Hindawi
Journal of Food Processing and Preservation
Volume 2023, Article ID 5578382, 21 pages
https://doi.org/10.1155/2023/5578382

Review Article

Encapsulation of Hydrophobic Bioactive Substances for Food Applications: Carriers, Techniques, and Biosafety

Darya O. Shavronskaya,[1] Alina O. Noskova,[1] Natalia N. Skvortsova,[1] Parise Adadi,[2] and Elena A. Nazarova[1]

[1]*SCAMT Institute, ITMO University, Lomonosova Street 9, 191002 St. Petersburg, Russia*
[2]*Department of Food Science, University of Otago, Dunedin 9054, New Zealand*

Correspondence should be addressed to Parise Adadi; pariseadadi@gmail.com and Elena A. Nazarova; nazarova@scamt-itmo.ru

Received 2 February 2023; Revised 3 June 2023; Accepted 28 October 2023; Published 28 November 2023

Academic Editor: Akhilesh K. Verma

Biologically active substances (BASs) are used as novel ingredients to design functional foods. These functional foods are alternate approaches to treat or cure chronic diseases. However, the application of BASs is limited due to their hydrophobic nature, low bioavailability, sensitivity to gastric acid, and environmental conditions (i.e., high temperatures, radiation, pH, and oxygen). Thus, research has been channeled to find ways of curbing these limitations. This review provides an overview of the modern methods for BAS encapsulation, carrier classifications, benefits, and drawbacks as well as the biosafety of encapsulated BASs. Encapsulation of BASs into organic/inorganic carriers or composites overcomes the limitations mentioned above. In addition, encapsulation enables the controlled release of active compounds to target cells. The market for encapsulated foods has grown globally at a significant pace due to their various applications as functional foods, dietary supplements, and other products. It is estimated that by 2027, the market worth of encapsulated foods will be valued at $17 billion.

1. Introduction

Biologically active food additives (BAFAs) are either natural or artificial biologically active substances (BASs) used to enhance nutritional values of plant- and animal-based food products in a form of functional foods [1]. BASs have been reported to exert numerous biological activities (i.e., antioxidant, anticancer, anti-inflammatory, antiangiogenic, neuroprotective, and antiobesity) of health benefits on humans [2, 3]. BASs are generally hydrophobic, chemically unstable in food system, and prone to degradation, especially when exposed to oxygen, light, humidity, and high temperature [4]. For example, the oxidation of phenolic compounds can develop unpleasant tastes and off-odors in food products, thus negatively influencing the shelf life and organoleptic features [1]. Therefore, encapsulation is considered as a feasible alternative to preserve the quality of BASs and enhance their applicability in the food industry [5].

Encapsulation is a process of incorporating bioactive compound (core material) into external shell commonly referred to as a carrier material [6]. It is a promising technique used to preserve the nutritional value [7], improve solubility [8, 9] and oxidation stability of active ingredient [10, 11]. The carrier, an encapsulating agent (also known as external phase, wall material, shell, or matrix) is used to shield BASs (designated as internal phase, active agent, or core) from light, oxygen, pH, moisture, heat, shear, or other extreme conditions (gastric juice) in a form of capping or coating [5]. The carriers protect the BASs from the harsh environment conditions until their controlled release, thus enhancing bioavailability [12]. It is reported that a carrier material must adhere to carefully selected desired release criteria [13]. Globally, as of 2022, the value of food encapsulation market is $11.4 billion and is expected to increase by 2027 to $17 billion. This market is dominated by the US due to health awareness, the need to prevent chronic diseases

coupled with promotion of lifestyle by patronizing nutraceutical and functional foods [14]. Other key players, mostly developed countries, include Germany, Ireland, The Netherlands, UK, Switzerland, Australia, Israel, and Italy [15]. Surprisingly, no developing countries made the list partly due to the cost involved in the research and development of encapsulated foods.

Encapsulation methods such as electrospinning [16], electrospraying [17, 18], spray drying [19, 20], microfluidics [21, 22], extrusion, 3D printing [23], coacervation [24], lyophilization [25], incorporation into nanotubes [26], porous micro-/nanospheres [27, 28], nanocomposites [29, 30], isoelectric precipitation [31], antisolvent coprecipitation [32], and ionic gelation [33] introduce hydrophobic phenolics, alkaloids, oils, vitamins, food colorants, and flavors into carriers without altering their chemical and biological properties. In addition, encapsulation masks unpleasant tastes and flavors in food, thereby increasing consumer satisfaction of a product. Therefore, this review highlights the recent advancements in encapsulation and biosafety of encapsulated BASs in the food industry.

2. Carrier Classification

Carbohydrates, proteins, lipids, and other organic and inorganic materials are used as carriers during encapsulation of BASs [5]. However, carrier material must meet certain criteria to be suitable for engineering encapsulation systems. Some of the criteria include the following characteristics (Table 1): (1) structural: composition and phase state; (2) functional: solubility, viscosity, particle size, morphology of the surface, and total charge of particles; (3) organoleptic: color, flavor, and aroma; (4) physicochemical: resistance to changes in pH, temperature, humidity, oxidizing agents, and radiation; (5) physiological: release mechanism, conformational changes in the gastrointestinal tract (GIT), release rate, and toxicity; (6) economic: financial availability of materials and technologies; (7) cultural, religious, and food restrictions [34, 35].

Carriers can further be divided into several groups (Figure 1) based on their morphological structure [36], phase state of substances [37], and nature of the material [36].

2.1. Organic Carriers. Natural polymers are preferred materials for encapsulating bioactive food compounds due to their unique characteristics such as nontoxicity, edibility, and biocompatibility. Organic carriers can be subdivided into 4 groups, namely, (1) lipids, (2) carbohydrates, (3) proteins, and (4) their composites: protein + protein, polysaccharide + polysaccharide, and protein + polysaccharide (Table 2) [4]. For instance, a lipid-based carrier can be a single oil/water (O/W), water/oil/(W/O), or double O/W/O, W/O/W emulsions, and liposomes which consist of a single or double layer of phospholipids. Encapsulation in liposome is one of the most popular methods of using lipids as the main wall components [5]. Lipid carriers can be used to encapsulate lipophilic (i.e., carotenoids and essential oils) and hydrophilic (i.e., water-soluble vitamins and flavonoids) bioactive compounds [43–46]. Nanostructured lipid carriers showed good physical stability, adjustable particle size, and controlled and extended release of bioactive compound [47].

Natural polysaccharides, notably starch [48], cellulose [49], chitosan [50], inulin [51], dextrin [52], hyaluronic acid [53], fucoidan [54], and pectin [55], are used as substrates to synthesize amphiphilic polysaccharides via octenylsuccination [56], acetylation [57], and esterification with fatty acids [58]. In addition, semisynthetic polysaccharides with grafted hydrophobic groups and synthetic polysaccharides had attracted attention as wall materials [59].

Chitosan, a cationic polyelectrolyte is widely applied in pharmaceutical and food industries due to its unique properties, such as mucoadhesiveness, nontoxicity, biocompatibility, biodegradability, and extractability from economically advantageous sources [60]. Chitosan is water-soluble and positively charged at lower pH and thus forms complexes with negatively charged molecules, such as gum Arabic (GA), carboxymethyl cellulose, alginate, and heparin [61]. Many studies have explored the interactions of chitosan with biopolymers or ions, to design particles/capsules loaded with BASs (Table 2).

Animal-derived proteins (whey protein isolate [62], whey protein concentrate [24, 63], soy protein isolate [63], egg protein [64], collagen [65], gelatin [63, 66], zein (corn protein) [16, 67, 68], and casein [69]) were successfully used as a carrier materials to encapsulate BASs, despite their allergenicity [4]. The demand for eco-friendly and vegan products forges the path for plant-based proteins as wall materials coupled with their abundance in nature, low cost, and less allergenicity [70].

The potential capsule formation from aqueous solutions of dextran, maltodextrin, resistance starch, pullulan, fructooligosaccharides, whey protein concentrate of milk, and soy protein isolate was investigated [71]. Among the materials, only dextran, pullulan, and whey protein formed capsules about 1 mm in size. The sprayability differences were associated with the low viscosity coupled with high surface tension values. Nevertheless, soy protein with high molecular mass (Mw 30,000-350,000) was not a suitable material due to strong inter- and intramolecular forces that hinderedchain entanglement [71]. The authors further explored electrospraying which denatured soy protein and improved the intermolecular interactions between protein chains and solvent. The addition of gums (guar or xanthan gum) and surfactant (Span20) modified the aqueous hydrocolloid dispersion properties and enhanced capsule formation through electrospraying [71].

