

Environmental and Dietary Transitions as Drivers of Advanced Pharmaceutical–Nutraceutical Delivery Systems for Functional Food Bioactives

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Abstract

Functional food bioactives and nutraceutical compounds are increasingly used in health-oriented food and pharmaceutical–nutraceutical products; however, their practical effectiveness is often limited by poor aqueous solubility, instability, oxidation, low bioaccessibility, limited bioavailability, weak gastrointestinal protection, and uncontrolled release. This systematic literature review examined recent evidence on advanced delivery systems used to improve the formulation performance of functional food bioactives. A structured review approach informed by PRISMA 2020 guidelines was followed. Literature published between 2021 and 2026 was identified through databases, publisher platforms, and manual reference checks. After screening 258 records and assessing 58 full texts for eligibility, 26 studies were included in the final synthesis. The included studies covered nanoencapsulation, micro/nanoencapsulation, nanoemulsions, Pickering emulsions, lipid-based nanocarriers, solid lipid nanoparticles, nanostructured lipid carriers, nano-suspensions, hydrogels, probiotic encapsulation systems, and co-encapsulation platforms. Lipid-based and emulsion systems were prominent for hydrophobic nutraceuticals, curcumin, omega-3 oils, DHA, functional lipids, and phytochemicals, while probiotic systems focused on viability protection and gastrointestinal survival. Hydrogels and co-encapsulation platforms supported controlled release and multi-bioactive delivery. Overall, advanced pharmaceutical–nutraceutical delivery systems provide important formulation strategies for translating functional food bioactives into stable, bioavailable, and application-ready products.

Keywords: Functional food bioactives; Nutraceutical delivery; Nanoencapsulation; Lipid-based nanocarriers; Bioavailability; Controlled release

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1. Introduction

Functional foods and nutraceuticals have attracted growing scientific and commercial interest, due to their original nutritional value and their ability to deliver bioactive compounds that can contribute to the maintenance of health, the prevention of diseases, and the promotion of physiological functions. Conventional foods are now being reformulated to become health promoting foods by incorporating nutraceutical ingredients, plant-derived bioactives, peptides, polyphenols, carotenoids, probiotics, omega-3 fatty acids and other functional compounds. This has deepened the bond between food science, pharmaceutical formulation, and preventive health, particularly in the case of foods with a specific functional benefit along with nutritional value that consumers are looking for [1].

From the point of view of the food industry, functional foods are defined as foods that can provide beneficial components to the body when consumed as a part of the normal diet. They are believed to have a potential role in

various pathways, including oxidative stress, metabolic health, gut function, immune regulation, and chronic disease prevention. The practical application of these products is not only dependent on the presence of bioactive compounds, but how these compounds remain stable, bioaccessible and biologically available during processing, storage, digestion and absorption [2].

In this context, plant-based bioactives are key since many fruits, vegetables, cereals, legumes, herbs and agro-industrial by-products are rich in phenolics, flavonoids, carotenoids, peptides, and other active molecules. They can be considered as useful compounds in functional food and nutraceutical development due to their antioxidant, anti-inflammatory, antimicrobial, cardioprotective, and metabolic properties [3]. Meanwhile, environmental and dietary shifts have sparked increasing interest in plant-based, resource-efficient and sustainable food systems. Formulation strategies are becoming more and more important in the design of healthier and more sustainable plant-based foods, as they are critical for preserving bioactive

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functionality while simultaneously ensuring safety, sensory quality and consumer acceptability [4].

However, many functional food bioactives have significant formulation challenges. They are not very soluble in water, chemically unstable, oxidizable, heat and/or mechanical labile, poorly bioaccessible, and poorly bioavailable in actual food and nutraceutical systems. Other food-derived bioactive peptides and compounds derived from food by-products must also be subjected to safety, stability, recovery, and feasibility of application studies before being commercialized [5]. Environmentally friendly extraction and processing methods have also reinforced the need for sustainable recovery of bioactive molecules along with suitable delivery systems for the development of functional products [6].

