Zelikina D. *et al.* incorporated curcumin and fish oil PUFAs ($n - 3$ and $n - 6$) into liposomes made from a WPI-chitosan conjugate *via* the Maillard reaction. The liposomes exhibited the sustained release, enhanced bioavailability, and mucoadhesiveness of the encapsulated nutraceuticals during gastric and small intestinal stages.⁹¹ Semenova M. *et al.* encapsulated a combination of lipophilic ($n - 3$ PUFAs, vitamin D3, and eugenol) and hydrophilic (γ -aminobutyric acid) nutraceuticals in phosphatidylcholine liposomes coated with a WPI-chitosan conjugate. These liposomes exhibited small particle size, remarkable encapsulation efficiencies (>80% for lipophilic and >49% for hydrophilic), and improved interaction with bile salts and mucin in the intestine. The study demonstrated the potential of phosphatidylcholine liposomes as novel oral carriers for lipophilic and hydrophilic bioactive compounds.⁹²

Liposomes and niosomes, with their tunable shape, surface properties, and multi-compartment structure, serve as efficient carriers for bioactives, ensuring improved stability, bioavailability, and targeted delivery. These attributes position them as promising candidates for nutraceutical and functional food applications. Despite their significant advantages, further research is needed to optimize these delivery systems by improving their stability in biological environments, ensuring large-scale reproducibility, and conducting extensive *in vivo* evaluations to confirm their therapeutic potential (Table 3).

2.4 Nanoparticles

Nanoparticles (NPs) are extensively employed as drug delivery systems due to their versatility in composition, and include a variety of materials, including proteins,⁹³ lipids,⁹⁴ and polymers such as poly-D,L-lactide-co-glycolide (PLGA),⁹⁵ polylactic acid (PLA),⁹⁶ poly- ϵ -caprolactone (PCL),⁹⁷ chitosan,⁹⁸ alginate,⁹⁹ and lignin.¹⁰⁰ These materials offer unique properties for encapsulating bioactives and ensuring controlled release. The use of food-grade materials is imperative to ensure safety and compliance for applications in the food and nutraceutical industries. Zein,¹⁰¹ chitosan,¹⁰² gelatin,¹⁰³ and lignin¹⁰⁴ are a few examples of the food-grade materials employed in NP formulations (Fig. 4). These materials not only provide biocompatibility and biodegradability but also align with the regulatory requirements, making them suitable candidates for delivering bioactive compounds in functional foods and dietary supplements.

2.4.1 Protein-based nanoparticles. Protein-based NPs, with particle sizes ranging from 10 to 40 nm, exhibit several desirable characteristics, such as bioavailability, biodegradability, non-antigenicity, high nutritional value, and exceptional binding capacity for various bioactive compounds.⁹³ These properties, combined with their non-toxic and biodegradable attributes, have increased research interest in their development. They can effectively deliver hydrophilic and hydrophobic nutraceuticals and are derived from sources such as bacteria, plants, animals, and fungi. Key methods for their synthesis include nanoprecipitation, emulsification, nano-spray drying, coacervation,





Table 3 Bioactive compounds loaded in liposomes and niosomes

Loaded bioactive compounds	Phospholipids and surfactants used	Methods of preparation	Outcomes	Potential applications	Ref.
All-trans retinoic acid (ATRA)	Phosphatidylcholine, cholesterol, and polyethylene glycol (PEG)	Reversed-phase evaporation	<ul style="list-style-type: none"> Reported particle size and EE% of 200 nm and 82%, respectively Exhibited remarkable stability in 60% FBS Enhanced anticancer effect on thyroid carcinoma cell lines (FRO, PTC-1, and B-CPAP) 	Potential therapy for anaplastic thyroid carcinoma	86
α -Tocopherol	Dicetyl phosphate (DCP), cholesterol, Span 60, and Tween 60	Film hydration technique	<ul style="list-style-type: none"> Showed a particle size range, ZP, EE%, and PDI of 107–190 nm, –30 mV, >80%, and 0.34 Improved stability with DCP and cholesterol Exhibited initial burst release followed by sustained release 	Novel oral carrier for α -Tocopherol and other lipophilic bioactives	87
Curcumin and α -tocopherol	Cholesterol and soy lecithin	Homogenization method	<ul style="list-style-type: none"> Reported a particle size range and EE% of 14–16 μm and more than 90%, respectively Encapsulated nutraceuticals did not alter the sensory attributes of the cookies Retained the antioxidant activities of the loaded bioactives 	Fortification of cookies and other food products with curcumin and α -tocopherol	88
Galic acid/curcumin and quercetin/vitamin C	Tween 60	Film hydration method	<ul style="list-style-type: none"> All niosomes had particle sizes from 500 nm to 700 nm Combination of two nutraceuticals substantially increased the antioxidant activity and aqueous solubility 	Alleviation of diseases caused by oxidative stress	89
Galic acid from Indian gooseberry and sappan wood	Poloxamer 407, cholesterol, Span 60, and Tween 80	Ethanol injection technique	<ul style="list-style-type: none"> Reported particle sizes between 96 and 400 nm Decrease in mucus penetration caused by incorporation of poloxamer 407 Enhanced anti-inflammatory activity due to the combination of two extracts 	Targeted transmucosal delivery system for mitigation of mucositis	90
Curcumin and fatty acids of fish oil ($n - 3$ and $n - 6$ PUFAs)	Phosphatidylcholine and biopolymers (WPI and chitosan)	Maillard reaction	<ul style="list-style-type: none"> Exhibited ZP and EE% of 29 mV and >92%, respectively Enhanced bioavailability, sustained release, and increased mucoadhesiveness of the encapsulated nutraceuticals at pH 1.2 and pH 6.8 Increased solubility and stability of curcumin 	Novel oral delivery system for lipophilic bioactives	91
Lipophilic: $n - 3$ PUFAs, vitamin D3, and eugenol Hydrophilic: γ -aminobutyric acid	Phosphatidylcholine and biopolymers (WPI and chitosan)	Maillard reaction	<ul style="list-style-type: none"> Reported remarkable encapsulation efficiencies for lipophilic (>80%) and hydrophilic bioactives (>49%) Reduced microviscosity and particle size leading to enhanced aqueous solubility and excellent stability Increased bioavailability of the encapsulated nutraceuticals resulting in their interaction with bile salts and mucin in the small intestine 	Targeted oral delivery system for lipophilic and hydrophilic nutraceuticals	92

desolvation, self-assembly, and cross-linking.¹⁰⁵ Protein carriers include gelatin, casein, whey protein, albumin, and collagen derived from animals, as well as soy- β -glycinin, wheat gliadin, and zein from plants.^{106–108}