2.2. Inorganic Carriers. The design of nanoparticles (NPs) and nanoencapsulation systems (considered dimensions of developed nanocarriers are less than 1 μm in the general case and less than 100 nm in the pharmaceutical and cosmetic fields) can significantly increase the surface area to volume ratio of nanosystems. It is reported that nanoscale particles can easily penetrate the cellular walls, thus improving bioavailability of BASs [36]. However, the size of the particles can enhance mucoadhesive ability and susceptibility to enzymatic degradation [36].

Table 1: Effect of various parameters on carrier efficiency.

Parameters	Purpose	Carrier material	BASs/BAFAs	Encapsulation effect	Ref
Structural	Composition of materials and auxiliary components	MD GA WPC MD-WPC GA-WPC GA-MD	Blackberry juice *Lactobacillus acidophilus*	Stabilized bioactive compounds and enhanced viability of *L. acidophilus*	[38]
Functional	Solubility Viscosity	GA MD	Propolis	Decreased viscosity and enhanced solubility of MD and GA	[39]
Organoleptic	Flavor	Palm oil Camellia oil Gelatin Sodium caseinate	Bitter peptides from wheat gluten	Masked bitterness by forming an intermediate lipid layer which reduces direct contact with taste buds	[40]
Physicochemical	Resistance to temperature	Potato starch	Curcumin	Enhanced thermal stability (180°C, 2 h) compared to unencapsulated curcumin	[41]
Physiological	Release mechanism and rate	Corn starch	Ascorbyl palmitate	Slowed release rate under simulated GIT conditions	[42]

GA: gum Arabic; MD: maltodextrin; WPC: whey protein concentrate.

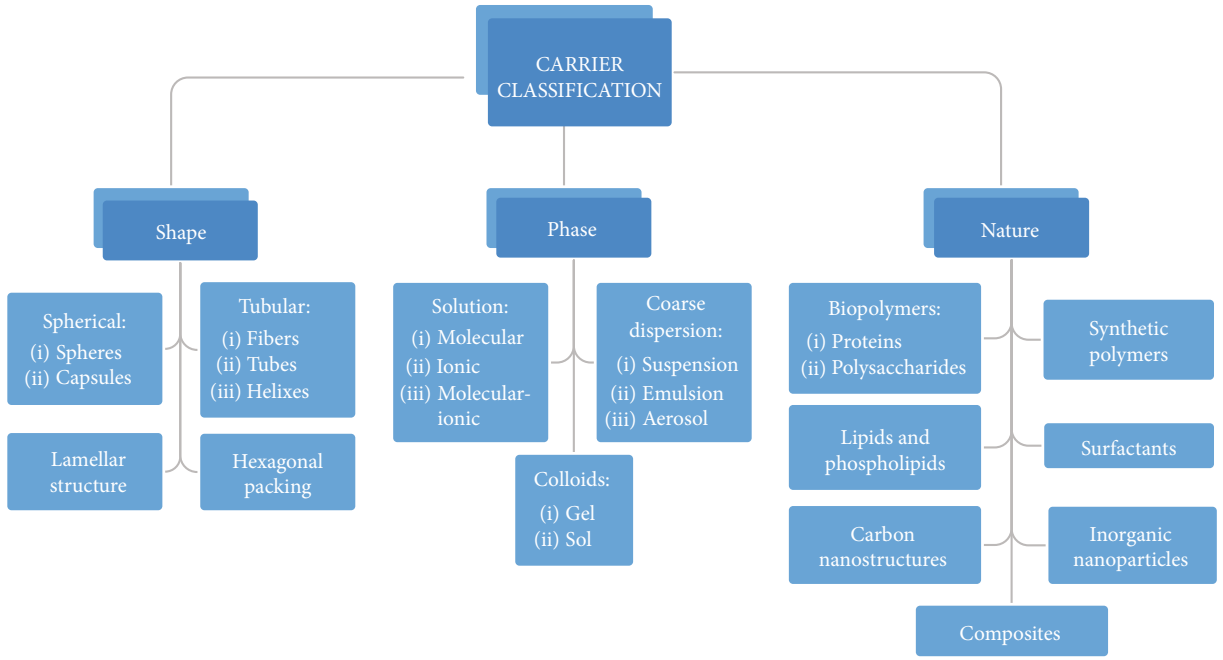

Figure 1: The scheme of carrier classifications.

Inorganic NPs as BAS carriers are characterized by easily synthesize, particle size control, high availability, biocompatibility, stability, and efficient affinity with encapsulated biomolecules [80, 81]. The difference in composition, shape, surface morphology, and charge significantly influenced the release mechanism and potential toxicity of nanocarriers (Figure 2) [82].

Inorganic NPs can be divided into several groups: (1) metals/metal oxides (mostly spherical): gold, silver, platinum zinc, aluminum, iron (II, III), or titanium (IV) oxide NPs [83]; (2) silicon oxide (IV) NPs [84]; (3) carbon (spherical, elliptical, cylindrical, and tubular) [85]; (4) quantum dots [86]; (5) layered double hydroxides (LDHs) which consist of positively charged hydrotalcite-like layers of metal hydroxide and interlayer regions occupied by anions and water molecules and stabilized by hydrogen bonding [87]. However, encapsulation of BASs into inorganic NPs is currently limited in the food industry. Metal NPs and their complexes are mainly used for drug and biomolecule (proteins and nucleic acids) deliveries to target cells as well as designing antimicrobial films and bionanosensor [88].

Table 2: Carrier-based natural polymer composites.

Carrier material	Addition to carrier material	Carrier formation mechanism	BASs/BAFAs	Encapsulation method	Particle size	Food application	Ref
Chitosan	GA MD	Electrostatic interaction and enzymatic cross-linking	Peppermint oil	Complex coacervation followed by spray drying	10–125 μm	Vegan system for potential applications in food	[72]
	GG	Intermolecular hydrogen bond interaction	Astaxanthin	Pickering emulsion	22–48 μm	Natural food-grade NPs for designing functional foods	[73]
	TPP	Electrostatic interaction between the phosphate group in TPP and the amino in CS or cross-linking/hydrogen bonds between CS and TPP	Curcumin	Ionic cross-linking	280 nm	Edible coating	[74]
WPI	BC	Hydrophobic interactions or hydrogen bonding	Catechin	Electrospraying	180–240 nm	Design catechin-encapsulated foods with longer shelf life	[17]
	LRA	Reactive sulfhydryl groups (-SH); C-N stretching vibration or N-H bending vibration; hydrogen bonding and hydrophobic interaction	Cholecalciferol	Heat-induced gelation	—	Delivery system of vitamin D3 as an additive in food industry, such as low-fat food, puddings, soft capsules, and fruit drinks	[75]
	Dextran	Conjugates prepared through Maillard-based glycation	*Lactobacillus plantarum*	Extrusion	7–8 μm	Development of functional probiotics	[76]
SA	SPI	Intermolecular hydrogen bonds and/or weak electrostatic attraction between the carboxylic anionic groups on the polysaccharide chain and cationic groups on protein surface	Lycopene	Emulsification (emulsion gel beads)	8 μm	Encapsulated food lipid-soluble nutrients	[77]
	CP MD	Electrostatic interactions (maximum binding capacity of Zn^{2+} is higher than that of Ca^{2+} because of the former's ability to bond to the OH− and COO− groups of alginate and pectin, while calcium can only interact with COO− groups)	α-tocopherol/ lime oil/ rosemary oil	Ionic gelation followed by spray drying	233–332 nm	Food additives	[78]
	CS	Electrostatic interaction between Ca^{2+} ions and $-COO^{-}$ group	*Moringa oleifera* leaf extract	Ionic gelation	80–120 nm	New advanced/intelligent food products	[79]

BC: bacterial cellulose; CP: citrus pectin; CS: chitosan; GA: gum Arabic; GG: guar gum; LRA: lotus root amylopectin; MD: maltodextrin; SA: sodium alginate; SPI: soy protein isolate; TPP: tripolyphosphate.

