RESEARCH PAPER

Nano-Encapsulation of Nutrients for Enhanced Bioavailability: Innovations in Functional Food Delivery Systems

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Abstract

The increase in the demand of functional foods that have superior health advantages has heightened the research on the enhancement of the bioavailability of nutrients and bioactive components. Numerous nutraceuticals, however, (vitamins, minerals, polyphenols, lipophilic compounds) have poor stability, low solubility and low gastrointestinal bioavailability, which underlies significantly limits their functional efficacy. Nano-encapsulation has proven to be a potential solution to address these restrictions by encapsulating bioactive compounds into nanoscale systems that increase their stability, dispersibility, and controlled release. This review has thoroughly covered the nano-encapsulation technologies of enhancing bioavailability of nutrients in functional foods systems. Several food-grade materials, such as lipids, proteins, polysaccharides and hybrid composites, are addressed in terms of their encapsulation efficacy and delivery behavior. The types of nano-delivery systems, including nanoemulsions, liposomes, solid lipid nanoparticles, polymeric nanoparticles, and nanogels are discussed, as well as the methods of creating them and their effects on the features of the systems. Particular attention is paid to the processes of the improved bioavailability, such as the increased solubility, gastrointestinal stability, bioaccessibility, and cellular uptake. Various examples of nano-encapsulation applied to the various types of nutrients are also discussed that illustrate its potential in improving the functional properties of vitamins, minerals, polyphenols and other bioactives. Moreover, innovative developments of smart delivery systems, sustainability methods, and nano-enriched foods are discussed. These developments notwithstanding, issues of safety, regulatory systems, scalability and consumer acceptance are also critical issues to consider. In general, nano-encapsulation is a revolutionary method in creating the next generation of functional foods that have enhanced nutritional effectiveness and health-related benefits.

Keywords: Nano-encapsulation; Bioavailability; Functional foods; Nutraceuticals; Nano-delivery systems

How to cite this article: Varma S, Patil M, Husein N, Rao R, Prabhat A, Patel D, Gandhi B. Nano-Encapsulation of Nutrients for Enhanced Bioavailability: Innovations in Functional Food Delivery Systems. Int J Drug Deliv Technol. 2026;16(59s): 1693-1706. DOI: 10.25258/ijddt.16.59s.194

Source of support: Nil

Conflict of interest: None

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1. Introduction

Over the last several years, the paradigm shift of the traditional nutrition towards the health-related dietary approach has taken place, which is why the functional food and nutraceutical markets have grown very rapidly. Functional foods are meant to supply nutrients as well as bioactive compounds that enhance health, lower the prevalence of chronic diseases, and complement physiological processes. Extensively studied are the antioxidant, anti-inflammatory, cardioprotective, and immunomodulatory effects of these bioactives: vitamins, minerals, polyphenols, carotenoids, fatty acids, and bioactive peptides. Nevertheless, their well-known health advantages are frequently restricted by their low oral bioavailability and unsatisfactory physicochemical stability, which greatly limit their practical utility when ingested by food systems[1,2].

Bioavailability is a multi-faceted, multi-stage process which entails the liberation of nutrients within the food mass, their conversion during digestion, diffusion across

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the intestinal epithelium, and their transport into the systemic circulation. The factors affecting this process include intrinsic factors like the molecular structure, polarity and solubility of the compound and extrinsic factors such as food composition, processing conditions, and gastrointestinal environment. Nutraceutical compounds, especially lipophilic and phenolic molecules have low aqueous solubility, are easily degraded by environmental factors (light, oxygen, temperature and pH) and have a low permeability across intestinal membranes. Consequently, the bioactives ingested pass through the digestive tract in significant proportions due to elimination by degradation or excretion before absorption or without biological actions[3,4].

Nanotechnology has come up to address these shortcomings and it has become a revolution in food science especially in the creation of nano-encapsulation systems. Nano-encapsulation is a process that entraps or incorporates bioactive compound into the carriers at the nanometer level, usually 1-1000 nm. At this level, materials have special physicochemical characteristics, namely higher surface area, greater reactivity, as well as better interaction with biological membranes. These properties allow nano-carriers to avoid the destruction of delicate nutrients, enhance their solubility and dispersion in aqueous systems, and their targeted release under defined physiological conditions. As a result, nano-encapsulation is an important factor in enhancing bio accessibility (availability to absorption) and bioavailability (degree of absorption and use) of functional food components[5,6].

Nano-delivery systems with a wide range of structural characteristics and functional benefits have been designed to be applied in functional foods. They are nanoemulsions, liposomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), polymeric nanoparticles, nanogels, and self-assembled micellar systems. Lipid-based systems are specially useful in the encapsulation of hydrophobic compounds, whereas protein- and polysaccharide-based carriers possess the added benefit of biodegradability, biocompatibility and food-grade safety. The choice of a suitable delivery system varies depending on various factors, such as the physicochemical characteristics of the bioactive compound, the desired release kinetics, stability needs, and compatibility with the target food matrix. In addition, the development of bio-manufacturing has made it possible to use natural biopolymers and food-based materials as encapsulation matrices, which increase the sustainability and safety of these systems[7,8].

Recent technological breakthroughs have further advanced the field to the next generation of nano-delivery systems that will have increased functionality. These involve intelligent and stimuli-reactive systems that can release nutrients based on environmental signals like PH variations, enzymatic activity or gastrointestinal factors. Also, hybrid nanocarriers consisting of two or more materials (e.g., lipid -polymer or protein -polysaccharide) have been produced to obtain synergistic effects, e.g., enhanced encapsulation efficiency, stability and targeting delivery. The idea of nano-fortified foods has not been left out either and nano-encapsulation has been applied to enrich the nutritional value of food products without affecting the sensory properties of the food products. These kinds of innovations already open the path to precise nutrition and customised dietary treatments, in which the provision of nutrients can be adjusted to the specific physiological requirements of the person[9,10].

Although the idea of nano-encapsulation technologies is promising, there are a number of challenges associated with their use in functional foods that need to be well considered. The issue of safety involved in ingesting nanoparticles, toxicity possibility, and the health consequences in the long run is a significant concern and requires in-depth toxicological analyses. Moreover, the regulatory systems in use of nanomaterials in food systems are not yet fully developed and differ depending on the regions, which poses challenges to commercialization. Other issues are the scalability of the nano-encapsulation processes, cost-effectiveness, storage stability, and the acceptance of nanotechnology-based food products by consumers. These obstacles must be overcome to make laboratory-scale innovations become commercially viable and widely adopted functional food products[11].