Sunflower seed protein isolate (SFPI) NPs encapsulated curcumin, a hydrophobic anti-inflammatory compound, significantly enhancing its solubility, stability, and anti-oxidant and anti-inflammatory properties. The encapsulation efficiency was observed at $83 \pm 3\%$, with improved curcumin solubility ($8.1 \mu\text{g ml}^{-1}$). Additionally, the encapsulated curcumin demonstrated higher lipoxygenase activity ($\text{IC}_{50} = 45.3 \mu\text{M}$) compared to free curcumin. However, the study did not explore the long-term stability or *in vivo* performance of SFPI-encapsulated curcumin, limiting its translational applicability.¹⁰⁹ Similarly, Liu L *et al.* synthesized soy- β -glycinin NPs employing urea-induced disassembly and reassembly techniques to deliver curcumin. These core-shell nanostructures, comprising an aggregated β -subunit core and hydrophilic α - and α' -subunit shell, achieved a remarkable EE% (79%) and improved curcumin bioaccessibility (40%) compared to free curcumin (20%). These soy β -conglycinin nanostructures offer a potential biocompatible delivery mechanism for hydrophobic substances.¹¹⁰ In a parallel investigation, casein NPs, synthesized *via* coacervation and stabilized with lysine or arginine, demonstrated gastro-resistance and enabled controlled intestinal release of vitamin B₉. These NPs, with an average size of 150 nm, contained 25 mg of vitamin B₉ per mg and improved oral bioavailability *in vitro*. However, the absence of *in vivo* pharmacokinetic data limits the conclusions regarding their efficacy as an oral delivery system for vitamin B₉.¹¹¹

Another study drew attention to the development of plant-based protein NPs encapsulating quercetin that were resistant to gastric digestion, had antioxidant properties, and were stable enough to withstand higher temperatures.¹¹² High-intensity sonication was employed to prepare soybean, rice, and walnut protein-based NPs with particle size < 110 nm and PDI < 0.20 . These NPs exhibited remarkable thermal stability, antioxidant activity, and resistance to gastric digestion while maintaining morphology during digestion. This study provided valuable insights into the development of plant protein-based NPs as promising delivery systems for bioactive compounds.¹¹²

Beyond nutraceutical delivery, protein-based NPs have emerged as promising candidates for targeted drug delivery in cancer therapy. A novel study synthesized capsaicin-encapsulated lactoferrin-functionalized carboxymethyl dextran-coated egg albumin NPs (Cap-LF-CMD-EA-NPs) for the treatment of colorectal cancer. The preparation involved esterification, Maillard reaction, and gelation, where hydrophobic interactions between capsaicin and protein polymers facilitated nanoparticle formation.¹¹³ Spectral analyses indicated the successful synthesis of smooth and spherical NPs with excellent EE% and DL%. Drug release studies revealed sustained release of capsaicin (up to 80% in 24 hours) in pH 5.8 with anomalous transport attributed to the CMD and EA matrix shell. Moreover, enhanced cytotoxicity against HCT116 and LoVo cell lines was observed owing to the overexpression of lactoferrin receptors in colorectal HCT116 cells. This study illustrates the potential of

functionalized protein carriers for the treatment of colorectal cancer.¹¹³

Overall, protein-based NPs present a versatile and biocompatible platform for the encapsulation and delivery of bioactive compounds. Their tunable physicochemical properties, combined with high encapsulation efficiency and controlled release capabilities, make them promising candidates for applications in nutraceuticals and targeted drug delivery. However, future research is warranted to optimize their stability, large-scale production, and *in vivo* performance to facilitate clinical translation.

2.4.2 Polymer-based nanoparticles. Polymeric NPs have emerged as promising vehicles for the targeted and controlled delivery of nutraceuticals, offering enhanced stability, biocompatibility, and therapeutic efficacy. These nanocarriers, composed of natural, synthetic, or semi-synthetic polymers, exhibit particle sizes ranging from 1–1000 nm.¹¹⁴ Their biocompatibility, biodegradability, and capacity for surface modification make them ideal candidates for addressing challenges associated with conventional drug and nutraceutical delivery systems. The natural polymers most commonly employed are gelatin, chitosan/chitosan derivatives, alginate, and lignin. Synthetic polymers include PLGA, PLA, PCL, and PAMAM (polyamidoamine).¹¹⁵

Chitosan nanoparticles (CS-NPs) have been extensively studied for their potential in targeted cancer therapy. In one of the studies, liver-targeting nanosystems were developed that utilized *trans*-resveratrol-loaded CS-NPs to target hepatic carcinoma. The researchers modified the nanoparticle surface with biotin (B-CS-NPs) or biotin and avidin (A-B-CS-NPs) to enhance cellular uptake and adhesion to cancer cell lectins.¹¹⁶ NPs were prepared *via* ionic gelation, a technique known for its simplicity and ability to encapsulate hydrophilic drugs. *In vitro* studies on HepG2 cells revealed that modified CS-NPs exhibited superior anticancer activity compared to free *trans*-resveratrol, showcasing enhanced cellular internalization and sustained drug release. However, chitosan's solubility limitations at physiological pH may restrict systemic applications, necessitating further optimization.¹¹⁶

A separate investigation brought attention to the development of PLGA-NPs encapsulating resveratrol modified with chitosan-folate (RSV-CS-F-PLGA-NPs), prepared using a single emulsion solvent evaporation method, as an innovative targeted delivery system for prostate cancer.¹¹⁷ This technique yields highly stable nanoparticles with remarkable drug-loading efficiency. Biological assays on the PC-3 prostate cancer cell line indicated that these NPs induced oxidative stress and apoptosis more effectively than free resveratrol. This study affirms the potential of RSV-CS-F-PLGA-NPs as an efficacious treatment option for prostate cancer. Despite their advantages, PLGA NPs may suffer from burst release effects, though the chitosan coating helps mitigate this limitation by providing an additional diffusion barrier.¹¹⁷

Another study explored the application of PLA nanoparticles to deliver quercetin, prepared using the solvent evaporation method, as a novel approach. The resulting NPs exhibited a particle size of 130 nm, remarkable EE% of 96.7%, and



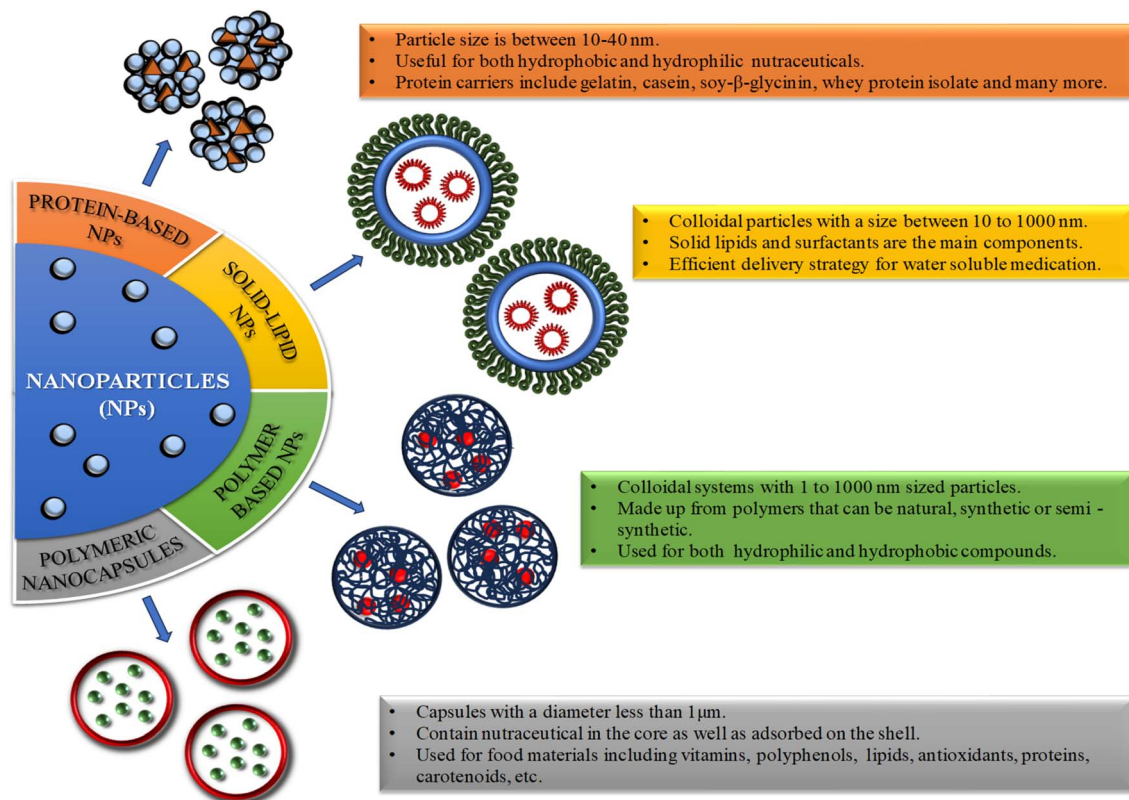


Fig. 4 Classification of nanoparticles based on the material used to prepare them for delivery of nutraceuticals.