The scale-up, production, packaging, storage, distribution, and consumption of the functional foods in the industry makes this an additional challenge, as bioactive compounds should be effective throughout the process. Therefore, the formulation system should be able to ensure the stability, repeatability, and compatibility with food systems and should be able to provide consumer-oriented product quality in large-scale functional food development [7]. Functional foods are not just about the nutrients they contain, but also the bioactive compounds that they can deliver, which brings together nutrition science and pharmaceutical applications, such as those concerning the design of the carrier, its release mechanism and biological activity [8]. Based on recent knowledge mapping, the functional food research is growing at an increasing rate and the bioactive ingredients, sustainability, product innovation, and health-oriented applications are gaining more importance in functional food research [9]. The literature is, however, spread out in food science, nutraceutical, pharmaceutical and nanotechnology areas. To understand the use of advanced pharmaceutical–nutraceutical delivery system to enhance stability, solubility, bioaccessibility, bioavailability, gastrointestinal protection, controlled release, and functional performance of food derived bioactives, a focused synthesis is required. The objectives of this systematic literature review are:

- To identify advanced pharmaceutical–nutraceutical delivery systems used for functional food bioactives.
- To classify the major bioactive compounds and delivery platforms reported in recent literature.
- To synthesize how these delivery systems address formulation challenges related to stability, solubility, bioaccessibility, bioavailability, digestibility, gastrointestinal protection, and controlled release.

2. Methods

2.1 Protocol and Reporting Standard

This systematic literature review was performed following a structured review process with guidelines from the PRISMA 2020. The identification, screening, assessment and synthesis of studies related to advanced pharmaceutical–nutraceutical delivery systems for functional food bioactives was adopted by following a

predefined procedure. The review was exclusively for delivery systems that aimed at enhancing the stability, solubility, bioaccessibility, bioavailability, digestibility, gastrointestinal protection, controlled release, or functional performance of food-derived bioactive compounds.

2.2 Data Sources and Search Strategy

Relevant literature was identified through databases, publisher platforms, and manual reference checks. The sources used during the search included Google Scholar, ScienceDirect, SpringerLink, Royal Society of Chemistry, Oxford Academic, Frontiers, MDPI, Nature/Scientific Reports, and Heliyon. These sources were selected because they provided access to studies directly related to nutraceutical delivery, functional food bioactives, encapsulation, nanoemulsions, lipid-based carriers, probiotic encapsulation, hydrogels, co-encapsulation, and bioavailability enhancement.

The search focused on studies published between 2021 and 2026. Search terms were adapted according to each source and included combinations such as “functional food bioactives” AND “delivery systems”, “nutraceutical delivery” AND “bioavailability”, “nanoencapsulation” AND “functional foods”, “lipid-based nanocarriers” AND “nutraceuticals”, “curcumin” AND “nanoemulsion”, “resveratrol” AND “oral delivery systems”, “quercetin” AND “nanoformulations”, “omega-3” AND “nanoemulsion”, “probiotic encapsulation”, “hydrogels” AND “food bioactive ingredients”, “beta-carotene” AND “delivery systems”, “co-encapsulation” AND “bioactive compounds”, and “functional lipids” AND “encapsulation”.

2.3 Eligibility Criteria

Studies were included if they were published in English between 2021 and 2026 and focused on functional food bioactives, nutraceuticals, phytochemicals, probiotics, carotenoids, omega-3 fatty acids, functional lipids, or related food-derived bioactive compounds. Eligible studies were required to discuss or evaluate a pharmaceutical–nutraceutical delivery approach, such as nanoencapsulation, nanoemulsions, Pickering emulsions, lipid-based nanocarriers, solid lipid nanoparticles, nanostructured lipid carriers, hydrogels, probiotic encapsulation, nano-suspensions, co-encapsulation, or other advanced delivery systems.

Studies were excluded if they focused only on general nutrition, environmental change, dietary patterns, or public-health outcomes without a clear delivery-system component. Articles were also excluded if they were not available in full text, were not in English, lacked sufficient relevance to formulation or bioactive delivery, or focused on unrelated pharmaceutical applications outside the functional food or nutraceutical context.

2.4 Study Selection Process

A total of 258 records were initially identified. Of these, 224 records were identified through databases and publisher platforms, while 34 records were identified

through manual reference checks. After removing 46 duplicate records, 212 records remained for title and abstract screening. During screening, 154 records were excluded because they did not directly address functional food bioactives, nutraceutical delivery systems, encapsulation, formulation performance, stability, bioavailability, bioaccessibility, digestibility, or controlled release.