It is against this backdrop that the current review seeks to present a comprehensive and systematic review of the nano-encapsulation approaches to improving nutrient bioavailability with a specific focus on the recent advances in functional food delivery systems. The review is a critical analysis of various forms of nano-carriers, encapsulation materials and methodologies, the principles of bioavailability promotion, and their uses in diverse classes of nutrients and bioactive compounds. Moreover, it addresses existing issues, safety issues and future outlook, to inform the creation of efficient, safe and sustainable nano-enabled functional food systems.

The specific objectives of this review are:

1. To critically analyse various nano-encapsulation systems and materials used for the delivery of nutrients and bioactive compounds in functional foods.
2. To evaluate the mechanisms by which nano-encapsulation enhances bioavailability, including improvements in stability, solubility, bioaccessibility, and controlled release behaviour.
3. To highlight recent innovations, applications, and challenges associated with nano-enabled functional food delivery systems, with an emphasis on safety, scalability, and future research directions.

2. Bioavailability Challenges of Nutrients in Functional Foods

2.1 Concept of Bioavailability and Bio accessibility

One of the determinants of the nutritional and functional efficacy of bioactive compounds used as functional foods is bioavailability. It is the percentage of an ingested nutrient that is absorbed via the gastrointestinal tract, into systemic circulation, and made available to physiological action. Intimately linked to this notion is bioaccessibility, which is the proportion of a compound that is liberated during food digestion and can be absorbed. These two parameters are dependent on each other, and they are the joint determinants of the efficiency of nutrient use in the human body. Notably, the fact that bioactive compounds occur in foods does not necessarily imply that they are effective since various physicochemical and biological obstacles can restrict their absorption and metabolic accessibility[12].

2.2 Physicochemical Factors Limiting Bioavailability

The bioavailability of nutrients is greatly affected by the intrinsic physicochemical characteristics of the nutrients. Most bioactive substances, especially polyphenols, flavonoids and fat-soluble vitamins are not well soluble in aqueous solutions, and this limits their dispersion within gastrointestinal fluids and their absorption. Also, molecular size, structural complexity and polarity are important factors in controlling permeability across intestinal membranes. Another significant issue is chemical instability, with numerous compounds being very sensitive to oxidation, hydrolysis, and thermal degradation. As an example, phenolic compounds can be quickly degraded by physiological and environmental factors, leading to decreased biological activity and loss of functional efficacy when added to food systems[13].

2.3 Influence of Food Matrix on Nutrient Release

The food matrix on which bioactive compounds are incorporated is very critical in controlling their release and consequent bioavailability. In the case of nutrients and macromolecules like proteins, lipids and polysaccharides, when they interact, they form complex structures that trap bioactives, hence reducing their release during digestion. Such reactions are capable of changing the physicochemical environment of the compounds, turning their solubility, stability, and accessibility. The food matrix can be found to increase the bioavailability in certain situations, by causing an easier emulsification or micelle formation, whereas in other scenarios, the food matrix can serve as a barrier that limits nutrient release and absorption. Thus, the knowledge of the interactions between the matrices and nutrients is critical to the development of efficient delivery in functional foods[14].

2.4 Gastrointestinal Barriers to Nutrient Absorption

The gastrointestinal tract is a dynamic environment, which is extremely challenging to nutrient stability and absorption. Bioactive compounds are subjected to different pH levels, digestive enzymes, and bile salts during the digestion process and may affect their chemical integrity and solubility. Sensitive compounds may be degraded in the acidic environment of the stomach and enzymatic activity in the intestine may alter their structure. Moreover, absorption via intestinal epithelial cells is frequently restricted by reduced permeability, efflux mechanisms and metabolic alterations. These physiological barriers have the potential to seriously diminish the proportion of bioactive compounds that finally arrive at systemic circulation[15].

2.5 Limitations of Conventional Delivery Approaches

Conventional methods of nutrient fortification into functional foods usually do not meet the issues of stability and bioavailability. Traditional delivery methods have normally not been designed to preserve bioactives against environmental and gastrointestinal breakdown, thus leading to significant losses during the processing, storage, and digestion. Moreover, they lack controlled or targeted release to these systems resulting in inefficient use of nutrients. Consequently, despite the fortification of functional foods with high concentrations of bioactive compounds, their physiological effects can still be minimal. This underscores the fact that more sophisticated strategies of delivery must be developed that can overcome these limiting factors[16].

2.6 Digestive Transformation and Absorption Constraints

Digestion is an important process of determining what happens to the nutrients in the body. After ingestion, bioactive compounds have to be released out of the food matrix, solubilized in the gastrointestinal fluids and integrated into mixed micelles, which are then able to penetrate the intestinal cells. This process is however less efficient with poorly soluble compounds, especially lipophilic molecules that cannot be absorbed unless they are digested by lipids and emulsified by bile. Also, changes in metabolism that take place in the intestinal wall and liver may further decrease the bioavailability of these compounds. All of these constraints in combination restrict the effectiveness of nutrient delivery and emphasize the difficulty of promoting the best bioavailability[17].

2.7 Stability Challenges During Processing and Storage

Besides the physiological barriers, nutrient stability is also lost in the process of food processing and storage. Sensitive bioactive compounds are sensitive to heat, oxygen, light, and moisture, which can cause degradation, loss of potency and functional value. To illustrate, flavonoids and other antioxidant molecules are especially prone to oxidative degradation, and some vitamins might become inactive during extended storage. These stability concerns not only affect the nutritional content of functional foods but also restrict the shelf life and commercial viability of these foods. Consequently, to safeguard bioactives over the whole lifecycle of food product, effective strategies are required[18].

2.8 Need for Advanced Nano-Delivery Systems

Due to the various obstacles that influence the nutrient bioavailability, there is a growing interest in the development of sophisticated delivery systems which can improve the stability, solubility and absorption of bioactive substances. The delivery systems based on nanotechnology provide a promising alternative as they can be used to encapsulate nutrients and package them in nanoscale-sized carriers that can protect against degradation, enhance dispersion in aqueous conditions, and release them under controlled conditions during digestion. These systems have also the potential to increase contact with biological membrane, and thus make them more efficient in absorption. Consequently, nano-encapsulation has become one of the main solutions to address the shortcomings of the traditional delivery method, as well as to improve the functionality of nutrients in food systems[19].