controlled quercetin release, preserving quercetin's bioactivity.¹¹⁸ Fluorescence quenching studies confirmed the protective effect of PLA NPs on quercetin stability. This study paved the way for encapsulating anti-oxidant nutraceuticals toward the development of better therapeutic compounds.¹¹⁸

Vitamin D₃ (VD₃)-loaded tyrospheres were developed for topical applications to enhance bioactive stability and skin penetration. These polymeric nanospheres demonstrated high drug loading efficiency and protected VD₃ from photo-degradation and hydrolysis. The ease of formulation and improved drug retention made tyrospheres attractive for dermatological applications, though their limited penetration depth may require complementary techniques for systemic effects.¹¹⁹ Furthermore, Prabhuraj *et al.* developed PLGA NPs loaded with curcumin, coated with polyethylene glycol (PEG), and conjugated with various targeting moieties, folic acid, hyaluronic acid, and transferrin. The solvent evaporation method produced homogeneous, well-coated NPs with enhanced circulation time and reduced macrophage uptake. TEM imaging confirmed a particle size increase from 85 nm to 124 nm upon PEGylation, correlating with prolonged drug release and enhanced efficacy against aggressive and metastatic MDA-MB-231 breast cancer cells. Nevertheless, PEGylation can sometimes trigger immune responses, which may limit clinical translation.¹²⁰

A composite nanoparticle system incorporating hydroxyapatite and PLA NPs encapsulating capsaicin (Cap-HA/PLA-NPs)

was developed utilizing the ultrasound-assisted dispersion method. SEM imaging revealed uniform, spherical NPs (approximately 50 nm), while pharmacokinetic studies demonstrated prolonged drug release and significantly enhanced bioavailability.¹²¹ The biphasic release profile, influenced by HA concentration, allows for an initial rapid release followed by sustained release. They exhibited remarkable biocompatibility and served as effective long-term controlled release carriers, thereby improving the solubility and bioavailability of lipophilic drugs. However, the complex synthesis process and potential for aggregation may present formulation challenges.¹²¹

Various other studies related to biodegradable polymers used to encapsulate nutritional supplements into polymeric nanoparticles along with their targeted applications have been summarized in Table 4. These studies highlight the versatility of polymeric NPs in nutraceutical delivery. While natural polymers offer superior biocompatibility and safety, synthetic polymers provide adjustable drug release kinetics and structural stability. The choice of polymer, surface modification strategy, and fabrication method must be tailored to the desired therapeutic outcome. Future research should focus on optimizing formulation parameters, scaling up production, and conducting comprehensive *in vivo* studies to facilitate clinical translation. By addressing these challenges, polymeric nanocarriers hold immense potential to revolutionize nutraceutical and drug delivery systems.



Table 4 Polymers used for encapsulating bioactive compounds in polymeric nanoparticles and nanocapsules

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Capsaicin	α -Lactalbumin	Self-assembly	<ul style="list-style-type: none"> Enhanced rate of capsaicin endocytosis Deep penetration and anti-lipogenesis impact on steatotic HepG2 spheroid model Enhanced cellular internalization of Cap-LNPs in HepG2 cells Decreased intracellular triglyceride accumulation in an OA-induced HepG2 cell model confirmed by oil red O staining and triglyceride quantification 	Treatment of non-alcoholic fatty liver disease (NAFLD)	122
Curcumin	β -Lactoglobulin (BLG)	Desolvation	<ul style="list-style-type: none"> Loading efficiency(LE) up to 157% The ideal level of glutaraldehyde dropped by 50% when the curcumin/protein ratio rose 	Targeted delivery of curcumin	123
	PLGA(polylactic-co-glycolic acid)	Solvent displacement	<ul style="list-style-type: none"> Hyaluronic acid and folic acid were superior targeting moieties amongst hyaluronic acid, folic acid, and transferrin 	Targeted therapy for breast cancer	120
	Chitosan	Oil-in-water emulsification and ionotropic gelation technique	<ul style="list-style-type: none"> Highly effective against metastatic MDA-MB-231 breast cancer cells Formed NPs demonstrated superior biopharmaceutical and biological activities compared with free curcumin Improved mucoadhesion, cytotoxicity, and cellular uptake against Caco-2 cells Showed improved antioxidant and anti-inflammatory properties in activated RAW264.7 cells 	Targeted therapy for colon cancer	124
	Alginate	Self-assembly	<ul style="list-style-type: none"> Hydrophilicity and bioavailability of curcumin increased 	Ulcerative colitis treatment	125
	Albumin	Self-assembly	<ul style="list-style-type: none"> Alg-Cur effectively reduced inflammation in RAW264.7 cells Encapsulation efficiency and loading capacity were 83.22% and 8.33% Showed glutathione (GSH)-triggered curcumin release <i>In vitro</i> results showed increased cytotoxicity against MDA-MB-231 triple-negative human breast cancer cells 	Targeted drug delivery system for breast cancer	126



Table 4 (Contd.)

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Resveratrol	Chitosan	Conjugation with biotin alone and along with avidin Solvent displacement method	<ul style="list-style-type: none"> Both B-CS-NPs and A-B-CS-NPs had improved anti-cancer activity against HepG2 cells Conjugation with biotin enhanced the hepatic tissue penetrability B-CS-NPs were less cytotoxic than A-B-CS-NPs Stability and solubility of resveratrol-loaded NPs were affected by their particle size Nanoencapsulation improved resveratrol solubility and stability Stability rose but solubility dropped with an increase in particle size Exhibited improved stability and anti-neoplastic activity of RSV Demonstrated remarkable drug loading efficiency (above 20% wt) SIL/BSA NPs reported to have a diameter of 90 nm Reduced acute liver damage caused by APAP and LPS/D-GaIN in mice Exhibited antioxidant benefits against intracellular oxidative stress Reported particle size of 284 nm Exhibited sustained release up to 48 h Improved cell inhibition in a human lung cancer cell line NP size (<200 nm) and encapsulation efficiency of 79.78% were reported <i>In vitro</i> results showed quercetin release of about 67.28% IC₅₀ value reduced in <i>in vitro</i> cytotoxicity assay Particle size, ZP, PDI, and EE% of NCs reported to be 230 nm, -17.5 mV, 0.383 and 93%, respectively Demonstrated biphasic release <i>i.e.</i>, initial burst release followed by sustained release More effective intranasally as compared with the oral route of administration 	Targeted resveratrol delivery for hepatic carcinoma	116
	Chitosan/ γ -polyglutamic acid (γ -PGA)	Ionic gelation		Targeted delivery system for resveratrol	127
	Alkali lignin	Self-assembly		Targeted delivery system for lipophilic drugs	128
Silibinin (SIL)	Bovine serum albumin (BSA)	Nano-precipitation		Innovative treatment strategy for acute liver injury	129
	PLGA/PCL	Double emulsion solvent evaporation technique		Targeted delivery system for pulmonary carcinoma	130
Quercetin	Chitosan	Ionic gelation		For the treatment of lung and breast cancer	131
	PCL	Modified nanoprecipitation technique		Innovative targeted delivery system for anxiety treatment	132



Table 4 (Contd.)