The full texts of 58 records were then assessed for eligibility. Of these, 32 records were excluded: 10 were

not directly related to pharmaceutical–nutraceutical delivery systems, 7 had no clear functional food bioactive or nutraceutical focus, 6 were inaccessible as full text, 5 had insufficient formulation or outcome details, and 4 showed conceptual overlap or were outside the final review scope. Finally, 26 studies were included in the final synthesis. The complete study selection process, including identification, duplicate removal, screening, eligibility assessment, exclusion reasons, and final inclusion, is presented in Figure 1.

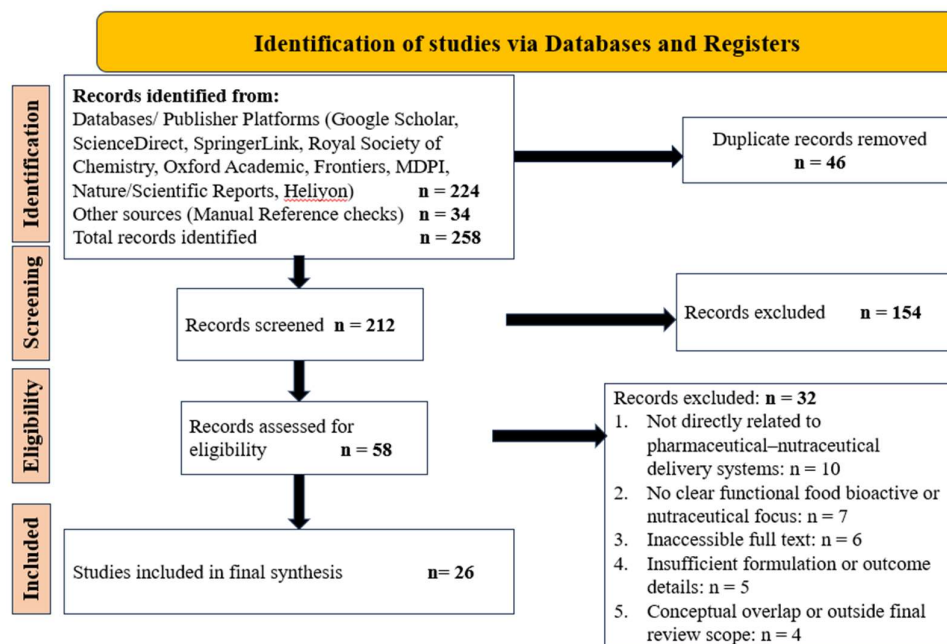


Figure 1. PRISMA Flow Diagram Illustrating the Study Selection Process

2.5 Data Extraction

Data were extracted using a standardized extraction form. The extracted information included author, year, journal, study type, bioactive compound or bioactive class, delivery system, formulation approach, carrier material, main delivery challenge, and key findings. Particular attention was given to outcomes related to stability, solubility, bioaccessibility, bioavailability, digestibility, encapsulation efficiency, gastrointestinal protection, controlled release, and functional or therapeutic relevance.

2.6 Data Synthesis

The type of study, bioactive compound, carrier system, method of formulation, and results reported in the included studies varied so it was not possible to conduct quantitative meta-analyses. Instead, a structured narrative synthesis was used. The studies were divided into major thematic areas such as general encapsulation and nanoencapsulation, lipid based nanocarriers, curcumin delivery systems, resveratrol delivery systems, quercetin and phytochemical delivery systems, omega 3 and functional lipid delivery systems, probiotic encapsulation, hydrogel based delivery systems, carotenoid delivery systems and co-encapsulation strategies. The current findings were compared with the

other studies for the common problems in delivery, formulation strategies, and reported benefits in terms of stability, bioavailability, bioaccessibility, digestibility, and controlled release.

2.7 Quality Assessment

The relevant studies included were evaluated for relevance and methodological competence. Evaluation criteria were: clarity of objectives, relevance to functional food bioactive delivery, appropriateness of the discussion or formulation method for the delivery system, clarity of reported outcomes, usefulness in understanding the performance of the delivery system of pharmaceutical–nutraceuticals. At the eligibility stage, studies were excluded that had weak relevance, were not clearly described, lacked a sufficient focus on the delivery system, or did not report sufficient outcomes as they were not relevant for this guideline.