Inorganic NPs can be a polymer matrix by nanocomposite formation. Nanocomposites are new class of materials, used as biodegradable and edible films [89]. The demerits of these nanocomposites include nonuniform dispersion of NPs through organic system and agglomeration. It is reported that modifying surface of particles may curb the issues and improve their applications [90]. LDHs can form positively charged layers within a three-dimensional grid of silicate layers of nanocomposites that improve the mechanical properties of final materials (Figure 2).

Encapsulation efficiency (EE, %) and loading capability (LC, %) are key quality indices of an encapsulation system. EE is defined as the ratio of the loaded amount of core material to the total mass of the employed core material, whereas LC is calculated as the loaded mass of core material, divided by the mass of the whole encapsulation system [91]. The EE and LC values vary widely and depend on the type of core materials used, the composition, ratio, and encapsulation method, among others [92, 93].

3. BAS Characteristics

Functional food is an emerging market worth over $267 billion by 2027 [94] in the food industry [1]. Functional food

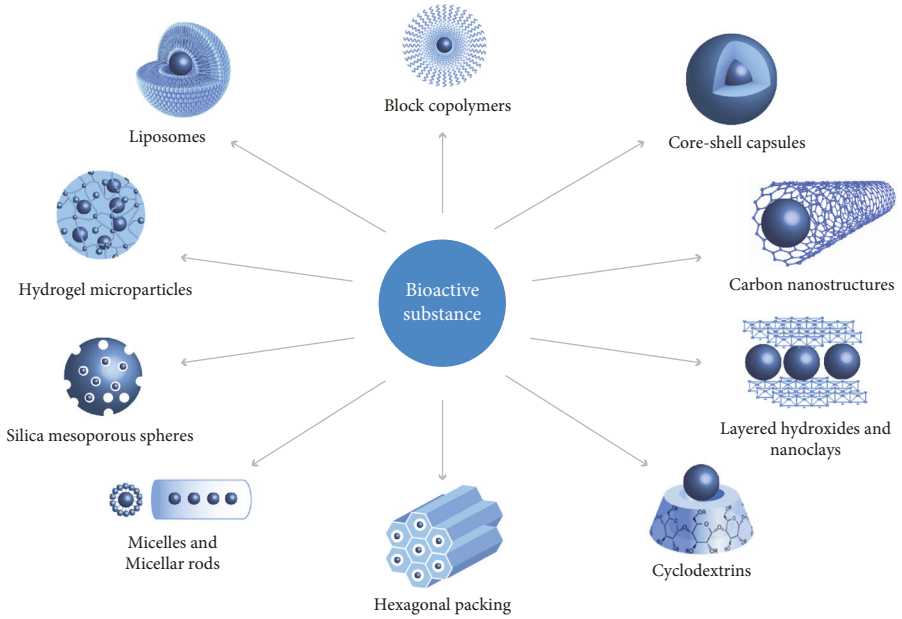

Figure 2: Encapsulation of biologically active substances in various types of carriers.

products enriched with bioactive compounds are limited due to their poor bioavailability, solubility, off-flavor, and less stability during processing and storage [1]. Different encapsulation systems have been developed to overcome these drawbacks.

Bioavailability is defined as the fraction of nutraceutical that reaches the systemic circulation and specific sites where it carries out biological functions on the consumer [95]. For example, a zein nanoparticle/oil double epigallocatechin gallate- (EGCG-) loaded Pickering emulsion was prepared [96]. The results showed that the encapsulated system released less EGCG with enhanced bioavailability compared to free-form EGCG. The EE was approximately 52% and remained unaltered for 8 weeks under different storage conditions [96].

Poor water solubility is one of the key characteristics of hydrophobic BASs (e.g. carotenoids, fat-soluble vitamins, polyphenols, and fatty acids) [97, 98]. Encapsulation of these ingredients broadens their application in the food systems. Others have used GA and maltodextrin as wall materials to encapsulate propolis extract by spray drying. The microparticles had high EE (79%) and enhanced antioxidant activity [39]. The authors used maltodextrin and GA due to their high solubility and low viscosity, thus simplifying the spray drying processes. The encapsulation showed good retention of compounds present in the propolis microparticles [39].

Masking off-flavors is an efficient tool for taste modification. Rajanna et al. [99] used pullulan (PUL) during electrospinning of bitter casein-derived peptides for milk fortification. The peptide-loaded nanofibers had a diameter and EE of 100 nm and 86%, respectively. Fourier-transform infrared spectroscopy (FTIR) spectra and X-ray diffraction (XRD) diffractograms showed no interaction between the functional groups of peptides and pullulan, thus retaining their functionality [99].

High stability of BASs in acidic conditions, UV light, temperature, and ionic strength should also be considered when designing encapsulation system. Iqbal et al. [8] utilized modified starch as an emulsifier in O/W nanoemulsions of curcumin and quercetin encapsulation. The results showed that 5 wt% modified starch, and 10 wt% oil formed a stable formulation with 175 nm particle size. Nanoemulsions maximized the solubility of the compounds compared to oil and water. In addition, nanoemulsions loaded with curcumin and quercetin were stabled for 5 months under different processing conditions and thus provide an avenue for future application in the food industry [8].

Drosou et al. [11] encapsulated β-carotene dissolved in corn oil to form food-grade nanofibers from pullulan (PUL) and whey protein isolate (WPI) via coaxial electrospinning. The EE of WPI: PUL and PUL nanofibers were 90% and 95%, respectively [11]. According to the kinetic plots of degradation, oxidation of the core substance (β-carotene) was delayed under different storage temperatures, water activity, and UV-Vis irradiation compared to PUL. This intriguing observation was ascribed to the stronger interactions between protein components and β-carotene from being closer to the surface of the nanofiber [11].

4. Encapsulation Methods

Electrospinning [16], electrospraying [17, 18], spray drying [19, 20], microfluidics [21, 22], extrusion, 3D printing [23], coacervation [24], lyophilization [25], incorporation into nanotubes [26], porous micro-/nanospheres [27, 28], nanocomposites [29, 30], isoelectric precipitation [31], antisolvent coprecipitation [32], and ionic gelation [33] are the main encapsulation methods and details (Figure 3 and Table 3) described below. It is important to consider the sensitivity of BASs and processing conditions, as this may influence its functionality (Table 3).

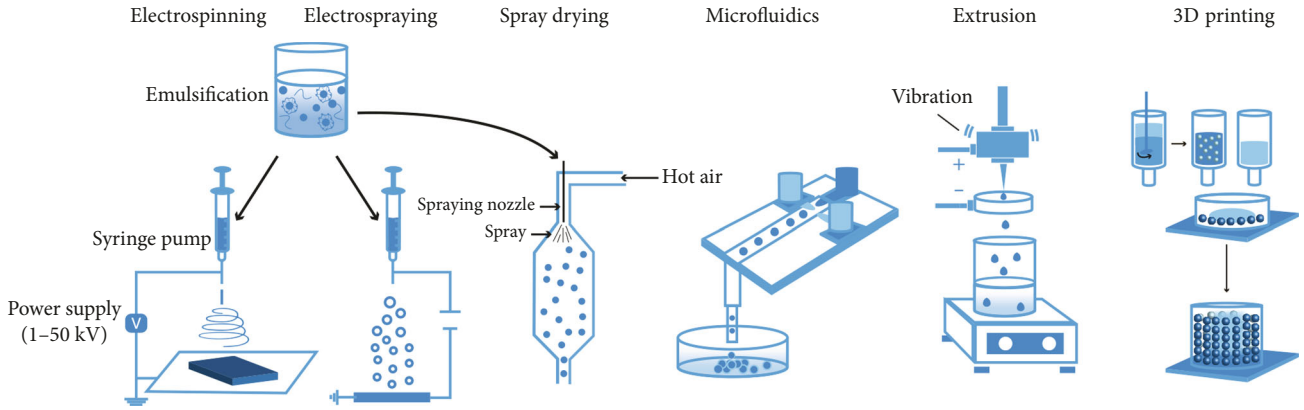

Figure 3: Main principles of different encapsulation methods used in the food industry.

4.1. Electrospinning and Electrospraying. Electrospinning and electrospraying are single-stage technologies which use high electrostatic potentials of stretching polymer solutions (or polymer melt) into fibers or particles, respectively. These technologies are cost-effective, straightforward with several benefits, including a wide range of reusable spinnable materials, controlled processing conditions, and the ability to produce fibers without high temperature or pressure [100, 101].