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
	<i>Prunus armeniaca</i> gum exudate	Ionotropic gelation	<ul style="list-style-type: none"> Exhibited remarkable EE% and sustained drug release Demonstrated significant reduction in bacterial load, IL-6 and IL-1β in the kidney tissues 	Targeted drug-delivery system for quercetin against antibiotic-resistant <i>S. aureus</i> bacteria	133
<ul style="list-style-type: none"> Greatly improved the intestinal permeation and stability of the bioactive compound 	Eudragit L-100	Sonication along with emulsification solvent evaporation	<ul style="list-style-type: none"> Administered orally to streptozotocin-induced diabetic rats for 21 days Exhibited significant anti-diabetic effect on rats 	Innovative targeted drug delivery system for diabetes	134
	PLA (polylactic acid)	Solvent evaporation	<ul style="list-style-type: none"> Exhibited remarkable antioxidant activity Reported to have a particle size of 130 nm and EE% of 97% 	Innovative delivery system for quercetin and other anti-oxidant bioactives	118
<ul style="list-style-type: none"> Demonstrated initial burst release followed by sustained release 	Alginate and chitosan	O/W emulsification and ionic gelation	<ul style="list-style-type: none"> Exhibited particle size, ZP, and EE% of 225 nm, 35.3 mV and 81%, respectively Displayed remarkable stability in simulated environmental conditions Improved bioavailability, anti-oxidant properties, and cytotoxicity in various cancer cells 	Innovative delivery system for fucoxanthin as well as other bioactives	135
Vitamin B ₉ (folic acid)	PLA	Nanoprecipitation technique	<ul style="list-style-type: none"> NP size, PDI, and EE% were reported to be 180 nm, 0.18, and 89% respectively Exhibited higher cellular uptake for breast(MDA-MB-231) and bladder (RT4) cancer cells 	Targeted glycoalkaloidic delivery strategy for breast and bladder cancer treatment	136
	PLGA	Nanoprecipitation	<ul style="list-style-type: none"> Cytotoxicity in normal and tumor cells was reported IC₅₀ for folic acid was 4 times lower than that of 5-fluorouracil-loaded PLGA NPs 	Targeted 5-fluorouracil delivery system for treatment of colon and breast cancer	137
Vitamin D ₃ (VD ₃) (Cholecalciferol)	Tyrospheres (tyrosine-derived nanospheres)	Centrifugation and dispersion	<ul style="list-style-type: none"> Shielded the bioactive compound against photodegradation and hydrolysis Enhanced the stability of VD₃ 	Topical delivery of vitamin D ₃	119



Table 4 (Contd.)

Loaded bioactive compounds	Polymers used for encapsulation	Methods of preparation	Outcomes	Targeted applications	Ref.
Vitamin K ₁ (VK ₁)	Ovalbumin	Water-in-oil-in-water double emulsion solvent evaporation method Nanoprecipitation	<ul style="list-style-type: none"> Inhibited the production of ovalbumin-specific-CTLs by intravenous administration of NPs Reported to have an average diameter of 211 nm and ZP of -15 mV Exhibited enhanced stability of VK₁ Demonstrated higher retention of VK₁ in the epidermal layer of skin Reported particle size of 21.9 nm and EE% of 77% Exhibited improved cell viability and anti-oxidant activity in human astrocyte spinal cord cells Reported to have a mean diameter of 165 nm and 172 nm at the lab and pilot scale, respectively Greatly improved antioxidant activity of vitamin E 	Anti-specific immune suppression Transdermal delivery of VK ₁	138 139
α -Tocopherol	Alginate	Iontropic gelation		Spinal cord injury treatment	140
	PLGA	Nanoprecipitation		Innovative delivery system for vitamin E	141

2.4.3 Polymeric nanocapsules. Polymeric nanocapsules represent a cutting-edge approach for encapsulating bioactive compounds within a polymeric membrane, enhancing stability, bioavailability, and therapeutic efficacy. Unlike polymersomes, nanocapsules have a hydrophobic liquid core, and their properties are highly influenced by polymer composition, molecular geometry, and relative monomer length (Fig. 5). Encapsulation boosts product storage stability, safeguards the health-promoting activities of nutraceuticals.¹⁴² The most popular encapsulation method for food materials including vitamins, polyphenols, lipids, antioxidants, proteins, carotenoids, *etc.* is spray drying, though other methods like nanoprecipitation, double emulsion, and self-assembly are widely employed.¹⁴³ Various polymeric wall materials, including sodium alginate, gum arabic, trehalose, whey protein, and modified starch, are commonly used to form the nanocapsule wall, each influencing the final nanoparticle properties.¹⁴⁴

One of the significant applications of polymeric nanocapsules is improving the bioavailability of essential nutrients. A study investigated the encapsulation of vitamin K₁ (VK₁) into sodium alginate nanocapsules using the nanoprecipitation method.¹³⁹ These nanocapsules reported an average diameter of 211 nm and a negative zeta potential of 15 mV. Franz-type diffusion and tape-stripping assays revealed enhanced VK₁ retention in the dermis while reducing unwanted systemic absorption. This highlights nanocapsules' potential in transdermal delivery, though their negative zeta potential may impact long-term stability.¹³⁹

Similarly, Khayata *et al.* developed α -tocopherol-loaded nanocapsules (α -T NCs) utilizing the membrane contractor approach, showcasing their promising potential at lab and pilot scales.¹⁴¹ These nanocapsules exhibited particle sizes of 165 and 172 nm at the lab and pilot scales, respectively, with remarkable encapsulation efficiencies of 98% and 97%. A six-month accelerated stability study revealed that α -T NCs were stable without significant changes in mean diameter, zeta potential, and drug encapsulation efficiency. More importantly, the antioxidant activity of vitamin E was significantly improved due to its nano-encapsulation, underscoring the potential of nanocapsules in improving the functionality of dietary antioxidants. Despite these benefits, membrane contractor methods may require precise parameter control for scalability.¹⁴¹

Expanding on the application of natural bioactives, Abbas *et al.* developed multilayered curcumin-loaded nanocapsules using the self-assembly method.¹⁴⁵ The study utilized the ultrasound-assisted NEs as templates, where the polyelectrolytes such as chitosan, partially deacylated chitosan, sodium carboxymethylcellulose (Na-CMC), and purity gum ultra (OSA-modified starch) were employed for the fabrication of stable multilayered curcumin nanocapsules. The outcomes suggested that regulated sonication played a crucial role in producing uniform NE droplets, providing a scalable approach for encapsulating hydrophobic bioactives with enhanced stability.¹⁴⁵

Beyond improving bioavailability, polymeric nanocapsules have shown remarkable therapeutic potential in the treatment