3. Food-Grade Materials for Nano-Encapsulation

3.1 Lipid-Based Materials

Lipid-based materials are one of the most actively researched and utilized types of nano-encapsulation carriers in functional food systems mainly because of high affinity to lipophilic bioactive compounds and improved solubilization and intestinal absorption. Among these materials are triglycerides, phospholipids, fatty acids, mono- and diglycerides and waxes, which are usually used in the creation of nanoemulsions, solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs). The lipid-based systems can be easily incorporated in their core and this can be attributed to the structure of the lipid-based systems, which facilitates the incorporation of the hydrophobic compounds in their core, making them easily dispersible in aqueous conditions. In the digestive process, lipid carriers are broken down enzymatically and give rise to mixed micelles which aid in the transportation of nutrients encapsulated in them through the intestinal epithelial lining. Lipid-based nanocarriers possess the ability to enhance solubility and offer a protective barrier against oxidative degradation, photodegradation and thermal instability that are typical of bioactive compounds like carotenoids, tocopherols, and omega-3 fatty acids. This versatility in the customization of lipid structure allows the size, crystallinity and kinetics of release to be controlled, providing a method of controlled or sustained nutrient delivery. Additionally, high biocompatibility and regulatory acceptance of food-grade lipids can be achieved, making such systems especially appropriate to be incorporated in beverages and dairy products as well as emulsified food systems. Nevertheless, other problems like lipid oxidation, polymorphic transitions, and stability in long-term storage should be well taken care to achieve optimal performance[20].

3.2 Protein-Based Materials

The availability of reactive functional groups and structural and physicochemical characteristics, such as amphiphilicity, conformational flexibility, and the presence of reactive functional groups, enable proteins to be a versatile and functional nano-encapsulation material. These features allow proteins to form a strong binding with a vast range of bioactive substances by hydrophobic interactions, hydrogen bonding, and electrostatic forces. Whey protein isolate and casein are both animal-derived proteins that have been used successfully in the creation of nanoparticulate delivery systems, as well as soy, pea, and legume proteins, which are plant-derived proteins. Depending on the processing conditions and environmental conditions such as pH and ionic strength, protein-based nanocarriers can take a variety of structures, such as nanoparticles, nanofibrils, nanogels and emulsifying layers. These systems have huge benefits in safeguarding encapsulated compounds against enzymatic and chemical breakdown especially during gastrointestinal passage. Moreover, the biodegradation of encapsulated nutrients can occur through the release of proteins by structural alterations and binding with digestive enzymes, which increases the bioavailability of the released proteins. A major benefit of protein-based systems is their nutritional value since they can be used concurrently as carriers of drugs and as nutritional elements. Moreover, recent advances of plant protein-based nanocarriers have been in line with the growing need in sustainable and plant based functional foods. Nevertheless, the potential issues that include protein denaturation, aggregation, and sensitivity towards processing conditions need to be tackled in order to preserve the structural integrity and encapsulation efficiency[21].

3.3 Polysaccharide-Based Materials

Polysaccharides are widely utilized in nano-encapsulation due to their excellent biocompatibility, biodegradability, and ability to form structurally diverse delivery systems. The typical polysaccharides applied in functional foods are chitosan, alginate, pectin, starch, carrageenan and derivatives of cellulose. Their materials show special rheological and gel-forming properties, and allow the optimization of nanoparticles, nanogels, as well as coating layers that are capable of efficiently entrap bioactive compounds and provide protection to them. Among the essential benefits of polysaccharide-based systems lies the fact that they can display stimuli-responsive behavior especially in reaction to pH and ionic environments in the gastrointestinal tract. As an example, carriers made of alginate can be stable gels in gastric acidic conditions and later release the encapsulated nutrients in the more neutral conditions of the intestine. Likewise, chitosan has mucoadhesive characteristics that increase the residence time of bioactive compounds in the intestinal tract, thus increasing the absorption efficiency. Polysaccharides also help in offering a physical shield that shields encapsulated compounds against oxidative, enzymatic, and environmental stressors during processing and storage. They are very ideal in functional food applications due to their ability to be compatible with a large variety of food matrices and their minimal effects on sensory properties. However, the differences in molecular weight, degree of substitution, and structural heterogeneity may affect their performance, and they have to be carefully selected and optimized to perform well in a particular applications[22].

3.4 Hybrid and Composite Materials

Hybrid and composite nano-encapsulation systems have been developed to be sophisticated delivery systems that combine the desirable characteristics of various material classes to realize the desired functionality. Such systems are usually built by assembling lipids, proteins, polysaccharides or synthetic nanomaterials to form multifunctional carriers that have enhanced encapsulation efficiency, stability and controlled release characteristics. The synergetic interplay of various elements makes possible designing carriers with specific physicochemical traits, including mechanical strength, better barrier qualities, and sensitivity to environmental signals. To illustrate, protein-polysaccharide complexes can be used to stabilize the structure and release the protein or polysaccharide in a controlled manner, possibly via a pH-sensitive release mechanism. Likewise, lipid-polymer hybrid systems merge the high loading capacity of lipid carriers and structural integrity and controlled release of polymeric matrices. Such hybrid systems are specifically useful in overcoming the drawbacks of the single-component carriers: instability, poor loading efficiency, or quick release. New opportunities in targeted delivery and multifunctional use, such as co-encapsulation of multiple bioactive substances and synergistic co-delivery of nutrients with others, are also presented by the development of composite nanocarriers. Although they have their advantages, their complexity of formulation and the challenges it may encounter in large-scale production need additional research and optimization to guarantee their viability in practical application in functional food systems[23].

3.5 Biogenic and Natural Nanomaterials

Biogenic and naturally available nanomaterials are increasingly being considered as sustainable options to nano-encapsulation in functional foods. Such materials are usually generated by the use of biological techniques or recovered by natural means, such as plants, microorganisms, and food waste. They are naturally low-toxic, biodegradable, environmentally compatible and aligned to clean-label trends in the food sector. Biogenic nanomaterials can be designed to be in the form of nanoscale delivery systems that have the potential to encapsulate a wide variety of nutrients and bioactive compounds (Table 1). An example of such is the natural protein nanoparticles, polysaccharide-based carriers, and mineral-based nanostructures, which have shown a lot of promise in improving the stability and bioavailability of nutrients. Also, the implementation of agricultural and food industry byproducts as the sources of encapsulation materials leads to the waste valorisation and sustainable use of resources. These materials are not only enhancing the performance of food ingredients encapsulated but also responding to increasing consumer demands of natural and eco-friendly food ingredients. Nevertheless, issues regarding standardisation, reproducibility, and mass production are the main concerns when their application should be extended[24].