A typical electrospinning and electrospraying consists of four components mainly a high voltage source (1-50 kV), syringe pump, spinneret, and a collector in the form of flat plate or rotating drum (Figure 3) [102]. In electrospinning and electrospraying, polymer solutions (or polymer melts) are injected into the capillary spinneret at 0.01–5 mL/h flow rate which forms droplets when exiting the needle nozzle. It is reported that when electric voltage passes through the spinneret and charges the droplet, it leads to the formation of a "Taylor cone" [103]. When the voltage exceeds the critical value at which the repulsive force overcomes the surface tension of the droplet from the end of "Taylor cone," an electrospun fiber is formed [104]. It is reported that the utilization of higher molecular weight substances can lead to jet formation which is ascribed to efficient entanglement of polymer chains. However, when the concentration of the solution is low, aerosol droplets are formed [104]. The highly charged droplets are deposited on the collector as micro NPs [105]. Electrospinning and electrospraying require no heating system and thus are suitable for encapsulating very sensitive BAFAs (i.e., probiotic bacteria) [106]. The main drawbacks are challenges with upscaling [107] and high fiber diameter distribution in the case of electrospinning [108].

The production of electrospun or electrosprayed particles are dependent on solution properties (i.e., conductivity, viscosity, and surface tension), tool parameters (i.e., applied electric field, solution flow rate, and distance between the needle tip and collector), and environmental conditions (i.e., temperature and humidity). By changing parameters, the size and morphology of encapsulated structures can be altered for specific applications [102]. The direct incorporation of BASs in polymer carrier or randomly distributed in fibers/particles (cosolubilization of core and wall materials) is commonly practiced during encapsulation. Another strategy is to form a core-shell structure using two capillaries, by inserting the smaller capillary into the larger one. The active component is delivered through the internal capillary spinneret while polymer solution is extruded via an external capillary tube [11]. This approach is multipurpose as the liquid core does not require electroforming.

Paximada et al. [17] applied electrospraying technique to encapsulate catechin in protein-cellulose particles. The EE was 98% with varied particle size between 180 and 240 nm. Further analysis showed that encapsulated catechin was stable and withstood heating, moisture, and dissolution [17]. This study demonstrated that,lectrospraying can be used to produce edible particles with prolonged shelf life. In addition, Khoshakhlagh et al. [109] designed a nanocapsule from *Alyssum homolocarpum* seed gum (AHSG) to encapsulate D-limonene by electrospraying at 20 kV and 0.1 mL/h flow rate. The addition of AHSG (0.5% w/w) with various concentrations of D-limonene (from 10% to 30% of the gum weight) and 0.1% Tween 20 formed stable smooth capsules [109]. The authors reported that 10 and 20% D-limonene decreased the surface tension and conductivity of the solution. In addition, the nanocapsule morphology was changed to nanofibers at 30% D-limonene O/W emulsion. The particle size ranged between 35 and 90 nm and increased with the increase of D-limonene concentration [109]. The EE and LC of D-limonene nanocapsules for 10%, 20%, and 30% O/W emulsions are listed in Table 3. These experiments showed that electrosprayed AHSG NPs are new and effective carriers for BAFA encapsulation.

Moreno et al. [16] encapsulated phenolic-enriched extracts (PEE) from pulp, seeds, and skin of orange chilto into zein-based matrixes using the electrospinning technique. The addition of zein matrixes increased the thermostability of PEE with high EE (more than 90%, see Table 3). The cross-linking of zein fibers with glutaraldehyde vapors improved the water and morphological stability of carriers. Furthermore, the release of phenolic compounds (rosemary acid, caffeic acid, and its derivatives) was delayed and thus increased the shelf life of their antioxidant properties [16]. This study demonstrated that it is possible to

Table 3: Efficiency comparison of BAS/BAFA encapsulation methods.

Encapsulation method	Carrier material	BAS/BAFA	EE (%)	LC (%)	Results	Ref
Electrospraying/ electrospinning	WPI-BC	Catechin	98		High thermostability High stability under moisture	[17]
	WPC (30%)	OLE (0.05%)	84		Improved polyphenol profile of OLE	[18]
		OLE (0.1%)	77			
	WPC (20%)	OLE (0.05%)	71			
		OLE (0.1%)	68			
	SPI	α-Linolenic acid	67		High thermostability Emulsions produced via high-speed homogenization (HSH) were significantly different compared to HSH and ultrasonication	[63]
	WPC		61			
	Gelatin		40			
	AHSG	D-limonene (10%)	93	9	Morphology of capsules changed (irregular shape → spherical → fibers) with enhanced flavor	[109]
		D-limonene (20%)	87	16		
		D-limonene (30%)	75	20		
	Zein	PEE (from pulp)	94		High thermostability Cross-linked zein fibers (with glutaraldehyde vapors) had high water stability coupled with slowed release of BASs	[16]
		PEE (from skin)	92			
		PEE (from seed)	90			
	WPC	Lycopene	75		High thermostability High stability under moisture	[156]
	Dextran		58			
	CS		3			
Spray drying	WPC	Lycopene	28		Temperature influenced the stability of BASs Poor encapsulation efficiency	[156]
	Dextran		16			
	CS		1			
	Rice protein	Propolis extract	90		Preserved antioxidant activity High thermostability (for particles produced with pea and soy proteins) Low hygroscopicity	[19]
	Pea protein		89			
	Ovalbumin		73			
	Soy protein		70			
	GA-XG (0% PJ)	Pomegranate seed oil	93	14	High thermostability Improved oxidative stability of oil PJ increased EE PJ increased phenolics and influenced powder color	[20]
	GA-XG (50% PJ)		94	14		
	GA-XG (100% PJ)		97	14		
Coacervation	SPI-CS	Algal oil	96		High oxidative stability Low polydispersity	[118]
	SPI-CS (with transglutaminase)		97			
	WPC-PE	D-limonene	88		WPC : PE = 4 : 1 had high L* index (color value)	[24]
	Casein-GT	β-Carotene	79		Increased antioxidant activity High physical stability	[69]
	Casein	Vitamin B_9	40	31	Lysine or arginine prevented aggregation of particles in an aqueous environment High oral bioavailability	[157]
Lyophilization	WPI-MD-SA (0% MD)	Flaxseed oil	27		Enhanced oxidation of the oil	[62]
	WPI-MD-SA (10% MD)		64			
	WPI-MD-SA (20% MD)		95			
	MD	Catechin NE (10% w/w MD)	77		Improved water solubility High antioxidant activity	[25]

Table 3: Continued.

Encapsulation method	Carrier material	BAS/BAFA	EE (%)	LC (%)	Results	Ref
	GA	Catechin NE (10% w/w GA)	82			
	MD-GA	Catechin NE (10% w/w MD-GA)	81			
	SPI	*Lactobacillus acidophilus*	95		Improved survival and viability in gastrointestinal conditions	[120]
	SA		92			
	I-CG		88			
	Starch		79			
Microfluidics	PCL	Chlorophyll	58		High photostability	[122]
	Liposomes	Vitamin D_3	88			
	Liposomes-CS (0.01% w/v CS)	Vitamin K_2	98		Improved aggregation stability and mucoadhesiveness (for polymer–lipid hybrid particles)	[22]
	Liposomes		94			
	Liposomes-CS (0.005% w/v CS)		98			
	W/O/W emulsion	Elderberry extract	55		High color retention	[21]
		Norbixin	75			
	O/W emulsion-protein (gelatin : casein = 1 : 1)	Fish oil			High oxidative stability	[126]
Extrusion (3D printing)	SA	*Lactobacillus acidophilus* LA3			Stabilized under storage conditions Improved survival and viability in gastrointestinal conditions	[134]
	SA-shellac					
	WPC (10%)	*Bifidobacterium longum* BL-05	85		Increased storage stability Improved survival and viability in gastrointestinal conditions	[135]
	WPC (7.5%) + PE (0.5%)		89			
	WPC (5%) + PE (1%)		93			
	PE (2%)		95			
	W/O/W emulsion-SA	*Bifidobacterium lactis* BB-12			Stabilized under storage conditions Improved survival and viability in gastrointestinal conditions	[136]
	SA	C-Phycocyanin			High thermostability	[129]
	SA	Microalga *Arthrospira platensis*			Improved color stability Maintained antioxidant activity	[23]
Introduction into nanotubes	MWCNTs (with peptide linkers)	Vitamin B_9			Enhanced resistance to enzymatic degradation	[85]
	α-LA	Lycopene (1 mg/mL)		5	High thermostability High photostability Released lycopene under low pH condition Improved antioxidant activity Improved colloidal stability	[26]
		Lycopene (0.8 mg/mL)		5		
		Lycopene (0.6 mg/mL)		2		
	α-LA	Caffeine (caffeine : α − LA = 1.5 : 20)	97	9	Improved physical stability	[142]
		Caffeine (caffeine : α − LA = 2 : 20)	97	12		

Table 3: Continued.