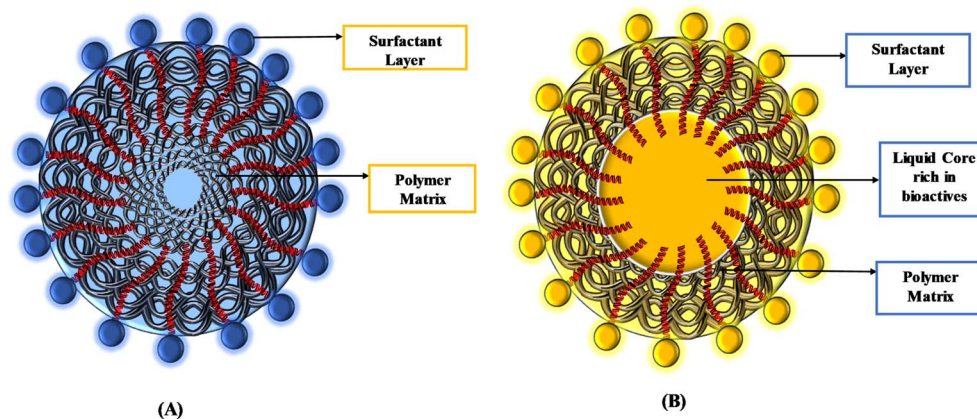


Fig. 5 (A) Polymeric nanoparticles; (B) polymeric nanocapsules.

of colorectal cancer.¹⁴⁶ For instance, the co-encapsulation of curcumin and salicylic acid within mucoadhesive copolymer m-PEG-*b*-PCL NCs demonstrated a sustained release profile and strong adhesion to colonic mucosa. They exhibited a particle size of less than 500 nm and a remarkable EE% of 14% and 91% for curcumin and salicylic acid, respectively. The ability to co-deliver multiple therapeutic agents highlights the versatility of nanocapsules in colorectal cancer treatment.¹⁴⁶

For advancing cancer treatment, dual-targeted folic acid-PLGA NCs encapsulating pterostilbene were developed for alleviating hepatocellular carcinoma (HCC).¹⁴⁷ They exhibited a particle size of 220 nm and sustained release of pterostilbene for up to 48 hours. More importantly, they demonstrated superior anticancer activity compared to free pterostilbene, with a 20-fold reduction in IC₅₀ against HepG2 cells. *In vivo* investigations conducted on HCC-induced animals further showcased the superiority of dual-targeted nanocapsules over the free pterostilbene while enhancing apoptotic signaling, reinforcing their potential for targeted cancer therapy.¹⁴⁷

In addition to synthetic polymeric carriers, natural nanocarriers have also been explored for bioactive delivery. A study utilizing lotus sporopollenin-based exine capsules for anthocyanin delivery, isolated from red cabbage, demonstrated their potential as an oral delivery system.¹⁴⁸ The prolonged acidolysis technique successfully converted microcapsules into nanocapsules with a hydrodynamic size of less than 220 nm and a PDI of less than 0.25, indicating uniform size distribution. HRSEM images confirmed the structural stability of these nanocapsules, even under gastric acid conditions, underscoring their potential as a promising vehicle for various plant-derived bioactive compounds. The natural origin of sporopollenin enhances biocompatibility, though the acidolysis process may affect production efficiency.¹⁴⁸

These studies underscore the versatility of polymeric nanocapsules in improving the bioavailability, stability, and targeted delivery of bioactive compounds. The integration of natural and synthetic polymers further expands the potential of nanocapsules, paving the way for innovative advancements in bioactive encapsulation. The choice of polymer, encapsulation method, and surface modification strategy directly impact the

efficacy and practicality of the delivery system. Future research should focus on optimizing these parameters, exploring alternative biodegradable polymers, and conducting long-term *in vivo* studies to ensure clinical translation.

2.4.4 Lipid-based nanoparticles. Lipid-based nanocarrier systems, particularly solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs), have gained significant attention for their ability to enhance the stability, bioavailability, and therapeutic efficacy of lipophilic bioactive compounds.^{149,150} SLNs consist of solid lipids and surfactants, forming colloidal particles ranging from 10 to 1000 nm, and serve as an efficient delivery strategy for corrective dynamic therapy and water-soluble medication.¹⁵¹ In contrast, NLCs contain an aqueous phase with surfactants and an unstructured solid lipid matrix, typically comprising a solid-to-liquid lipid ratio of 70:30 to 99:9:0.1, with surfactant concentrations between 1.5% and 5% (w/v).¹⁵⁰ Various techniques, including ultrasonication, solvent evaporation, solvent emulsification-diffusion, and supercritical fluid methods, are employed for their synthesis.¹⁵²

Liposoluble nutraceuticals, including carotenoids, vitamins A, D, and E, omega-3 fatty acids, and essential oils, are compatible and miscible with the lipid matrix used in these nanovehicles.^{153–155} For instance, researchers have improved the physicochemical stability of β -carotene by encapsulating it within WPI-stabilized SLNs containing palmitic acid and corn oil. The palmitic acid crystals developed a protective shell around the oil droplets' surface, enhancing the oxidative stability, while WPI contributed to colloidal stability. This strategy highlights the potential of SLNs in improving the shelf life and bioavailability of carotenoids in functional foods and supplements.¹⁵⁶

Another promising nutraceutical, lutein, acts as a free radical scavenger and blue light filter, making it a valuable candidate for skincare applications.^{157,158} Researchers formulated lutein into SLNs, NLC, and NEs using a high-pressure homogenization technique, with particle sizes ranging from 150 to 350 nm.¹⁵⁹ NEs exhibited the highest *in vitro* release of lutein among the three forms. The study underscored the potential of these nanocarriers as novel antioxidants and



photoprotective agents, capable of shielding the skin from blue-light induced oxidative stress and photodamage.¹⁵⁹

In another study, ergocalciferol (vitamin D₂) was encapsulated in tripalmitin-based SLNs stabilized with Tween 20 using a nozzle-type high-pressure homogenizer and the hot homogenization method. The SLN dispersion, formulated with 5% w/w ergocalciferol, exhibited particle sizes between 65 and 120 nm, depending on the vitamin concentration. The outcomes indicated that the higher vitamin D₂ concentrations enhanced the stability of the lipid crystal structure, improving protection against oxygen and light exposure. This approach presents an alternative delivery strategy for vitamin D₂ in functional foods, such as fortified milk and margarine, though further studies are needed to ensure sustained bioavailability post-ingestion.¹⁶⁰

Beyond nutraceuticals, SLNs have also been explored for their therapeutic applications. One study focused on improving the intestinal permeability and bioavailability of γ -tocotrienol (γ -T₃), a member that belongs to the vitamin E family with limited absorption due to its lipophilicity.^{161,162} Encapsulation of γ -T₃ in SLNs *via* the solvent evaporation technique led to a marked enhancement in oral bioavailability by increasing passive permeability, as confirmed by *in vivo* investigations. However, the study emphasized the need for further optimization to maximize absorption efficiency and metabolic stability.¹⁶²

The therapeutic potential of lipid nanocarriers extends to cancer treatment. Researchers developed quercetin-encapsulated SLNs employing stearic acid and tripalmitin, stabilized with Tween 80 and Span 80, and optimized their formulation using the Box-Behnken design approach.¹⁶³ The resulting SLNs exhibited spherical shapes with a reduced particle size of 132 nm and outstanding EE% of 98%, facilitating gradual release of quercetin for up to two days. Furthermore, the *in vitro* cytotoxicity investigations conducted on the Caco-2 cell line at IC₅₀ of 49 μ M ml⁻¹ demonstrated the therapeutic effectiveness of quercetin-loaded SLNs by inducing apoptosis along with minimal necrosis and oxidative stress in the cancer cells. However, challenges such as large scale production, long-term stability, and *in vivo* biodistribution remain areas for future research.¹⁶³

Overall, SLNs and NLCs offer a versatile platform for the delivery of nutraceuticals and therapeutics, with applications ranging from functional foods to cancer therapy. Despite their advantages, challenges such as scale-up feasibility, long-term stability, and precise control over drug release kinetics must be addressed. Future research should focus on optimizing formulation parameters, improving biocompatibility, and conducting extensive *in vivo* studies to validate their efficacy and safety for clinical applications.