3. Results

3.1 Characteristics of the Included Studies

In the final synthesis, 26 studies were included that were published from 2021 to 2026. Literature included primarily was review articles, and some original formulation studies and 1 systematic review with meta analysis. The studies were on pharmaceutical–

nutraceutical delivery systems for functional food bioactives, such as nutraceuticals, food bioactive compounds, curcumin, resveratrol, quercetin, docosahexaenoic acid (DHA), algal oil rich in omega-3 fatty acids, probiotics, β -carotene, phytochemicals, natural compounds, plant-derived bioactives and functional lipids.

The types of the delivery systems which were used across the last studies encompassed: encapsulation systems, nanoencapsulation, micro/nanoencapsulation, nanoemulsions, Pickering emulsions, lipid-based

nanocarriers, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), nano-suspensions, hydrogels, probiotic encapsulation systems, nanocarrier-mediated probiotic delivery, co-encapsulation platforms. The primary formulation outcome domains were: stability, bioaccessibility, bioavailability, gastrointestinal protection, digestibility, oxidation stability, controlled release, probiotic viability and food system applicability. The characteristics of all included studies are presented in Table 1.

Table 1. Characteristics of Included Studies

Sr. No.	Study	Study type	Bioactive / compound focus	Delivery system focus	Main result domain
1	[10]	Review	Food bioactive compounds	Encapsulation systems	Protection, controlled release, food-system application
2	[11]	Review	Nutraceuticals	Nanoencapsulation	Stability, bioavailability, functional-food application
3	[12]	Review	Functional food bioactives	Nanoencapsulation and related systems	Delivery efficiency, stability, sustainability, controlled release
4	[13]	Review	Nutraceuticals	Lipid-based nanocarriers	Gastrointestinal protection, absorption, bioavailability
5	[14]	Review	Hydrophobic nutraceuticals and bioactives	SLNs and NLCs	Food-grade lipid nanovehicles, hydrophobic bioactive delivery
6	[15]	Review	Bioactive compounds	Lipid-based nanoparticles	Delivery efficiency and therapeutic performance
7	[16]	Review	Nutraceuticals	Nanotechnology-based targeted delivery systems	Targeted delivery, solubility, stability, controlled release
8	[17]	Original formulation study	Curcumin	Nanoemulsions	Bioavailability enhancement, safety, emulsifier effect
9	[18]	Review	Curcumin	Pickering emulsions	Bioaccessibility and nutraceutical delivery
10	[19]	Original formulation study	Curcumin	Cellulose nanoparticle-stabilized emulsions	Encapsulation, stability, antioxidant properties

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11	[20]	Original formulation study	Curcumin	Nanoemulsions	Curcumin protection, processing stability, sterilization resistance
12	[21]	Review	Resveratrol	Oral delivery systems	Functional-food application, oral bioaccessibility, bioavailability
13	[22]	Review	Resveratrol	Encapsulation, derivatization, combination strategies	Bioavailability enhancement
14	[23]	Review	Quercetin	Nanoformulations	Solubility, stability, bioavailability
15	[24]	Review	DHA / omega-3 fatty acid	DHA delivery systems	Bioavailability, functionality, food and health applications
16	[25]	Original formulation study	Long-chain omega-3 algal oil	Nanoemulsions	Stability and digestibility under in vitro digestion
17	[26]	Original formulation study	Curcumin and echium oil	Nanoemulsions	Characterization and co-delivery potential
18	[27]	Review	Probiotics	Probiotic encapsulation systems	Viability, gastrointestinal protection, food-industry application
19	[28]	Systematic review and meta-analysis	Probiotics	Nanocarrier-mediated probiotic delivery	Biological effects and probiotic delivery performance
20	[29]	Review	Food bioactive ingredients	Hydrogels	Carrier design, swelling behavior, controlled release
21	[30]	Review	β -carotene	Loaded food delivery systems	Digestive fate, stability, release behavior
22	[31]	Review	Natural compounds	Nanoencapsulation strategies	Bioactive protection and food-industry application
23	[32]	Review	Phytochemicals	Nano-suspensions and nano-emulsions	Solubility enhancement and phytochemical delivery
24	[33]	Review	Multiple bioactive compounds	Co-encapsulation systems	Compatibility, synergistic delivery, controlled release
25	[34]	Review	Plant-derived and agro-industrial by-product bioactives	Micro/nanoencapsulation systems	Sustainability, valorisation, food application

26	[35]	Review	Functional lipids	Encapsulation systems	Oxidative stability, gastrointestinal stability, bioaccessibility
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3.2 Encapsulation and Nanoencapsulation Platforms

The largest category of delivery systems in the literature reviewed were those of encapsulation and nanoencapsulation. The systems were mostly reported for bioactive compounds in food, nutraceuticals, natural compounds and plant derived bioactives. The main formulation challenges solved in this cluster were: instability, degradation during processing or storage, limited drug release control, low bioavailability, and limited compatibility with food matrix.