Encapsulation method	Carrier material	BAS/BAFA	EE (%)	LC (%)	Results	Ref
Introduction into porous micro-/ nanospheres	MSNs-fucoidan	Curcumin (0.25 mg)	≈100	6	Improved water solubility Improved release rate (>80% within 24 h) Enhanced antitumor activity	[28]
		Curcumin (0.50 mg)	93	9		
	MSNs	Curcumin (0.25 mg)	89	5		
		Curcumin (0.50 mg)	81	9		
	MSNs-PLA	CEO			Sustained cumulative release profile Effective against *S. aureus* and *E. coli*	[27]
Development of nanocomposite materials	ZnFe-LDHs MgFe-LDHs	Vitamin C			Improved stability	[145]
	Zn-Al LDHs	Benzoate		24	Efficient antimicrobial activity Slowed release kinetics	[29]
		2-Chloro-5-nitrobenzoate		40		
		p-Hydroxybenzoate		42		
	MMT-CS	Rosemary EO			Improved antimicrobial property Improved solubility and tensile strength	[158])
	SA-clay	Marjoram EO Cinnamon EO clove EO			Improved antimicrobial activity Marjoram EO had a higher antimicrobial effect	[159]
	MMT HNT	Thyme oil/orange oil Thyme oil/orange oil			Modulated aroma release	[30]
Isoelectric precipitation	Chickpea protein	Curcumin	79	9	High thermostability High photostability	[149]
	Krill protein	Krill oil (oil : protein = 20 : 80)	24	8	Reduced LC and EE Krill oil/krill protein ratio influenced surface structure Lipid classes and fatty acid composition were not influenced	[31]
		Krill oil (oil : protein = 40 : 60)	14	6		
		Krill oil (oil : protein = 60 : 40)	10	5		
Antisolvent coprecipitation	Zein-lecithin (zein : lecithin = 1 : 1)	Curcumin	≈100	5	High thermostability High photostability Improved solubility	[67]
	Zein		42	4		
	Lecithin		87	9		
Stepwise antisolvent precipitation	Gliadin	Curcumin	44	3	High thermostability High photostability Improved antioxidant properties	[32]
	Lecithin		71	5		
	Gliadin/lecithin		91	6		
	Gliadin/lecithin		87	6		
	Lecithin/gliadin		77	5		
Ionic gelation	GA-CS (GA : CS = 1 : 1)	Saffron extract (5 mg/mL)	29		High thermostability High photostability Improved oxidative stability	[33]
	GA-CS (GA : CS = 1 : 2)	Saffron extract (10 mg/mL)	52			

Carrier materials: AHSG: Alyssum homolocarpum seed gum; BC: bacterial cellulose; CS: chitosan; GA: gum Arabic; Gli: gliadin; GT: gum tragacanth; HNT: halloysite (clay); I-CG: iota-carrageenan; LDHs: layered double hydroxides; MD: maltodextrin; MMT: montmorillonite (clay); MSNs: mesoporous silica NPs; MWCNTs: multiwalled carbon nanotubes; PE: pectin; PLA: poly(lactic) acid; PLC: polycaprolactone; SA: sodium alginate; SPI: soy protein isolate; TP: tremella polysaccharide; WPC: whey protein concentrate; WPI: whey protein isolate; XG: xanthan gum; α-LA: α-lactalbumin. BAS/BAFA: CEO: clove essential oil; EO: essential oil; OLE: olive leaf extract; PFAs: polyunsaturated fatty acids; PEE: phenolic-enriched extracts; PJ: pomegranate juice; NE: nanoemulsion.

develop bioactive coating structures based on zein fibers containing chilto PEE as a promising packaging material for hydrophilic or lipophilic food ingredients.

Soleimanifar et al. [18] prepared NPs containing olive leaf extract (OLE) from whey protein concentrate (WPC) via electrospraying. The sizes of the spherical NPs (mean size = ~232.3 to 659.8 nm) depended on the concentration of applied WPC and OLE. The increase in concentration of OLE and WPC enhanced the EE (%). High performance liquid chromatography (HPLC) analysis showed that

nanocarriers from 15% WPC with 500 ppm phenolics had the highest concentrations of oleuropein, tyrosol, and caffeic acid. In contrast, carriers from 15% WPC and 1000 ppm phenolics presented the highest level of hydroxytyrosol [18]. This study further demonstrated that sensitive OLE can be encapsulated and used to design functional food and nanodelivery of pharmaceuticals. In the study of Fareed et al. [110], *Lactobacillus acidophilus*, a probiotic, was encapsulated in blended nanofibers of GA and polyvinyl alcohol using an electrospinning technique. The results showed that probiotic-encapsulated nanofibers had high average size, zeta potential, moisture contents, thickness, tensile strength, and elongation at break compared to the free probiotics. *In vitro* assay showed that encapsulated probiotics had a significantly high viability rate compared to free cells, which lost their viability under simulated gastrointestinal conditions [110]. The addition of starch/water soluble yellow mustard mucilage to electrosprayed nanocapsules loaded with thymol and carvacrol improved EE (84.10%), surface morphology, and release kinetics [111].

4.2. Spray Drying. Spray drying is a method of producing microparticle core-shell by rapid drying of dispersed substance under hot gas flow to disperse medium into insoluble shells [112]. In the nozzle of a spray dryer, the liquid flow disintegrates into small droplets which transit into a solid state due to rapid evaporation of the dispersed medium. It is reported that the significant increase in surface area led to intense mass and heat exchange between hot dry gas jets and droplets. Nowadays, spray drying is one of the commonly used methods of drying and microencapsulation of lipophilic compounds in the food industry [113].

The microencapsulation of propolis extracted from rice, pea, soy, and ovalbumin proteins as wall materials through spray drying followed by *in vitro* digestion analysis of the obtained microcapsules was reported [19]. Propolis is flavonoid-enriched material that confers health benefits to consumers. However, the utilization of propolis in the food sector is limited due to its undesirable aroma and poor solubility in water. Thus, microencapsulation masked the undesirable aroma, enhanced antioxidant activity, and EE (90.20%). The *in vitro* digestive system showed that pea protein-loaded microparticles with Minas frescal cheese had the best-controlled release profile compared to other proteins. Furthermore, rice protein-loaded microparticles were suitable for pudding fortification due to an excellent release of phenolic compounds (i.e., 100%) [19].

Yekdane and Goli [20] screened the properties and oxidative stability of pomegranate seed oil (PSO) microcapsules made from GA, xanthan gum enriched with pomegranate juice (PJ). Different concentrations (i.e., 0%, 25%, 50%, 75%, and 100%) of PJ were introduced into the solution of the capsule material before being spray-dried. The addition of 100% PJ increased EE (96.3%) of microcapsules with an intact and quite smooth surface. The experiment demonstrated that the encapsulation with pomegranate juice enhanced the oxidative stability of PSO [20]. Others have recently speculated that the addition of water-soluble yellow mustard mucilage enhanced the emulsion stability, EE (91%), and the release pattern ($R^2 = 0.991$) of the essential oils, thymol and carvacrol, and polyphenols [114].

4.3. Coacervation. Coacervation is a method of producing polymer droplets from the solution of a high-molecular compound (HMC), when conditions (i.e., temperature and composition) change [115]. Coacervation enables the transition from unrestricted mutual solubility of liquids, mixed freely, to a restricted mutual solubility. This system is divided into two layers: the layer of equilibrium liquid with a low content of HMC and the layer with a high concentration of HMC also called coacervate. Coacervation occurs in two- and multicomponent solutions of organic and inorganic compounds. However, aqueous solutions of proteins and polysaccharides are the most studied [116]. There are simple and complex coacervations. Simple coacervation is the interaction of the dissolved film-forming polymer with a low-molecular-weight nonsolvent (i.e., gelatin with ethanol or sodium sulfate). The simple coacervation method is used to microencapsulate oils, oil solutions, and water-insoluble BASs. On the other hand, complex coacervation involves the interaction of two polymers whose macromolecules are oppositely charged (i.e., aqueous solutions of gelatin and GA, acetone solutions of cellulose ethers, and polysiloxane) [115].