Table 1: Food-Grade Materials Used in Nano-Encapsulation

Material Type	Examples	Functional Properties	Applications	References
Lipids	Triglycerides, phospholipids	Improve solubility, protect from oxidation	Vitamins, carotenoids	20, 5
Proteins	Whey, casein, soy protein	Emulsifying, biodegradable	Peptides, polyphenols	21
Polysaccharides	Chitosan, alginate, pectin	pH-responsive, gel-forming	Controlled release systems	22
Hybrid systems	Lipid–protein, protein–polysaccharide	Multifunctional, improved stability	Co-encapsulation	23
Biogenic materials	Plant-based nanomaterials	Eco-friendly, biodegradable	Sustainable delivery systems	24, 38

3.6 Criteria for Selection of Encapsulation Materials

When designing effective delivery systems of functional foods, the choice of appropriate materials to be used in nano-encapsulation is a critical step. Ideally, an encapsulation material must be biocompatible, biodegradable, non-toxic, and regulator-acceptable, especially when it is used in food. It must also offer the high encapsulation efficiency, prevent the degradation of bioactive compounds in the environment and gastrointestinal tract, and be capable of controlled or targeted release under certain physiological conditions. Such other considerations as being compatible with the physicochemical properties of the bioactive compound, stability during processing and storage, scalability of production, and having minimal effect on sensory properties (taste, texture, and appearance) are also important. An important factor is also economic feasibility since cost-effective materials and processes are needed to be commercially viable. Moreover, the chosen material must coincide with the consumers' preferences, especially concerning the natural origin and sustainability. Rational and application-specific choice of encapsulation materials is thus necessary to realise the successful development and commercialisation of nano-enabled functional food systems. Ongoing innovations in the field of material science and nanotechnology are likely to increase the list of materials that are available and improve their functionality in terms of bioactive compounds delivery[25].

4. Classification of Nano-Delivery Systems in Functional Foods

4.1 Nanoemulsions

One of the most common types of nano-delivery systems that has been used in functional foods is nano emulsions, since it can improve the solubility and stability of lipophilic bioactive compounds. The systems are commonly a mixture of oil and water phases that are stabilized by surfactants and the droplet sizes are 20 to 200 nm. The high dispersion of hydrophobic nutrients, like carotenoids, essential oils, and vitamins dissolved in water is highly enhanced by the large interfacial surface area provided by the small droplet size.

Nanoemulsions have high kinetic stability, which does not allow them to phase separate or settle and this property is especially desirable when attempting to incorporate such emulsions into beverages and functional foods based on liquids. Moreover, nanoemulsions help to enhance digestion by raising accessibility of lipids to digestive enzymes which leads to the development of mixed micelles and subsequent absorption of encapsulated compounds (Figure 1). They are also easily fabricated by high-energy or low-energy techniques, which further indicates their applicability in industry. Nevertheless, the difficulty in the form of the selection of surfactants, long-term stability, and environmental sensitivity should be overcome to achieve the best performance[26].

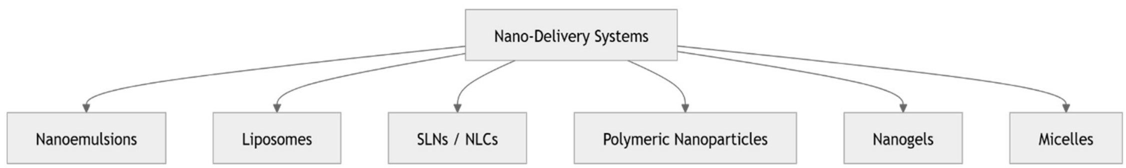

Figure 1 : Types of Nano-Delivery Systems

4.2 Liposomes and Nanoliposomes

Liposomes are vesicles made of phospholipid bi-layers with the ability to contain hydrophilic and lipophilic bioactive molecules in their aqueous core and lipid bilayer, respectively. At nanoscale size, they are known as nanoliposomes and find special use in functional food applications as they are biocompatible and structurally related to biological membranes. The liposome bilayer can offer a good protection against environmental degradation by as much as possible shielding sensitive nutrients like vitamins, enzymes and polyphenols against oxidation and enzyme degradation. In addition, liposomes are also capable of increasing the bioavailability of encapsulated compounds by increasing their interplay with cell membranes, thus increasing cellular intake. In spite of these strengths, liposomes are usually limited in terms of physical instability, leakage of compounds carried by the liposomes, and its high cost of production. Continued studies are being done to enhance their stability by coating approach and hybrid formulations[27].

4.3 Solid Lipid Nanoparticles (SLNs)

Solid lipid nanoparticles (SLNs) are nanoparticles made of solid lipids that are crystalline in their state at room and body temperature. The systems offer a stiff grid which is capable of entrapping bioactive compounds and shielding them against chemical degradation. SLNs are especially effective in the delivery of lipophilic nutrients, and the benefits it has are that it has a controlled release, enhanced stability and it can resist oxidation. The viscous lipid matrix minimises leakage and improves stability in shelf-life due to the solid nature of the lipid matrix, which reduces the mobility of encapsulated compounds. Furthermore, SLNs have the ability to tune release kinetics which enables the prolonged delivery of nutrients. Nonetheless, it has been limited due to low loading capacity and possibility of expelling bioactives during lipid crystallisation. These issues have resulted in the creation of more superior systems, including nanostructured lipid carriers (NLCs), that overcome some of these limitations.

4.4 Nanostructured Lipid Carriers (NLCs)

Nanostructured lipid carriers (NLCs) are a new generation of lipid-based delivery systems aimed at eliminating the drawbacks of SLNs. These systems are a blend of both solid and liquid lipids, which make the crystalline structure less organized, thereby increasing the loading capacity and stability of the encapsulated compounds. The lipid matrix is imperfect, which gives extra space to bioactive molecules to minimize the chances of expulsion during storage. NLCs provide a higher encapsulation rate, enhanced release profile control, and stability than SLNs. They are especially useful in the delivery of sensitive lipophilic substances and have demonstrated to be of great promise in enhancing bioavailability of nutraceuticals. They can be used in most types of functional food applications due to their versatility and adaptability, such as fortified dairy products and nutraceutical formulations[28].