The evidence demonstrated that the encapsulation was frequently used for the protection of food bioactives for

the improvement of functional properties. Nanoencapsulation was found to be specifically linked to enhanced stability, improved dispersion, controlled release, and delivery for bioavailability enhancement. Within this theme, sustainability also appeared, notably in the application of delivery systems with natural compounds, plant derived bioactives and by-products bioactives from agro-industry. The main findings from encapsulation and nanoencapsulation studies are shown in Table 2.

Table 2. Encapsulation and Nanoencapsulation Platforms

Delivery theme	Bioactive focus	Main formulation problem	Delivery-system result	Study
Broad food bioactive encapsulation	Food bioactive compounds	Instability and limited release control	Encapsulation was reported as a strategy for improving protection, release behavior, and food-system application	[10]
Nutraceutical nanoencapsulation	Nutraceuticals	Poor stability and low bioavailability	Nanoencapsulation was associated with stability improvement and bioavailability-oriented performance	[11]
Functional-food nanoencapsulation	Functional food bioactives	Degradation, weak delivery efficiency, and release limitations	Nanoencapsulation was linked with improved delivery, stability, sustainability, and controlled release	[12]
Targeted nutraceutical delivery	Nutraceuticals	Poor solubility, instability, and non-specific delivery	Nanotechnology-based systems were reported as useful for targeted delivery and controlled release	[16]
Natural compound encapsulation	Natural compounds	Sensitivity during processing and storage	Nanoencapsulation was identified as a protective approach for food-industry application	[31]
Plant-source valorisation	Plant-derived and by-product bioactives	Instability and limited use of plant-source compounds	Micro/nanoencapsulation was linked with sustainable food applications and bioactive valorisation	[34]

3.3 Lipid-Based Nanocarriers and Functional Lipid Delivery

Lipid-based delivery systems were primarily linked to the delivery of hydrophobic nutraceuticals, lipid-soluble bioactive compounds, DHA, algal oil with omega-3 fatty acids and functional lipids. All these systems were focused on the formulation problems dealing directly with pharmaceutical–nutraceutical development, such as poor water dispersibility, digestive instability, lipid oxidation and limited bioavailability.

Lipid based nanocarriers could be beneficial as a gastrointestinal protection and support for gastrointestinal absorption system. SLNs and NLCs were found to be lipid nanovehicles for hydrophobic nutraceuticals and bioactives that are suitable for food applications. In addition, lipid-based nanoparticles showed enhanced delivery efficacy and therapeutic activity of bioactive molecules.

A more specific formulation pattern was observed in the omega-3 and functional lipid studies. These studies

encompassed the oxidative stability, digestibility, gastrointestinal stability, bioaccessibility and bioavailability-related performance as the major outcome domains. Omega-3 algal oil was encapsulated

in a nanoemulsion whereas more extensive protection of functional lipids was mentioned for encapsulation systems. The lipid-based and functional lipid delivery findings are presented in Table 3.

Table 3. Lipid-Based Nanocarriers and Functional Lipid Delivery

Delivery system	Bioactive focus	Main formulation problem	Delivery-system result	Study
Lipid-based nanocarriers	Nutraceuticals	Poor absorption and gastrointestinal instability	Lipid nanocarriers were reported to support gastrointestinal protection and bioavailability enhancement	[13]
SLNs and NLCs	Hydrophobic nutraceuticals and bioactives	Poor aqueous solubility and delivery of hydrophobic compounds	Food-grade lipid nanovehicles were identified for hydrophobic bioactive delivery	[14]
Lipid-based nanoparticles	Bioactive compounds	Limited delivery efficiency	Lipid nanoparticles were associated with improved delivery and therapeutic performance	[15]
DHA delivery systems	DHA / omega-3 fatty acid	Bioavailability and functionality limitations	DHA delivery systems were reported to support food and health applications	[24]
Omega-3 algal oil nanoemulsions	Long-chain omega-3 algal oil	Digestive instability and formulation-dependent performance	Nanoemulsions enabled assessment of stability and digestibility under in vitro digestion	[25]
Curcumin–echium oil nanoemulsions	Curcumin and echium oil	Need for combined polyphenol–lipid delivery	Nanoemulsions supported characterization of combined delivery potential	[26]
Functional lipid encapsulation	Functional lipids	Oxidation and gastrointestinal instability	Encapsulation was associated with improved stability, bioaccessibility, and bioavailability-related performance	[35]