In microencapsulation of BASs via complex coacervation, two high-molecular-weight compounds interact with each other, thus one film-forming polymer, and the second is a precipitating polymer. Hydrophobic BASs are dispersed in an oil solution which is emulsified in a film-forming polymer solution. A high-molecular-weight nonsolvent is added to the emulsion, and pH adjusted (below isoelectric point) to charge the opposite polymers. Finally, the pair of macrocation and macroanion are attracted to each other and form the shell of the microcapsule [116, 117].

Yuan et al. [118] investigated the complex coacervation of soy protein isolate (SPI) with chitosan (CS) and algal oil. The results showed that the optimal complexation pH and CS/SPI ratio were 6.0 and 0.125 g/g, respectively. The rheological and microstructure analyses showed that SPI-CS coacervates had a viscoelastic solid behavior with a highly interconnected gel-like network structure [118]. The SPI-CS coacervate showed an increased EE (95.94%) with improved oxidative stability compared to the SPI-encapsulated microcapsule. Further transglutaminase of cross-linking enhanced the EE (97.36%) with lower lipid hydroperoxides and hexanal values [118].

Ghasemi et al. [24] encapsulated D-limonene in whey protein concentrate- (WPC-) pectin nanocomplexes. The results showed that nanocomplex fabrication of mixing 4% w/w WPC, 1% w/w low methoxyl pectin, and 50% w/w maltodextrin solutions at pH 3 had the least stability (83%), higher viscosity (35 mPa·s), and brightness (L^* index = 75.14) [24]. Atomic force microscopy revealed spherical NPs of WPC-pectin nanocomplexes with average size of 100 nm. The highest EE was 88% at pH 3. Finally, the optimum WPC/pectin nanocomplex (the ratio is 4 : 1) loaded with D-limonene may be used in the food industry to shield flavor active compounds during processing and storage with controlled release [24].

4.4. Lyophilization/Freeze Drying. Lyophilization is a soft drying technique of thermolabile substances (i.e., probiotics, fatty oils, and flavonoids). These thermolabile BASs are usually frozen, and the solvent is sublimated in a specialized vacuum unit before drying [119]. The advantages of lyophilization include low-temperature treatment and preservation of the dispersed phase, the structural integrity is maintained, and the biological activity of BASs is not altered.

Fioramonti et al. [62] lyophilized flaxseed oil microcapsules with maltodextrin (MD) at various concentrations (0, 10, and 20% w/w). The multilayer emulsions with interfacial layer were obtained by electrostatic precipitation of sodium alginate on oil droplets coated with whey protein isolate at pH 5. MD was added and exposed to freeze drying (-20°C) for 3 days at 40 Pa [62]. The results showed that sonication coupled with freeze drying significantly enhanced the oxidation of the oil. The addition of 20% MD to the emulsion increased the EE (95.44%). Also, an increase in the concentration of MD enhanced the water activity of microcapsules from 0.14 to 0.33 [62]. Others have also reported that an increase in wall materials improved the hygroscopicity and water solubility (92%) of catechin nanoemulsion [25]. In addition, catechin nanoemulsion which contained GA and mixture of GA and MD had high EE and flavonoid recovery values compared to MD alone. Furthermore, MD and mixture of GA and MD samples exhibited higher antioxidant activity compared to GA-treated samples [25]. The findings of the study may be applied to develop effective ingredients for functional foods or beverages.

Lactobacillus acidophilus encapsulated through lyophilization using various wall materials such as SPI, sodium alginate (SA), iota-carrageenan (I-CG), and starch was recently reported [120]. The EE of SPI (95%) and SA (92%) microbeads were higher compared to I-CG (88%) and starch (79%). Also, SPI and SA microbeads showed better survival rate compared to I-CG and starch ones. These findings suggest that SPI and SA are feasible materials for the microencapsulation of probiotics with improved viability under simulated gastrointestinal conditions and in food matrixes.

4.5. Microfluidics. Over the last two decades, microfluidic techniques have attracted great interest and grown exponentially in various fields, particularly in food science for the encapsulation of ingredients. An essential characteristic of microfluidic systems is the use of tiniest concentrations (up to 10^{-18} L) of fluids moving in a laminar flow within channels with dimensions ranging from tens to hundreds of microns (Figure 3) [121]. Microfluidic technology enables the repetitive fabrication of micron-size particles in a narrow size distribution and uniform shape. A common drawback of microfluidic technique is the inability to accurately control over processing variables; meaning one parameter cannot be changed independently over the other. However, various microfluidic strategies such as droplet microfluidics [122, 123], continuous flow thin film microfluidic [124], and rapid mixing microfluidic [125] enable control over the process parameters of the encapsulated particles, enhance stability and solubility of bioactive compound, and improve shelf life of functional foods.

Droplet microfluidics was used to formulate spherical polycaprolactone particles loaded with chlorophyll of 68 to 247 μm size. Encapsulation enhanced chlorophyll stability and thus harness its food applications [122]. Nanoliposomes encapsulated with vitamin D_3 and K_2 were successfully designed via semicontinuous microfluidic technique. The addition of chitosan enhanced the mucoadhesiveness and stability of designed liposomal structures and thus may be used to develop nutraceuticals [22]. Others have encapsulated natural pigments [21] and fish oil [126], using microfluidic. Norbixin and anthocyanins encapsulated W/O (palm oil)/W emulsions with particle sizes 180 μm and 190 μm and EE 60% and 50%, respectively, were reported [124]. In addition, the particle sizes of fish oil in casein, gelatin, and hydrolyzed whey protein O/W emulsions ranged between 80 and 100 μm. The authors claimed that the thin film vortex fluidic device (VFD) simplified W/O/W emulsions of fish oil to a one-step process without undesirable organic solvents inappropriate in food production, thus saving time and money [124]. A scale-up of microfluidic approaches can enhance high-throughput encapsulation of chemically diverse active ingredients [127].

4.6. Extrusion and 3D Food Printing. Extrusion is a direct and convenient method used to encapsulate biologically active compounds with the aim to extend shelf life [128, 129], controlled release [130–132], protective effect [133] of active ingredient in the food industry. Extrusion does not require organic solvents or high temperatures thus safe and suitable for encapsulating thermolabile biologically active compounds. This technique entails mixing the core component with a carrier, extruding the mixture through a nozzle and collecting droplets in a solidification bath, forming matrix-type particles (Figure 3). To improve the preservation of BASs, coextrusion method is preferred for the production of reservoir-type particles through coaxial nozzles [134]. A comparison of extrusion and coextrusion showed that *Lactobacillus acidophilus LA3* encapsulated via the latter method using alginate was 17% viable after 60 days of storage compared to the former [134]. Beside alginate, extrusion using whey protein concentrate and pectin was proposed as a novel technology of encapsulating BASs and probiotics against harsh gastrointestinal conditions [135]. Additionally, extruded *Bifidobacterium lactis* had a higher (98.5%) survival rate and *in vitro* gastrointestinal simulation (up to 86.1%) in various pH conditions [136]. Others have reported that extrusion enhanced the stability and shelf life of C-phycocyanin colorant compared to the free form (unencapsulated) [129]. Therefore, extrusion technology provides high encapsulation throughput for delicate and valuable BASs. Others have documented that coupling vibrating equipment with the extrusion process helped achieve a uniform droplet size (Figure 3) [128, 134, 137]. Dripping-extrusion method of encapsulation retained more hibiscus anthocyanin (48%) and color stability ($\Delta E = 1.42$) of yogurt during storage compared to the free extract [128]. Encapsulation parameters are essential as they influenced microparticle characteristics and the effectiveness of

protecting bioactive compounds from environmental and gastrointestinal conditions [137].

The optimum consumer preference of processed foods may be deciphered by understanding flavor perception in different encapsulation structures. Melt extrusion and fluidized bed drying encapsulated flavors in long chewable products obtained increased the flavor perception for an extended period. The authors further mentioned that various encapsulation techniques can be coupled to design desirable food products based on the intended purpose [132].