2.5 Nanocrystals

Nanocrystals are nanosized formulations composed of drug particles stabilized using appropriate stabilizers or surfactants, which typically fall within the nanometre size range, often between a few nanometres and 1000 nm.¹⁶⁴ These nanocrystals are often formulated as nanosuspensions by dispersing them in an aqueous medium.¹⁶⁵ Unlike polymeric or lipidic

nanoparticles, nanocrystals consist entirely of the active pharmaceutical ingredient or nutraceutical molecule, offering a pure drug delivery system. Their synthesis involves either the application of high-energy size reduction techniques to macro-sized drug dispersions in the presence of stabilizers or precipitation of the drug from an organic solvent upon the addition of an aqueous solution of surfactant or stabilizer.¹⁶⁶

Recent studies have demonstrated the potential of nanocrystals in improving the bioactivity and stability of various bioactive compounds. For instance, Akhlagi *et al.* encapsulated vitamin C (VC) in cellulose nanocrystals grafted with chitosan oligosaccharide *via* ionic complexation with tripolyphosphate. This formulation significantly improved the stability and free radical scavenging activity of VC. Notably, these nanocrystals exhibited encapsulation efficiencies of 72% and 91% at pH 3 and 5, respectively. These findings underscore the potential of nanocrystals in preserving the functionality of antioxidant molecules; however, further investigation into their long-term stability and release kinetics is warranted.¹⁶⁷

Similarly, another notable study investigated the synthesis of quercetin-loaded-cellulose nanocrystals (QCT-CNCs) derived from celery stalks. Morphological analysis using FESEM and TEM revealed spherical nanocrystals with a reduced particle size from 600 nm to 400 nm.¹⁶⁸ X-ray diffraction analysis confirmed the successful hydrolysis of the cellulose, and FTIR analysis indicated reduced crystallinity due to quercetin-cellulose interactions. Furthermore, binding affinity studies with human holo transferrin (HHT) demonstrated fluorescence quenching, confirming the interaction between QCT-CNCs and HHT. These findings suggest that QCT-CNCs represent a promising nanocarrier delivery strategy for quercetin and other bioactive compounds. However, challenges such as optimizing drug loading efficiency, stability, and *in vivo* bio-distribution requires further investigation.¹⁶⁸

Beyond preserving the natural structure and bioactivity of nutraceuticals, nanocrystals also aid in improving the therapeutic index of various bioactive compounds. One such study by Ndong Ntoutoume *et al.* explored the application of curcumin-loaded-cyclodextrin/cellulose nanocrystals (Cur-CdxCNS) for the treatment of colorectal and prostate cancer. These nanocrystals were prepared *via* ionic association with cationic β -cyclodextrin (CD). The *in vitro* assessments demonstrated promising anti-cancer activity on colorectal and prostatic cell lines, although the study was limited by the absence of *in vivo* validation, highlighting the necessity for further preclinical evaluation to assess its pharmacokinetics and therapeutic efficiency.¹⁶⁹

Delving further into the therapeutic potential of nanocrystals, Manca *et al.* synthesized quercetin nanosuspensions *via* the wet medium milling technique, employing Tween 80 and Poloxamer 188 as stabilizers for treating skin disorders.¹⁷⁰ The resulting quercetin nanocrystals, characterized by DSC, FTIR, and X-ray powder diffractometry, exhibited mean particle diameters ranging from 326 to 474 nm with a PDI below 0.30. This nanosizing approach significantly improved the solubility and bioavailability of quercetin, enhancing its potential for treating skin disorders. *In vitro* evaluations utilizing keratinocytes confirmed its dermatological applications; however,



further clinical studies are required to determine its efficacy in human subjects and assess potential cytotoxicity concerns at higher concentrations.¹⁷⁰

While nanocrystals offer a versatile platform for enhancing drug solubility, stability, and bioavailability, several limitations must be addressed before their clinical translation. These include the need for comprehensive pharmacokinetic studies, optimization of large-scale production techniques, and assessment of potential toxicity associated with prolonged exposure. Future research should emphasize refining nanocrystal formulations for targeted delivery, controlled release, and enhanced therapeutic outcomes in diverse biomedical applications.

3 Navigating the pros and cons of nanocarriers

Nanoformulations provide significant advantages for the encapsulated nutraceuticals, including enhanced bioavailability, improved physicochemical stability, targeted delivery, controlled release, protection against photodegradation, thermal, and oxidative degradation.^{171,172} Their nano-size enables superior drug delivery efficiency compared to conventional formulations, facilitating improved therapeutic outcomes. Given these attributes, nanoformulations hold immense potential as preventive and therapeutic alternatives for various diseases such as cancer, diabetes, ocular diseases, neurodegenerative disorders, NAFLD, cardiovascular diseases, obesity, mucositis, and many more.^{173–181}

Despite their numerous merits and potential applications, concerns regarding their safety, environmental impact, and biocompatibility are ambiguous. The reduced particle size of the nanoparticles, liposomes, niosomes, and nanocrystals increases their surface reactivity, potentially contributing to undesirable interactions in the biological systems, cytotoxicity, and other adverse health problems.¹⁸² The different materials used in nanoformulation development, such as polymers, surfactants, cross-linkers, solvents, drugs, and probes, pose additional risks, including cytotoxicity and hemotoxicity. Furthermore, there is a lack of comprehensive, evidence-based studies addressing the long-term toxicity, absorption, clearance, and biodistribution of nutraceutical-loaded nanoformulations in biological systems, contributing to concerns regarding their safety profile.^{54,91,92} Another critical challenge is the stability of nanoformulations during storage and transportation. Nanoparticles are prone to aggregation and degradation due to environmental conditions, which can significantly compromise their efficacy.¹⁸³ Additionally, the high production cost associated with nanoformulations, driven by the requirement for sophisticated technology, specialized equipment, and stringent manufacturing conditions, limits their large-scale commercialization.¹⁸⁴ Regulatory challenges further complicate the widespread adoption of nanoformulations. The absence of standardized guidelines and discrepancies among regulatory authorities has created inconsistencies in evaluating the safety and efficacy of these formulations.¹⁸⁵ Consequently, extensive preclinical and clinical

investigations are necessary to establish their therapeutic potential, prolonging the approval process and delaying market entry. Table 5 illustrates a comparative analysis of different nanoformulations discussed in this review based on their production cost, scalability concerns, regulatory challenges, and environmental impact.