3.4 Polyphenol, Phytochemical, and Carotenoid Delivery Systems

The evidence on polyphenol, phytochemical and carotenoids was the most compound specific. Curcumin was the most common individual bioactive. The various studies on curcumin focused on its low aqueous solubility, its low bioaccessibility, its degradation during processing, low oral bioavailability and its stability under post treatment conditions and during sterilization. Most curcumin delivery system was nanoemulsions. The type of emulsifier was an important variable in curcumin nanoemulsions, particularly for safety and performance in terms of bioavailability. The bioaccessibility of curcumin was reported as particle stabilized emulsions (pickering emulsions). The antioxidant property,

emulsion stability, and curcumin encapsulation were correlated with the cellulose nanoparticle-stabilized emulsions.

The studies of resveratrol were concentrated on oral delivery and enhancing bioavailability. The approaches to delivery were: oral delivery systems, encapsulations, derivatizations, and combinations. Nanoformulations were found to be platforms to overcome poor solubility, instability and limited bioavailability in Quercetin studies. The manipulation of digestive fate, release behavior, and the performance in food-matrices was presented as an example of loaded delivery systems for β -carotene as a carotenoid case study. These findings are organized in Table 4.

Table 4. Polyphenol, Phytochemical, and Carotenoid Delivery Systems

Bioactive focus	Delivery system	Main formulation problem	Delivery-system result	Study
Curcumin	Nanoemulsions	Low oral bioavailability	Nanoemulsions were evaluated for bioavailability enhancement and safety, with emulsifier type affecting performance	[17]
Curcumin	Pickering emulsions	Poor bioaccessibility	Pickering emulsions were reported as systems for improving curcumin bioaccessibility	[18]
Curcumin	Cellulose nanoparticle-stabilized emulsions	Instability and limited antioxidant performance	Cellulose-stabilized emulsions supported curcumin encapsulation, stability, and antioxidant activity	[19]
Curcumin	Nanoemulsions with post-treatment	Processing-related degradation	Emulsifier type and post-treatment influenced curcumin protection and emulsion stability	[20]
Resveratrol	Oral delivery systems	Low oral bioavailability and food-incorporation barriers	Oral delivery systems were reported as relevant for functional-food application	[21]
Resveratrol	Encapsulation, derivatization, and combination approaches	Low bioavailability	Encapsulation was identified as one strategy for improving resveratrol bioavailability	[22]
Quercetin	Nanoformulations	Poor solubility and instability	Nanoformulations were reported to improve quercetin delivery feasibility	[23]
Phytochemicals	Nano-suspensions and nano-emulsions	Poor solubility and limited formulation performance	Nano-suspension and nano-emulsion approaches were identified for phytochemical delivery	[32]
β -carotene	Loaded food delivery systems	Instability and variable digestive fate	Delivery-system design was reported to influence β -carotene release and food-matrix behavior	[30]

3.5 Probiotic, Hydrogel, and Co-Encapsulation Systems

Probiotics delivery was different from polyphenol and lipid-based systems as the main formulation target was microbial viability. Probiotic encapsulation was primarily linked to protection in the processing/ storage period, as well as during gastric exposure, bile exposure and intestinal transit. The biological performance and

delivery protection with nanocarrier mediated probiotic delivery were also reported.

The food bioactive ingredients were found to be expected to be carried in a structured way, namely by hydrogels. The principle delivery related result domains they had were carrier design, swelling behavior, protection, and controlled release. Multiple bioactive delivery was tackled by co-encapsulation systems.

Compatibility between bioactives, release control, protection of compounds with different physicochemical properties and potential synergistic delivery were the

key formulation challenges in this group. Table 5 presents the findings for probiotic, hydrogel, and co-encapsulation delivery systems.