4.5 Polymeric Nanoparticles

Polymeric nanoparticles consist of polymers, be it natural or synthetic, and are extensively employed in delivering bioactive compounds as they are structurally stable and can be delivered via controlled release. Natural polymers like polysaccharides and proteins are used in functional food applications because they are biodegradable and are safe. The nanoparticles can be designed to control particular release behaviour such as sustained, delayed or targeted release when environmental triggers are present. Polymeric systems provide excellent safeguards against environmental degradation and may enhance stability of sensitive compounds during process and storage. They can also be used to alter their surface properties to increase the interaction and adhesion with the intestinal cells and, therefore, increase absorption. Polymeric nanoparticles are very versatile since their physicochemical characteristics can be customised to deliver a variety of nutrients and bioactives[29].

4.6 Nanogels and Hydrogel Nanoparticles

Nanogels are crosslinked polymer networks in the form of 3-d nanoscaffolds which are able to absorb and retain a lot of water and still retain their structural integrity. The systems are also very applicable in encapsulating hydrophilic bioactive compounds and preserving them against degradation. Nanogels are made to respond to environmental stimuli, including pH, temperature, and ionic strength, due to their high water content and soft structure and, therefore, can be used in controlled and targeted delivery. Nanogels in functional food systems can be trained to deliver encapsulated nutrients in particular sites within the gastrointestinal system, to increase bioavailability. They can be released precisely due to environmental variations by swelling and shrinking, and control of kinetics. In addition, they are also biocompatible and have the least effect on sensory qualities, which is why they are appealing in food applications[30].

4.7 Micelles and Self-Assembled Nanostructures

Micelles are self-assembled colloidal particles composed of amphiphilic molecules in aqueous solutions, in which the hydrophobic parts cluster into a core, and the hydrophilic parts cluster into an outer shell. Such systems are especially useful in solubilizing poorly water-soluble compounds, and enhancing their bioavailability. Micellar systems are also important in improving the absorption of lipophilic nutrients in functional food applications as they will be incorporated in mixed micelles during the digestive process. Nanostructures that are self-assembled, such as casein micelles and systems based on surfactants, offer a natural and effective system of bioactive compound delivery. What is inherent with these systems is their simplicity, stability and the capacity to develop spontaneously in favorable conditions. Their application in the food systems is beneficial in that it can be used alongside naturally available ingredients and requires low processing levels[31].

4.8 Inclusion Complexes and Emerging Nano-Systems

Another significant category of nano-delivery systems, which are employed in the encapsulation of bioactive compounds, is inclusion complexes and especially those which are built around cyclodextrins. These systems are the entrapment of guest molecules within the hydrophobic cavity of host molecules, thereby enhancing solubility, stability, and bioavailability. Inclusion complexes particularly prove helpful with volatile, delicate, or insoluble compounds (Table 2). Along with the classic systems, there are new nano-delivery systems like multifunctional nanocarriers, co-encapsulation systems, and bio-inspired nanostructures, which are also being studied. These sophisticated systems are aimed at delivering a combination of bioactive at the same time, increasing synergistic effects, and offer target delivery. Nanotechnology application in food science is still advancing innovations in the field, resulting in the creation of more effective and advanced delivery mechanisms[32].

Table 2: Classification of Nano-delivery Systems Used in Functional Foods

Nano-Delivery System	Structure	Suitable Compounds	Advantages	Limitations	References
Nanoemulsions	Oil-in-water dispersions	Lipophilic compounds	Improved solubility, high stability	Surfactant dependency	26, 5
Liposomes	Phospholipid bilayer vesicles	Hydrophilic & lipophilic compounds	Biocompatible, dual encapsulation	Leakage, instability	27; 32
SLNs	Solid lipid core	Lipophilic nutrients	Controlled release, protection	Low loading capacity	20
NLCs	Solid + liquid lipid matrix	Sensitive bioactives	High loading, improved stability	Complex formulation	24
Polymeric nanoparticles	Polymer-based matrix	Polyphenols, proteins	Controlled release, stability	Processing complexity	29; 12
Nanogels	Crosslinked polymer networks	Hydrophilic compounds	Stimuli-responsive, high loading	Swelling variability	22
Micelles	Self-assembled amphiphiles	Hydrophobic compounds	Enhanced solubility	Dilution instability	31
Inclusion complexes	Host–guest systems	Volatile/unstable compounds	Improved stability and solubility	Limited capacity	49

5. Fabrication Technologies for Nano-Encapsulation

5.1 Overview of Fabrication Strategies

Nano-encapsulation fabrics are important in dictating the physicochemical properties, stability, and functional activity of nano-delivery systems in functional foods. The choice of a proper fabrication technique has a direct bearing on the value of parameters like particle size, encapsulation efficiency, release kinetics and structural integrity of the carrier system. Nano-encapsulation methods can broadly be categorised into top-down methods (Figure 1) (that is, the formation of nanoscale structures by breaking down larger structures into smaller ones) and bottom-up methods (Figure 2), that is, the formation of nanostructures by assembling molecules. Both methods have their own benefits and drawbacks based on the nature of the bioactive compound, encapsulation material and the purpose of use[33].

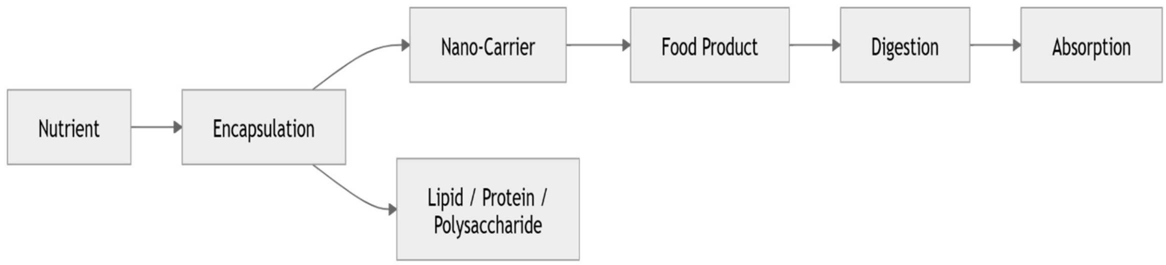

Figure 2 : Simple Nano-Encapsulation Process

5.2 Top-Down Approaches

Top-down methods refer to the use of mechanical forces in order to decrease bigger particles or droplets into nanoscale structures. These techniques are common in the food industry because they are scalable and can be used in conjunction with existing processing technologies.