4 Regulatory considerations and limitations

The integration of nanotechnology in nutraceuticals necessitates stringent compliance and safety regulations to protect consumers and maintain public confidence.^{195,196} However, the current global landscape lacks standardized, mandatory legal frameworks specifically governing nano-encapsulated nutraceutical products.¹⁹⁷ Consequently, major global regulatory authorities such as the United States Food and Drug Administration (USFDA), the European Chemical Agency (ECHA), the European Food Safety Authority (EFSA), and the World Health Organization (WHO) have introduced comprehensive guidelines and frameworks to regulate nanotechnology applications in nutraceuticals worldwide.¹⁹⁸ In 2021, EFSA established a structured risk assessment approach for nanomaterials in numerous food and feed products, emphasizing physicochemical characterization, scientific evaluation procedures, transparency in regulatory communication practices, and active stakeholder engagement through public consultations.¹⁹⁹ Similarly, in 2022, the USFDA issued guidance on key regulatory considerations, including quality assurance, manufacturing protocols, safety assessment, characterization techniques, analytical validation, risk management strategies, and regulatory submission requirements of nano-based drug and biological products, ensuring transparency in procuring new materials, addressing ethical and environmental issues, and promoting international trade and conformity worldwide.²⁰⁰ ECHA governs nanomaterials under the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulation, yet its adaptation to nano-specific risks remains a challenge due to the evolving nature of nanotechnology.²⁰¹ WHO, recognizing the increasing global reliance on nanotechnology, has recommended a risk-based regulatory framework that incorporates both hazard identification and lifecycle assessments of nano-nutraceuticals, addressing potential long-term implications, bioaccumulation risks, and environmental impact in humans.^{202,203} WHO also emphasizes the need for interdisciplinary research collaborations, promoting the integration of nanotechnology risk management strategies into global public health policies.²⁰⁴

International initiatives have been launched to harmonize risk assessment methodologies to enhance regulatory oversight and ensure the development of standardized testing protocols. The 'Malta Initiative' fosters collaboration between ECHA, Member States, the European Commission, and industry to refine test guidelines that address nano-specific regulatory requirements.^{205,206} Similarly, the Horizon 2020-funded Nano-Harmony project aims to accelerate the development of



Table 5 Comparative analysis of different nanoformulation strategies

Nanoformulations	Production cost	Scalability	Regulatory complexity	Environmental impact	Ref.
Nanogels	High due to the need for specialized polymers and cross-linking agents	Complex synthesis may hinder large-scale manufacturing	Limited clinical data may delay regulatory approval	Potential environmental persistence raises concerns	186 and 187
Nanoemulsions	Moderate due to the utilization of relatively straightforward manufacturing techniques	Amenable to industrial-scale production due to established emulsification methods	Generally safe, but novel formulations still require comprehensive evaluation	Generally considered eco-friendly depending on constituent materials	187 and 188
Liposomes	Substantial costs as they incorporate high-purity phospholipids and necessitate stringent production conditions	Feasible but requires meticulous control over size and encapsulation efficiency	Several FDA-approved liposomal drugs exist; however, new formulations must undergo rigorous testing	Biodegradable components minimize environmental risks	189–191
Niosomes	Cost-effective alternative to liposomes as they employ non-ionic surfactants	Simpler preparation methods facilitate scalability	Face uncertain regulatory pathways as they are emerging carriers	Biocompatibility suggests low ecological impact	189 and 190
Nanoparticles	Cost is determined by the materials used for production. For instance, gold nanoparticles are notably more expensive than polymeric nanoparticles	Scalability is material-dependent. For instance, polymeric nanoparticles are generally easier to produce in bulk compared to metallic ones	Concerns about toxicity and long-term effects necessitate extensive safety assessments	Non-biodegradable variants, such as certain metals, may accumulate in ecosystems, leading to potential toxicity	189, 192 and 193
Nanocrystals	Moderate to high costs due to the involvement of sophisticated crystallization techniques	Challenges in controlling crystal size and purity can impede large-scale production	Regulatory bodies require detailed characterization and proof of stability	Environmental effects are largely material-specific and require thorough investigation	188, 191 and 194



harmonized test methods by aligning research institutions with the OECD and ECHA.^{207,208} The ‘MACRAMÉ Project’, an initiative between the European Green Deal and Chemical Strategy for Sustainability, is intended to ensure the safety and sustainability of advanced materials such as carbon nanofibers, polymeric nanoparticles, *etc.*, by developing standardized methodologies for their detection, characterization, and risk assessment throughout their life cycle.²⁰⁹ Complementing traditional toxicity assessments, computational modeling techniques, including quantitative structure–activity relationships (QSARs) and read-across frameworks, are being increasingly adopted to predict nanomaterial behaviour based on existing datasets. Organizations such as OECD, ECHA, and EFSA are actively supporting research efforts to advance these predictive modeling approaches, thereby improving the efficiency and reliability of safety evaluations. These initiatives collectively contribute to a more robust regulatory landscape, facilitating transparent risk assessments, promoting scientific advancements, and ensuring the safe integration of nanotechnology into nutraceutical applications.^{210,211}

Despite significant advancements in regulatory guidelines, several gaps persist in understanding the long-term safety implications of nano-encapsulated nutraceutical products in biological systems, potentially contributing to ambiguities in risk assessments and insufficient safety measures. The rapid evolution of nanotechnology further complicates regulatory adaptation, rendering guidelines susceptible to obsolescence.²¹² The absence of a globally unified regulatory environment exacerbates these challenges, as discrepancies between international regulatory bodies result in inconsistencies in the requirements and standards imposed.²¹³ This regulatory fragmentation leads to duplicity, market barriers, and potential discrepancies in product safety and quality across different jurisdictions. Furthermore, while current regulatory frameworks prioritize human and animal health, the potential environmental impact of nanomaterials remains an underexplored domain.²¹⁴ The fate of nanoformulations in ecosystems, their bioaccumulation potential, and their long-term environmental interactions require systematic evaluation to prevent unforeseen ecological consequences. Addressing these challenges necessitates dynamic and evolving standards of regulatory mechanisms that can adapt to new emerging technologies and scientific enlightenment.

A multifaceted approach must be adopted to enhance the effectiveness of regulatory oversight in nanonutraceuticals. A key priority is harmonizing global standards, which requires a collaborative effort among international regulatory bodies to establish unified guidelines. Furthermore, advancements in risk assessment methodologies are essential to accurately evaluate the interactions of nanomaterials at both molecular and systemic levels. The development of advanced toxicological models and *in vitro/in vivo* studies is needed to assess nanomaterial interactions at the molecular and systemic levels. Regulatory bodies must integrate continuous scientific advancements to ensure relevance and efficacy in risk management.

5 Conclusion and future perspectives

Nutraceuticals and dietary supplements play a pivotal role in promoting health and preventing various chronic conditions, including cardiovascular diseases, neurodegenerative disorders, dermatological problems, cancer, NAFLD, ocular diseases, and inflammatory conditions. However, their clinical efficacy is often limited by inherent physicochemical drawbacks such as low bioavailability, high susceptibility to environmental degradation (light, oxygen, and temperature), instability during storage and delivery, and poor aqueous solubility. Nanotechnology has emerged as a transformative strategy in the food and pharmaceutical industries, offering solutions that enhance the bioavailability, stability, and controlled release of nutraceuticals encapsulated in nanocarriers enhancing their biological efficacy. Despite many significant advantages of nano-enabled strategies, several challenges hinder their widespread adoption, including scalability constraints, the requirement of sophisticated equipment, potential toxicity concerns, regulatory ambiguities, and environmental impact. This comprehensive review underscores the applications of nanotechnology in nutraceutical delivery, demonstrating how polymeric and lipid-based nanocarriers facilitate targeted and controlled release of bioactives. The utilization of GRAS biopolymers, including chitosan, alginate, lignin, zein, and casein, further ensures safety, biodegradability, and non-toxicity, making nanotechnology a viable approach for nutraceutical delivery. Additionally, this review critically evaluates existing regulatory frameworks, highlighting the need for harmonized guidelines, robust safety assessments, and transparent policies to enable the integration of nanotechnology into the nutraceutical industry.