In recent years, 3D food printing technology has successfully been introduced in the food industry. The principles of the 3D printing technique involve a system based on gelatin, agar, and alginate. These, with other physical or chemical cross-linkers, undergo a liquid-solid transition and become hydrogels with the desired shape during printing (Figure 3). Cookies enriched with extract of microalga *Arthrospira platensis* were recently produced via 3D printing [23]. The encapsulated extract in alginate microbeads was stable under light, heat, and oxygen during baking with an extended shelf life compared to the free form [23].

3D printing of artificial plant tissues may open exciting possibilities to design a novel combination of aromas and textures with great potential in personalized food products. Others have encapsulated live plant cells in pectin gels and printed 3D objects (5×10^6 cells/mL) with precision and reproducibility. 3D food printing had no effects on cell viability and thus kept its functionality [138].

Enzyme encapsulation in hydrogels is of great interest as a reusable system in biocatalysis or analytical applications. Functional biological compositions can be implemented in microreactors, microfluidic devices, biosensors, or in the form of spheres for various applications. For these and other purposes, the transition to 3D structures may provide new opportunities in the food industry [139]. To be precise, the interaction of biomolecules encapsulated in a hydrogel with the surrounding liquid phase is a serious concern to consider when it comes to leaching of undesirable compounds, release control, and other molecule penetration. The combination of 3D bioprinting and automated high-throughput screening of β-galactosidase encapsulated in hydrogels based on poly(ethylene glycol) diacrylate using a mold and fill printing procedure was reported [140]. Therefore, 3D printing technology could be a promising alternative to encapsulate bioactive substances for designing functional foods.

4.7. Introduction of BASs into Nanotubes. Carbon nanotubes (CNTs) are nanoscale hollow tubular structures of carbon atoms, formed by rolling graphene sheet into a tube-like structure (Figure 2). CNTs are classified into single-walled carbon nanotubes (SWCNTs) and multiwalled carbon nanotubes (MWCNTs). The outer diameter of the tubes ranged between 0.4 and 2 nm for SWCNTs and 2 to 100 nm for MWCNTs [141]. Fraczyk et al. [85] encapsulated folic acid in multiwalled CNTs through peptide linkers. It was reported that the conjugated folic acid linked to MWCNTs was not toxic to cellular function and resisted proteolytic degradation for up to 7 days [85]. Others have documented the stability and functionality of caffeine nanotubes derived from α-lactalbumin (α-LA) [142]. Partial enzymatic hydrolysis of α-LA in the presence of a divalent ion produced edible nanotubes with a high potential in the food and cosmetic industries. The results showed that EE of caffeine reached 96.96% and loading capacity 9.21% for the 1.5/20 (w/w) ratio of caffeine/α-LA. Also, the increase in the ratio of caffeine/α-La (2/20 w/w) elevated the EE (97.16%) and LC (12.30%). It was estimated that more than 50% of caffeine encapsulated in α-LA nanotubes remained encapsulated at 8°C and pH 7.5 in the presence of 75 μg/mL EDTA [142]. Recently, Chang et al. [26] developed food-sourced protein nanotubes by self-assembly of partially hydrolyzed α-lactalbumin for lycopene encapsulation. The α-La nanotubes were characterized by 20 nm in diameter and 200–1000 nm in length. The encapsulated lycopene was stable under different temperature and UV light compared to unencapsulated ones [26]. During transition via gastrointestinal conditions, the nanotubes biotransform to nanospheres with a controlled release of lycopene to the target cell. The colloidal stability and antioxidant activity of the loaded lycopene were enhanced, and thus, lycopene-loaded α-La nanotubes can be incorporated into the dairy or other sorts of drinks [26].

4.8. Introduction of BAS into Porous Micro-/Nanospheres. Properties such as large surface area, ability to change pore diameters (from 2 to 50 nm), versatility (able to encapsulate both hydrophilic and lipophilic compounds), highly biocompatible, precise controlled release in the intestinal pH, and high thermal and chemical stability make mesoporous silica NPs (MSNs) (Figure 2) ideal candidates for encapsulating very sensitive BASs [141].

A complex NP containing disulfide bonds as a curcumin carrier using fucoidan and MSNs as the polymer matrix was designed. Scanning electron microscopy (SEM), transmission electron microscopy (TEM), dynamic light scattering, FTIR, N_2 adsorption, and desorption test showed that the mass ratio of MSNs to fucoidan was 2 : 1, with the smallest nanosphere particle size (295.6 ± 1.0 nm, -35.2 ± 0.8 mV). The EE and cumulative release rate were 90 and 80%, respectively, over 24 h [143]. This study further demonstrated that NPs are a promising composite for delivering BASs. Lu et al. [27] reported immobilized MSNs/clove essential oil incorporated into poly(lactic acid) films. The increase in MSN content in MSN/clove essential oil/poly(lactic acid) improved tensile strength, module,glass transition temperature, and antimicrobial activity of the nanocomposite. The results indicated that the nanoencapsulation system of clove essential oil immobilized in MSNs incorporated in poly(lactic acid) matrix could potentially be used to design active food packaging materials [27].

4.9. Development of Nanocomposite Materials. Nanocomposite materials exhibit functionalities that make them ideal in the food industry. Some of these functionalities include a unique structure of layered nanoclay that makes it possible to incorporate biomolecules into interlayer spaces (Figure 2) without altering the chemical and functional properties. Secondly, nanoclays can easily penetrate cells with precise

controlled release of BASs. Lastly, they are less toxic (in some cases, not toxic at all) materials.

Nanoclays had attracted the attention of the packaging industry due to low cost (affordability) and easier to fabricate. Montmorillonite (MMT) and halloysite (HNT) are widely used natural clays to design polymer-clay nanocomposites. The choice of HNT (tubular shape), MMT (platelet-like) clays, nanofiller shape, and their morphology influenced the properties of the crafted nanocomposites [144].

Gasser [145] loaded ascorbic acid (vitamin C) into the interlayer space of layered double hydroxides (ZnFe-LDHs and MgFe-LDHs) also called anionic clay using the anion-exchange method (Figure 2). It was reported that the fabrication stabilized the vitamin C and preserved its biological activity. In addition, the release of the interlayer content (vitamin C) was achieved without altering the functionality due to the ion-exchange reaction or dissolution of the LDH framework [145]. Further study showed the potential applications of cationic and anionic layered nanoclays as nanocarriers for vitamins, antioxidant, and linoleic acid in the food industry [146].

Mishra et al. [29] have developed an antibacterial composite material by encapsulating benzoate and its two derivatives (para-hydroxybenzoic acid and 2-chloro-5-nitrobenzoic acid) between the interlayer distance of Zn–Al LDH. The nanocomposites demonstrated potent bactericidal effects against Gram-positive *Staphylococcus aureus* and Gram-negative *Escherichia coli* strains [29]. The study proved the feasibility of using composites as active antimicrobial materials.

Others have reported that a multilayer film reservoir loaded with clay (MMT or HNT)/essential oil (orange or thyme) had higher adsorption, better interactions with thyme oil, and continuous aroma release compared to HNT. Thus, polymer-clay nanocomposites can be used as aroma-controlled release systems in the food and pharmaceutical (drugs) applications [30].

4.10. Isoelectric Solubilization/Precipitation. Isoelectric point (pI) is the pH of a solution at which the net charge of protein becomes zero. Likewise, isoelectric precipitation of protein is the process that leads to precipitate formation due to the decrease of hydration level and repulsive electrostatic force [147]. It is reported that the protein molecules trap BASs present in the medium [148].

Shi et al. [31] reported the feasibility of krill protein isolated with isoelectric solubilization/precipitation as wall material to encapsulate krill oil via freeze drying. Although the capacity of loading oil into microcapsules increased, the EE and LC decreased. Ariyarathna and Karunaratne [149] encapsulated curcumin into a chickpea (*Cicer arietinum*) protein matrix by isoelectric precipitation. The results showed that protein coating protected curcumin by more than 40% at 50°C and 25% at 25°C and 37°C. In addition, the release of curcumin from protein matrix was slower at pH 4 but reached ~100% (pH 2). Lastly, the protein matrix decreased curcumin photodegradation by 60%. Thus, chickpea protein capsules can be used as a protective coating for curcumin in the food industry and as a slow-release carrier in the pharmaceutical industry [149].