5.2.1 High-Pressure Homogenization

One of the most widely utilised methods of nanoemulsions and lipid-based nanoparticles production is high-pressure homogenization. In this, a coarse emulsion is compelled through a fine opening under high pressure, resulting in high shear, turbulence, and cavitation forces that shrink the droplet size to the nanoscale. It is especially useful to encapsulate lipophilic compounds and obtain stable nanoemulsions with a homogeneous size distribution of particles. The high energy input can, however, cause degradation of bioactive compounds that are sensitive to heat and optimisation of processing conditions must be carefully considere[34].

5.2.2 Ultrasonication

Ultrasonication is a method that uses sound waves of high frequency to create cavitation forces within liquid systems, which causes the creation of nano-sized droplets or particles. The method is very popular in the preparation of nanoemulsions and dispersions as it is very simple and effective. Ultrasonication can be used to form fine and stable nanostructures with a relatively low processing time, although it is possible that the effects of prolonged exposure lead to oxidation or degradation of sensitive compounds due to localised heating effects[35].

5.2.3 Milling and Mechanical Size Reduction

The particle size of solid materials can be reduced to the nanoscale by mechanical methods of milling, including ball milling and high-energy grinding. The techniques have found applications especially in entrapment of poorly soluble compounds and enhancing their solubility. Although efficient, these methods can cause contamination through milling media and can cause the structural damage of sensitive bioactive compounds, restricting their use in particular food systems[36].

5.3 Bottom-Up Approaches

Bottom-up methodologies entail the creation of nanostructures by self-assembly of molecules and by using controlled aggregation reaction. The methods provide a high precision in control of particle size, morphology and internal structure and are therefore very applicable in the design of the advanced nano-delivery systems.

5.3.1 Nanoprecipitation

Nanoprecipitation is a common method of producing polymeric nanoparticles with a solution of the bioactive material and polymer being introduced to a non-solvent that causes the precipitation to occur quickly resulting in the creation of nanoparticles. The technique is also especially useful when it comes to encapsulating hydrophobic compounds and enables the generation of particles with a high level of narrow size distribution. This technique is appealing to functional food applications due to its simplicity and low power of operation[37].

5.3.2 Self-Assembly and Coacervation

Self-assembly is spontaneous assembly of molecules into ordered nanostructures through non-covalent forces like hydrophobic forces, hydrogen bonding and electrostatic interactions. A closely related process is coacervation where the separation of phases of polymers is performed to create a coating of bioactive compounds. These are the best methods to encapsulate sensitive nutrients and obtain controlled release. They also enable the establishment of complex structures like micelles, vesicles and nanogels, which are extensively applied in delivery systems of functional foods[38].

5.3.3 Ionic Gelation

Ionic gelation is a method that is often utilized to prepare polysaccharide-based nanoparticles in which crosslinking takes place via ionic interactions between oppositely charged molecules. As an example, tripolyphosphate can be crosslinked with chitosan to create stable nanoparticles. The technique is quite appropriate in the entrapment of bioactive compounds that are to be preserved in the acidic environment and to be released in the intestine. Ionic gelation is beneficial because it has weak processing conditions and can be used with sensitive compounds[39].

5.4 Drying and Stabilization Techniques

After the formation of nanoparticles, they may need to be stabilized to enhance shelf life and ease their inclusion in food products. Most drying techniques like spray drying or freeze drying are frequently applied to transform liquid nano-dispersions to solid forms that are not easy to dissolve. Spray drying is commonly employed as it is cost effective and can be scaled but it can potentially subject bioactive to thermal stress. Freeze drying is, however, preservative of structure and bioactivity but requires more energy and is more costly. Other methods like coacervation and entrapment within edible films or coating can also be used to increase stability and safeguard bioactive against storage and processing. The methods are especially applicable in incorporation of nano-encapsulated ingredients into solid food matrices[40].

5.5 Industrial Feasibility and Scale-Up Considerations

Scalability and industrial feasibility should be taken into consideration to allow the nano-encapsulation technologies to be effectively utilized in functional foods. Although most of the fabrication methods perform well at the laboratory level, their application to large-scale production is frequently constrained by factors like high energy needs, equipment price and complexity of the process. High-pressure homogenization and spray drying techniques are more easily scaled and commonly used in the food industry, and other nanoprecipitation and self-assembly are less common and might need additional optimization to be used on a larger scale. Other important factors that affect the commercial viability of nano-encapsulation systems are economic factors such as cost of raw materials, energy use, and efficiency in production. Hence, the creation of affordable, scalable and reproducible fabrication strategies continues to be a major thrust in the progress of the nano-enabled functional food technology[41].

6. Mechanisms of Bioavailability Enhancement by Nano-Encapsulation

6.1 Protection Against Chemical and Environmental Degradation

The protection of bioactive compounds against chemical and environmental degradation is one of the main mechanisms that nano-encapsulation promotes the nutrient bioavailability. Most nutrients, especially vitamins, polyphenols, and unsaturated fatty acids are too sensitive to external conditions like oxygen, light, temperature and pH variations. Nano-encapsulation offers a physical shielding of these compounds, which prevents oxidative and hydrolytic degradation of these compounds in foods, storage, and gastrointestinal transit. This is a protective effect, which maintains the structural integrity and functional activity of the bioactives, making sure that a greater percentage is available at the absorption site in an active form.

6.2 Improvement of Solubility and Dispersibility

The poor aqueous solubility of a significant number of nutraceuticals, especially lipophilic compounds like carotenoids, flavonoids, and fat-soluble vitamins, is a significant drawback. Nano-encapsulation enhances the apparent solubility and dispersibility of such compounds to a considerable degree through the reduction in particle size to nanoscale (Figure 3) and therefore, surface area and interactions with other media. The nano-carriers make it easy to evenly distribute the food systems in the aqueous system to avoid aggregation and sedimentation. The increase in the dispersion allows better exposure of bioactives to digestive enzymes and to their inclusion in micelles, which is crucial to intestinal absorption[42].

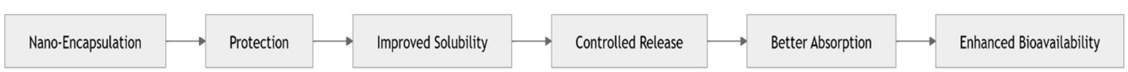

Figure 3: Mechanism of Bioavailability Enhancement

6.3 Enhancement of Gastrointestinal Stability

The gastrointestinal tract is a challenging environment with fluctuating PH levels, presence of enzymes and interaction with bile salts, which can adversely affect the stability of bioactive compounds. The design of nano-encapsulation systems should resist these extreme environments and offer structural protection during transit in the gut and release in the intestinal area. As an example, the encapsulation matrices may avoid the degradation of bioactive compounds in the acidic environment of the stomach and liberate them in the more favourable environment of the small intestine. This specific safeguard increases the survival of nutrients and their overall bioavailability.