Advancements in nanotechnology continue to open new frontiers in nutraceutical delivery. Future research should focus on the development of sustainable nanocarriers derived from eco-friendly, biodegradable polymers to mitigate environmental concerns. Innovations in biopolymeric nanoparticles present significant potential for improving targeted delivery under conditions such as NAFLD, cardiovascular diseases, and metabolic disorders. Additionally, nanogels and nano-emulsions hold promise for transdermal and ocular delivery of nutraceuticals, enhancing the therapeutic efficacy for eye and skin disorders. Emerging technologies such as artificial intelligence (AI) and machine learning are set to revolutionize nanocarrier design by optimizing formulation parameters, predicting stability and encapsulation efficiency, and improving drug release kinetics. AI-driven models can accelerate the development of next-generation nanocarriers by simulating interactions between encapsulated nutraceuticals and biological systems, thus reducing reliance on extensive *in vivo* experimentation. The integration of AI and sustainable materials in nanocarrier development not only enhances the efficacy and safety of nutraceutical delivery systems but also paves the way for more cost-effective, scalable, and environmentally responsible solutions. Moreover, the integration of wearable biosensors with nanotechnology could enable real-time monitoring of



nutraceutical delivery and metabolic responses, facilitating personalized nutrition and precision medicine approaches. With increasing concerns about nanotoxicity and environmental impact, future research should focus on the development of biodegradable smart nanocarriers composed of bioresorbable polymers to ensure safe degradation and minimal ecological footprint. Expanding beyond conventional drug delivery, stimuli-responsive nanocarriers could be tailored for precise gene editing and RNA-based therapies. These systems could enhance CRISPR-Cas9 and siRNA delivery, enabling targeted genetic interventions with minimized off-target effects. The combination of microfluidic nanocarrier synthesis with organ-on-a-chip platforms could accelerate preclinical validation of nanoformulations, reducing the reliance on animal studies and improving translational research outcomes.

To further advance nanotechnology-based nutraceuticals, interdisciplinary collaboration among materials scientists, biotechnologists, regulatory bodies, and industry stakeholders is imperative. Addressing regulatory challenges, ensuring scalability, and prioritizing safety assessments will be crucial for translating laboratory-scale innovations into commercial products. In conclusion, nanotechnology holds immense potential to revolutionize nutraceutical formulations, paving the way for enhanced therapeutic efficacy, precision-targeted interventions, and sustainable health solutions.

Abbreviations

PUFA	Polyunsaturated fatty acids
CAGR	Compound annual growth rate
GRAS	Generally recognized as safe
SPI	Soy protein isolate
ARPI	Acyated rapeseed protein isolate
WPI	Whey protein isolate
BSA	Bovine serum albumin
PLGA	Poly(lactic-co-glycolic acid)
PCL	Poly-ε-caprolactone
PLA	Poly(lactic acid)
PAMAM	Poly(amidoamine)
γ-PGA	γ-Polyglutamic acid
TNF-α	Tumor necrosis factor alpha
NE	Nano-emulsion
SIRT1	Sirtuin 1
VK ₁	Vitamin K ₁
VD ₃	Vitamin D ₃
PDI	Polydispersity index
EE	Encapsulation efficiency
AcKPI	Acyated kidney bean protein isolate
PoV	Peroxide value
TARS	Thiobarbituric acid reactive substances
ATRA	All-trans retinoic acid
DCP	Dicetyl phosphate
Chol	Cholesterol
HLB	Hydrophilic-lipophilic balance
ZP	Zeta potential
SFPI	Sunflower seed protein isolate

NPs	Nanoparticles
β-CG	Soy-β-conglycinin
IC ₅₀	Half-maximal inhibitory concentration
SDS-PAGE	Sodium dodecyl sulphate polyacrylamide gel electrophoresis
DPPH	2,2-Diphenyl-1-picrylhydrazyl
CS-NPs	Chitosan nanoparticles
B-CS-NPs	Biotin chitosan nanoparticles
AIA	Anti-inflammatory activity
A-B-CS-NPs	Biotin and avidin chitosan nanoparticles
BLG	β-Lactoglobulin
Cap-LF-CMD	Capsaicin-encapsulated lactoferrin-
EA-NPs	functionalized carboxymethyl dextran-coated egg albumin NPs
NAFLD	Non-alcoholic fatty liver disease
LE	Loading efficiency
GSH	Glutathione
SIL/BSA NPs	Silibinin bovine serum albumin nanoparticles
APAP	Acetaminophen
LPS/D-GaIN	Lipopolysaccharide/D-galactosamine-induced acute liver injury
CTLs	Cytotoxic T lymphocytes
MRT	Mean retention time
Cap-HA/PLA-NPs	Capsaicin loaded hydroxyapatite and polylactic acid NPs
TEM	Transmission electron microscope
PEG	Polyethylene glycol
Cur	Curcumin
RA	Retinoic acid
HCT116	Human colorectal carcinoma cell line
ARPE-19	Human retinal pigment epithelial cell line dopaminergic
RA-NPs	Retinoic acid nanoparticles
m-PEG- <i>b</i> -PCL	Copolymer m-PEG- <i>b</i> -PCL nanocapsules
NCs	
MPTP	1-Methyl-4-phenyl-1,2,3,6-tetrahydropyridine
SN	Substantia nigra
PD	Parkinson's disease
AST	Aspartate aminotransferase
ALT	Alanine aminotransferase
ALP	Alkaline phosphatase
AFP	α-Fetoprotein
Bcl2	B-cell lymphoma 2
HCC	Hepatocellular carcinoma
Na-CMC	Sodium carboxymethylcellulose
OSA	Octenyl-succinic-anhydride
α-T NCs	α-Tocopherol-loaded nanocapsules
SLNs	Solid lipid nanoparticles
NLCs	Nanostructured lipid carriers
γ-T3	γ-Tocotrienol
VC	Vitamin C
Cur-CdxCNs	Curcumin-loaded-cyclodextrin/cellulose nanocrystals
CD	β-Cyclodextrin
DSC	Differential scanning calorimetry
FT-IR	Fourier transform infrared spectroscopy
QCT-CNCs	Quercetin-loaded-cellulose nanocrystals
HHT	Human holo transferrin
USFDA	United States Food and Drug Administration



Review

ECHA	European Chemical Agency
EFSA	European Food Safety Authority
WHO	World Health Organization
REACH	Registration Evaluation Authorisation and Restriction of Chemicals
OECD	Organization for Economic Cooperation and Development
QSARS	Quantitative structure–activity relationships
AI	Artificial intelligence

Data availability

No primary research results have been included and no new data were generated as part of this review.

Author contributions

JM: collection of the information, drafting of the manuscript, and writing review; KP: writing review; SVP: data curation; conceptualization, planning, analysis, review, and editing. All authors approved the final submitted version of the manuscript.

Conflicts of interest

None.

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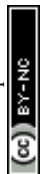
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