Table 5. Probiotic, Hydrogel, and Co-Encapsulation Delivery Systems

Delivery category	Bioactive focus	Main formulation problem	Delivery-system result	Study
Probiotic encapsulation	Probiotic cells	Loss of viability during processing, storage, and gastrointestinal transit	Encapsulation was associated with probiotic protection and food-industry application	[27]
Nanocarrier-mediated probiotic delivery	Probiotic cells	Need for improved protection and biological performance	Nanocarrier-mediated delivery was reported as relevant for probiotic biological effects	[28]
Hydrogel delivery	Food bioactive ingredients	Need for structural protection and controlled release	Hydrogels were reported to support swelling-based protection and release control	[29]
Co-encapsulation	Multiple bioactive compounds	Compatibility and multi-bioactive release challenges	Co-encapsulation was associated with combined delivery and controlled-release design	[33]

4. Discussion

Advanced delivery systems for pharmaceutical–nutraceutical delivery are vital to functional performance of food-derived bioactive compounds, as revealed in this review. The overall formulation challenges in the included studies were found to be low aqueous solubility, degradation during the formulation and storage, poor bioaccessibility, low oral bioavailability, oxidative degradation, lack of gastrointestinal protection, controlled release problems, and loss of probiotic viability. In particular, these barriers are of great relevance for product development of pharmaceutical and nutraceutical bioactive products since the biological value of the bioactive in a functional food product is not only related to its intrinsic activity, but also to its stability, dispersion, gastrointestinal stability, and bioavailability in the target site of action. The most common delivery method in the evidence reviewed were encapsulation and nanoencapsulation. The discovery indicates that encapsulations are not only about protecting sensitive ingredients, but are also a multi-functional formulation approach that can enhance stability, release profiles, sensory integration, and performance in the context of absorption. Nanoencapsulation mainly involves small carrier size and high surface area along with better dispersion properties which could be useful for those compounds which are poorly soluble and therefore poorly bioavailable in hydrophobic solvents or those which are chemically labile. In line with this, the overall idea is that with proper selection of carrier material and processing conditions, nanoencapsulation can benefit the improvement of absorption, stability, functionality, and food-product acceptability [36].

Nutraceutical compounds are mostly hydrophobic which is the reason for the increased importance of lipid-based nanocarriers, SLNs, NLCs and nanoemulsions. The

functional lipids, DHA, omega-3 oils, Quercetin, Curcumin, Resveratrol, and β -carotene all need carrier systems to enhance dispersibility and to shield from chemical or digestive degradation. Lipid carriers are particularly well suited for these types of compounds as they can improve solubilisation within the gastrointestinal tract, aid in digestion mediated release from the carrier and enhance bioaccessibility. Results also show that the lipid-based systems cannot only be considered as passive carriers. The formulation characteristics are influenced by the type of lipids, type and concentration of emulsifier, particle size, composition at the interface and matrix compatibility. An important application is functional food and nutraceutical, where plant-based and food-compatible colloidal system is particularly important. The evidence reviewed demonstrated a growing interest in protein, polysaccharide, phospholipid, plant lipids and natural ingredients based carriers. These systems can be useful as they deliver performance and are acceptable by consumers, they are sustainable and they are compatible with food matrices. This is especially relevant for the implementation of principles of pharmaceutical delivery into food and nutraceutical products where safety, clean label requirements, digestibility and sensory attributes are significant formulation challenges [37].

The findings specific to the compound also illustrate how the selection of the delivery system should be tailored to the significant physicochemical constraint for each bioactive. The low solubility and poor bioaccessibility of curcumin were overcome by using nanoemulsions, Pickering emulsions, and particle-stabilized emulsions in curcumin studies. Studies on resveratrol and quercetin focused on oral delivery systems, encapsulation and nanoformulations for better bioavailability and formulation feasibility; studies on the functional lipids focused on the oxidation sensitivity and

digestive fate. The results exhibited that no single universal carrier can be suggested for all functional bioactives. Rational formulation design, however, should take into account the following: the carrier structure should be formulated to be compatible with the polarity of the compound to be carried, the pathway for degradation, gastrointestinal behavior, intended food matrix, and the desired release profile.