6.4 Improved Bioaccessibility During Digestion

Bioaccessibility is the proportion of a nutrient which is released by the food matrix and is available to be absorbed during digestion. Nano-encapsulation increases bioaccessibility through the ability to release and solubilize bioactive compounds. The small size of nanoscale and high surface area of delivery system enhances quick interactions with digestive enzymes resulting in enhanced breakdown of carrier materials and release of encapsulated nutrients. Also, lipid-based nano-carriers help in development of mixed micelles that are important in delivering lipophilic compounds across the intestinal barrier. This increased digestion process makes a big difference in availability of nutrients to be taken in[43].

6.5 Increased Intestinal Absorption and Cellular Uptake

Intestinal absorption of bioactive compounds may be improved by using nano-encapsulation systems that can increase the interaction of the bioactive compounds with the intestinal epithelium. The low sizes of nanocarriers result in greater proximity to the intestinal mucosa, enhancing the possibility of uptake via passive diffusion, endocytosis, or carrier-mediated uptake processes. Nanocarriers are also said to be mucoadhesive and this increases their residence time in the gastrointestinal tract leading to high absorption efficiency. Moreover, some nano-delivery systems are capable of aiding the delivery of nutrients across biological membranes, and therefore making them more systemically available.

6.6 Controlled and Targeted Release Mechanisms

A second useful application of nano-encapsulation to enhance bioavailability is the decrease in losses of nutrients during processing, storage and digestion. Nano-delivery systems may minimise the interactions of the other food ingredients and bioactives degradation or leaching by entraping bioactives in protective matrices. This leads to an increase in the retention of active compounds in the end product and functional performance (Table 3). Nano-encapsulation can also be used to hide the unwanted flavours or Odours associated with certain bioactive compounds, thereby increasing consumer acceptance and increasing the amount of compound that can be incorporated into functional foods. Not only does this improve on the nutritional composition of food products but also makes sure that the nutrients that are delivered are still biologically effectives[44].

6.7 Reduction of Nutrient Losses and Improved Functional Efficiency

A second valuable way in which nano-encapsulation increases bioavailability is by reducing losses of nutrients in processing, storage, and digestion. Nano-delivery systems can reduce the interactions of other food ingredients and degradation or leaching of bioactives through the entrapment of bioactives within protective matrices. This leads to an increase in the retention of active compounds in the end product and functional performance (Table 3). Also, nano-encapsulation has the potential to conceal the undesired flavours or Odors linked to some bioactive compounds, thus enhancing consumer acceptability and allowing higher levels of incorporation into functional foods. Not only does this improve on the nutritional composition of food products but also makes sure that the nutrients that are delivered are still biologically effective.

Table 3. Mechanisms of Bioavailability Enhancement by Nano-Encapsulation

Mechanism	Description	Impact on Bioavailability	References
Protection	Shields bioactives from degradation (heat, pH, oxidation)	Preserves active compounds	42
Solubility enhancement	Reduces particle size, increases surface area	Improves dissolution and dispersion	43
Controlled release	Sustained or targeted delivery in GI tract	Enhances absorption efficiency	32
Bioaccessibility improvement	Facilitates digestion and micelle formation	Increases available fraction	44
Cellular uptake	Enhances interaction with intestinal cells	Improves absorption	37
Reduced interaction loss	Minimizes interactions with food matrix	Maintains nutrient efficacy	10

7. Nano-Encapsulation of Major Nutrient and Bioactive Classes

7.1 Overview of Nutrient Applications

Nano-encapsulation has found extensive use in a broad spectrum of nutrients and bioactive compounds to address the drawbacks of low stability, low solubility and bioavailability. These are vitamins, minerals, polyphenols, carotenoids, proteins and plant-based antioxidants. The success of nano-delivery systems also relies on the physicochemical properties of the nutrient, and the compatibility of the encapsulation substance and carrier system. Nano-encapsulation can be used to improve the functionality of these compounds in food systems by offering protection against environmental degradation, and regulation of release.

7.2 Vitamins and Minerals

Vitamins, especially the fat-soluble ones, A, D, E, and K are very prone to degradation and have low aqueous solubility, which hinders their absorption in the gastrointestinal tract. Their dispersibility and stability are enhanced by nano-encapsulation and prevent easy absorption due to increased micelle formation. On the same note, other minerals like iron and zinc are normally associated with issues of low bioavailability and unwanted sensory responses in food matrices. Nano-encapsulations are used to separate these minerals with the rest of the matrix, decreasing reactivity and enhancing solution and uptake capability. Specifically, nano-iron formulations have shown enhanced bioavailability and fewer side effects than traditional methods of fortification[45].

7.3 Polyphenols, Flavonoids, and Antioxidants

Plant-based antioxidants such as polyphenols, flavonoids, and other antioxidants are well-known to promote health including providing antioxidant and anti-inflammatory effects. They are however limited in their use in functional foods because of their inability to remain stable, degrade easily and because of their low bioavailability. Nano-encapsulation offers a protection layer that inhibits degradation by light, oxygen and change in pH, and enhances solubility, and controlled release. To increase the biological efficacy of these compounds, encapsulation systems like nanoemulsions, liposomes and polymeric nanoparticles, would promote the bioaccessibility and absorption of these compounds. This is especially critical to compounds such as anthocyanins and phenolic acids which are very sensitive to environments.

7.4 Lipophilic Compounds and Proteins

Lipophilic bioactives (carotenoids and essential fatty acids) pose a serious problem because they are not soluble in water and are prone to oxidation. Nano-encapsulation makes them better dispersible in water and helps to prevent their degradation, thus increasing their stability and uptake. It is the lipid-based nanocarriers that are especially effective in enabling their inclusion in functional food and increasing their absorption in the gastrointestinal tract. Moreover, bioactive proteins and peptides are also of interest because of their nutritional and therapeutic properties, although their bioavailability is often limited by their enzymatic degradability (Table 4). Nano-encapsulation, in particular, protein-based carriers and nanogels, also shield digestion and allows controlled release to enhance their absorption and functional performance. These are being considered more and more in specialised nutrition products, such as sports and medical foods[46].