This review also indicates the need for physical characterization to understand delivery performance. Not only are these parameters technical, but they dictate the ability of a carrier to be useful in a nutraceutical or functional food system. The delivery systems used for food colloidal food product need careful characterization since their stability can be affected by aggregation, creaming, coalescence, Ostwald ripening, phase separation, and oxidation that may lead to degradation of the protection of the bioactives and affect the final product performance [38].

Emulsion-based delivery systems played a particularly significant part in the evidence included. Curcumin, omega-3 oils, phytochemicals and other lipophilic bioactives were recurrently associated with the nanoemulsions and Pickering emulsions. They are appealing since they can enhance the dispersion of hydrophobic compounds and can be designed to have controllable digestibility and release by varying emulsifier and interfacial characteristics. But there's also a need to consider where ingredients come from, environmental stability, processing tolerance, and storage characteristics in emulsion systems. The growing adoption of natural and sustainable emulsifiers is thus important to the development of functional products, with respect to their technological efficiency and acceptability for use in the food sector [39].

The probiotic delivery findings also differed from the phytochemical and lipid-based delivery findings as the primary aim was not improving the solubility of the probiotics but preserving their viability. Probiotic encapsulation and nanocarrier-mediated delivery were primarily related to the protection of living cells from stress in the processing and storage phase and from gastric acid, bile salts, and intestinal transit. The discussion continued with hydrogels and co-encapsulation systems, which extended the discussion of delivery to include controlled delivery, multi-bioactive compatibility, and synergistic formulation design. The results indicate that future requirements for pharmaceutical–nutraceutical delivery systems will be to incorporate more than one formulation objective, and not to address a single stability or solubility problem.

The review focuses on convergence in the pharmaceutical delivery science and functional food formulation from a pharmaceutical delivery perspective. The most important conclusion is that the delivery system of a nutraceutical should be evaluated from a formulation perspective based on the composition of the carrier, stability, release, bioaccessibility, digestibility, safety, scalability and reproducibility. Nanotechnology-based encapsulation offers valuable solutions to achieve these goals, but there are significant challenges that need

to be addressed to ensure that the encapsulated products are safe for consumption, compliant with regulatory requirements, technically viable to manufacture, and successful when applied to actual food products [40].

In general, the studies herein presented confirm that complex delivery systems are needed to ensure the stable, bioavailable and application-ready delivery of the functional food bioactives in the form of effective pharmaceutical–nutraceutical products. Further studies are needed to incorporate carrier evaluation, standardized digestion models, storage stability testing, release kinetics, safety assessment, and scale-up parameters. The better correlation of the pharmaceutical delivery principles with the design of food grade carrier will make its nutraceutical products even more reliable and translatable [41].

5. Conclusion

This is a systematic review that extracted the latest evidence regarding advanced pharmaceutical–nutraceutical delivery systems for functional food bioactives. Results indicate that the design of the delivery system plays a key role in achieving the functional application of bioactive compounds. The following formulation issues were reported in the studies included in this review: low aqueous solubility, poor stability during processing and storage, low bioaccessibility, limited bioavailability, sensitivity to oxidation, low gastrointestinal protection, uncontrolled release, and low viability of probiotics. There are several major delivery approaches, such as nanoencapsulation, micro/nanoencapsulation, nanoemulsions, Pickering emulsions, lipid-based nanocarriers, SLNs, NLCs, hydrogels, probiotic encapsulation systems, nano-suspensions and co-encapsulation platforms. Emulsion-based systems showed a strong representation in functional lipid delivery, curcumin, and phytochemical delivery; meanwhile, the lipid-based systems were relevant to hydrophobic nutraceuticals, omega-3 oils, DHA, and functional lipids. Probiotic delivery systems primarily appeared to be correlated to microbial protection and viability, while hydrogels and co-encapsulation platforms appeared to be correlated to controlled release and/or multi-bioactive formulation design. The review emphasizes the growing similarities between pharmaceutical delivery science and functional food development. The biological potential of functional food bioactives is not the only parameter to take into account when evaluating their performance; their formulation stability, carrier compatibility, release behavior, digestibility, and performance on the basis of bioavailability is to be taken into account. In general, the advanced delivery systems offer a potential pathway to transform food-based bioactives into stable, bioavailable, and application-ready pharmaceutical–nutraceutical products. Comparative formulation studies, standardized in vitro digestion models, long term stability testing, safety evaluation, scale up feasibility and validation in real food matrices should be a focus of future studies to develop reliable functional food and nutraceutical delivery systems.

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