Table 4: Nano-Encapsulation Strategies for Major Nutrient and Bioactive Classes

Nutrient / Bioactive Class	Key Challenges	Nano-Encapsulation Strategy	Benefits Achieved	Typical Delivery Systems
Vitamins (A, D, E, K)	Poor solubility, light & heat sensitivity	Lipid-based encapsulation, nanoemulsions	Improved stability, enhanced absorption	Nanoemulsions, Liposomes, NLCs
Minerals (Iron, Zinc)	Low bioavailability, reactivity, sensory issues	Encapsulation within protective matrices	Reduced interactions, improved solubility	Polymeric nanoparticles, Nano-complexes
Polyphenols	Low stability, rapid degradation, poor absorption	Polymeric and lipid-based encapsulation	Protection from oxidation, controlled release	Liposomes, Polymeric nanoparticles
Flavonoids / Anthocyanins	pH sensitivity, light degradation	Encapsulation in protein/lipid carriers	Improved stability and bioavailability	Nanoemulsions, Inclusion complexes
Carotenoids	Poor water solubility, oxidation	Lipid-based nano-carriers	Enhanced dispersion and absorption	Nanoemulsions, SLNs, NLCs
Proteins / Peptides	Enzymatic degradation, low absorption	Encapsulation in nanogels/protein carriers	Protection and sustained release	Nanogels, Protein nanoparticles
Antioxidants (Plant-derived)	Oxidation, instability during processing	Encapsulation in polymer/lipid systems	Improved stability and delivery efficiency	Polymeric nanoparticles, Micelles
Emerging Bioactives	Poor stability, low bioavailability	Hybrid and multifunctional systems	Enhanced delivery and synergistic effects	Hybrid nanoparticles

8. Safety, Toxicological, and Regulatory Considerations

Although nano-encapsulation of functional foods brings about considerable benefits in terms of nutrient bioavailability, it has also raised critical issues of safety and potential health hazards. Nanoparticles can have some physicochemical characteristics because of their small size that are not typical of food ingredients; this can affect their interaction with biological systems differently. These interactions consist of higher surface reactivity, cellular uptake, and cellular ability to penetrate biological barriers, which can result in undesirable tissue deposition. Therefore, perception of behavior, destiny and long-term implications of nano-encapsulated systems in the human body is paramount in guaranteeing safe applications of nano-encapsulated systems in the food industry. Research has also shown that the particle size, surface charge, composition and dosage are some of the determinants of the toxicological profile of nanocarriers and that it is necessary to carry out detailed safety analyses[47].

Toxicological evaluation of nano-encapsulated systems entails a blend of in vitro and in vivo experiments to determine the possible negative impact at cellular, tissue, and systemic levels. Cytotoxicity, oxidative stress, and inflammatory responses are studied in vitro, and in vivo studies are used to gain insights into absorption, distribution, metabolism, and excretion of nanoparticles. Such assessments play a vital role in determining whether there is a risk of any chronic exposure to nano-encapsulated nutrients. In addition, the effects of nanoparticles on gastrointestinal microbiota and immune systems are a developing field of research that needs to be further explored. Under these complex interactions, standardised testing procedures and safety assessment models should be developed to help maintain some degree of uniformity and dependability in the assessment of nano-enabled food systems.

Besides the safety issues, regulatory issues pose a great obstacle to the mainstream implementation of nano-encapsulation technologies in the food industry. Laws and regulations on the application of nanomaterials in food systems are still developing and vary by region, which results in inconsistencies in approval procedures and safety regulations. Most of the food safety regulations in place were not initially formulated to deal with nanoscale materials and hence risk assessment and labelling requirements are not present. Regulatory bodies are also coming to understand the necessity of establishing special guidelines to the use of nanotechnology in food, such as the definition, standardisation of characterisation processes and effective safety assessment requirements. The international harmonisation of such regulations is necessary to enable international trade and consumer protection. Another important consideration that has impact on the successful use of nano-encapsulation in functional foods is consumer acceptance. The safety, naturalness, and transparency issues tend to affect the perception of nanotechnology in food products[48]. Lack of awareness and understanding of nanotechnology can lead to skepticism and resistance among consumers. Thus, there is a need to establish trust and acceptance through proper communication strategies, clear labels, and educating the population. Highlighting the advantages of nano-encapsulation, including better nutritional value and better health outcomes, and discussing safety issues can help close the gap between technological development and customer trust.

All in all, nano-encapsulation has a bright future in enhancing nutrient delivery in functional foods, but its use should be based on overcoming the challenges of safety, toxicological, regulatory, and consumer concerns. The sustainable development and commercialisation of nano-enabled food systems will require a balanced approach that involves scientific innovation, rigorous safety assessment and open regulatory practices[49].

9. Conclusion

Nano-encapsulation of functional food systems is projected to grow tremendously in the next few years due to the development of material science, nanotechnology, and nutritional studies. Future advances may be made in designing next-generation nano-delivery systems, which are efficient in increasing bioavailability, but are also personalised dietary interventions and precision nutrition. The incorporation of intelligent and stimulus-responsive nanocarriers with the ability to deliver nutrients site-specifically and in a controlled way will also enhance the targeted delivery of the nutrients, which will maximise their physiological effects. Besides this, natural, biodegradable, and food-grade materials, and green synthesis technologies will be essential in sustainability issues and compliance with clean-label production desired by the consumer. The other noteworthy future research direction would be to produce strong clinical and in vivo research to substantiate the effectiveness and safety of nano-encapsulated nutrients. Although many have shown to become more stable and bioavailable at the lab level, there is still a need for standardised evaluation guidelines and long-term safety tests. The future of nano-biomaterials is also anticipated to be aided by the development of better methods of analysis and computer modeling to learn more about nano-bio interactions and create more effective and safe delivery systems. Moreover, it will be necessary to overcome obstacles which are associated with scalability, cost-effectiveness and regulatory approval as a way of applying nano-encapsulation technologies to commercial functioning food products. To sum it up, nano-encapsulation is a revolutionary method in improving the stability, solubility and bioavailability of nutrients and bioactive compounds in functional foods. Nano-enabled platforms offer great possibilities to enhance the nutritional value and health benefits of food items by surpassing the constraints of traditional delivery systems. Although there are many issues surrounding safety, regulation and industrial implementation, continued innovations and interdisciplinary studies will see the successful penetration of nano-encapsulation into the mainstream food systems. Finally, the future of functional foods and nutraceuticals will be greatly influenced by the further evolution of safe, efficient, and sustainable nano-delivery technology that will result in better nutrition and health of the population across the globe.

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