4.11. Antisolvent Precipitation and Coprecipitation. Antisolvent coprecipitation is a promising technique of encapsulating polysaccharide- and/or protein-based NPs. This is a cheap process that does not require special-purpose equipment [150]. The bioactive compound to encapsulate is dissolved in a binary solvent (usually water and an organic solvent). Different solvent is added to reduce the solubility of bioactive compound and thus supersaturate and precipitate forming NPs [143]. Others have designed ultrafine particles with controlled size distribution using devices such as impinging jet, T-mixer, static mixer, and multi-inlet vortex mixer. However, particle agglomeration may occur due to insufficient repulsion after formation. It was speculated that utilization of ultrasound and the devices mentioned above curbed particle agglomeration [151, 152].

Dai et al. [67] designed zein-lecithin NPs loaded with curcumin by antisolvent coprecipitation with 99.83% EE. FTIR analysis showed that hydrogen bonding and electrostatic and hydrophobic attractions bonded zein, lecithin, and curcumin together. In addition, the bioactive component in zein-lecithin NP composite was stable under heat treatment, UV irradiation, and high ionic strength compared to single zein and lecithin NPs. Therefore, composite zein-lecithin NPs can be used as a delivery system for water-insoluble bioactive compounds with high EE and chemical stability [67].

Yang et al. [32] fabricated curcumin-loaded NPs with gliadin and lecithin via antisolvent precipitation. High EE, low turbidity, improved delivery efficiency with smaller particle size were achieved via antisolvent precipitation compared to stepwise antisolvent precipitation. In addition, antisolvent coprecipitation gliadin-lecithin-curcumin NPs had smoother surface, resistance against light and temperature compared to stepwise antisolvent precipitation of NPs [32].

4.12. Ionic/Ionotropic Gelation. Ionic/ionotropic gelation is an effective technique of synthesizing NPs or hydrogel microparticle (Figure 2) by the electrostatic cross-linking of hydrophilic polymeric chains in the presence of hydrophobic ions. The anions combine with the polyvalent cations and thus induce gelation by binding mainly to the anion blocks [153]. It is reported that the utilization of hydrogel beads as carriers enhanced the bioavailability of BASs with sustained controlled release of bioactive compounds [154]. Chitosan NPs prepared by ionotropic gelation technique are widely used for drug delivery. Despite many studies on chitosan NPs, the lack of reproducibility due to varied formulation parameters coupled with a poor understanding of its formation has hindered their potential applications [155]. Nevertheless, Rajabi et al. [33] encapsulated saffron extract into GA-chitosan nanocomplexes by ion-gelation. FTIR and XRD confirmed the bond formation between functional groups ($-COO^-$ and $-NH_3^+$) of two biopolymers and the amorphous structure. TEM analysis showed that the nanocomplexes are spherical, smooth shapes with uniform particle size distribution. In addition, the ratio of CS, GA, and saffron extract significantly influenced the functional properties of nanocomplexes and EE due to increased

attraction between positive and negative biopolymer groups [33]. The release rate of saffron bioactive component–picrocrocin (more than 80% for 60 min) was higher in acidic condition compared to neutral (70% after 4 h) partly due to the presence of high CS in acidic solution. Thus, nanocomplexes can be used as effective carriers to preserve biologically active compounds of saffron for safe delivery via the gastrointestinal tract [33]. Also, Algharib et al. [155] synthesized chitosan NPs with mean particle size and zeta potential of 67.60 ± 0.11 nm and $+33.23 \pm 1.20$, respectively. Further analyses showed that the NPs had spherical shapes with good particle size distributions. The identified control parameters forge the path to widen the potentials of chitosan NPs in future food and pharmaceutical applications.

5. Biosafety and Bioavailability

The aim of food biosafety is to analyze and eliminate/manage risks that may have adverse effects on human health and the environment. Some carrier materials used in encapsulation systems might be unsafe/toxic; thus, biocompatible materials that integrate into host (human) without injurious effects should be used. It is reported that carrier materials are unsafe if they [46]

(i) interfere in digestion and absorption processes

(ii) are cyto- or genotoxic

(iii) contaminate food products (including transfer from packaging materials).

Sonin et al. [160] reported that the potential cytotoxicity of an encapsulated nanoparticle is dependent on size, shape, surface area, and attraction between opposite charges.

Polysaccharide-based particles obtained by covalent/ionic cross-linking, polyelectrolyte complexation, or self-assembled with hydrophobic molecules showed null toxicity like natural-based biopolymers. However, their safety can only be guaranteed if the residues of unreacted covalent cross-linkers posed no effects on humans [161]. It is worth mentioning that some solvents used are toxic. Thus, the utilization of Food and Drug Administration (FDA) approved generally recognized as safe solvents can assure the biosafety of polysaccharide-based materials.

It is reported that some inorganic NPs are insoluble in the gastrointestinal tract (e.g., titanium dioxide and silicon dioxide), while others are partially or completely soluble (e.g., silver oxide and zinc) [82, 162]. Partially/completely soluble NPs can stimulate the overproduction of reactive oxygen species (ROS) and thus induce oxidative stress leading to an imbalance physiological redox-regulated functions, DNA damage, and cell death via apoptosis [81]. Others have documented that anionic clay is rapidly excreted from the body and does not accumulate in organs, whereas silicon NPs are biodegradable and excreted as orthosilicic acid [163, 164]. Nanoclays are biocompatible and had low or null toxicity and thus may be used as mineral supplements [165]. *In vivo* analysis with Wistar rats using low-molecular-weight chitosan (1–4 mg/kg) showed low cytotoxicity. In addition, intravenous administration had no side effects on the systemic hemodynamics [160].

Oral administration of carbon NPs with mice at various concentrations showed no effects on reproductive health, hormonal levels, and sperm quality [166, 167]. On the other hand, chicken embryo exposed to carbon NPs at 50, 500, and 5000 μg/mL showed a dose-dependent decrease in survival rate [168]. Furthermore, an increase in intracellular vacuoles, severe cell membrane, and mitochondrial damage was observed [168]. Others have documented that high dose (50 mg/kg/day) of single-walled carbon nanotubes significantly ($p < 0.05$) decreased sperm count, viability, and motility and increased oxidative stress compared to multiwalled carbon nanotubes [169]. Intravenous administration of nanoscale NPs (~2000 μg/mL) to mice showed evidence of DNA fragmentations, and chromosomal aberrations of the spermatozoa. In addition, the pregnant functionality of the female mice decreased significantly compared to control [170]. The observed contradiction with regards to biosafety of nanomaterials used as wall material for encapsulation of BASs raises serious concern and thus calls for a robust, high-throughput standardization of biomaterial safety. The Center for Food Safety and Applied Nutrition is currently researching some approaches of determining biomaterial toxicity. The potential toxicity of biomaterials for encapsulation may be minimized or curbed by using FDA-approved nanomaterials.

The term bioavailability means the concentration of encapsulated BASs absorbed and transported into the bloodstream to elicit physiochemical processes [171]. The release of BASs during digestion to be absorbed in the small intestine is termed bioaccessibility [171, 172]. It is reported that shape, form, and wall material can significantly influence the bioavailability of encapsulated BASs [172]. Peng et al. [173] demonstrated that encapsulated curcumin NPs were highly (2.7-3.6-fold) bioavailable compared to the free (control) curcumin. In addition, gastric acids triggered the transformation of the control NPs (88.3%) compared to the encapsulated curcumin (48%) and thus had significantly lower bioaccessible (9.1%) curcumin [173]. Similarly, *in vitro* simulated poultry GIT conditions demonstrated that encapsulation enhanced the release of enzymes from alginate NPs with concomitant good bioavailability of phosphorus and calcium in chicken [49]. A recent study showed that *Phaeodactylum tricornutum* (PE) extract encapsulated with alginate-casein (A-C-PE:PE) and chitosan (A-C-PE) showed a controlled release of fucoxanthin and improved adsorption (1.8-fold) using Caco-2/TC7 cells compared to control. *In vivo* experiments further demonstrated the significant bioavailability of fucoxanthin in blood plasma compared to the control PE [174]. Others have recently encapsulated vitamin A in FDA-approved basic methacrylate copolymer to curb the menace of vitamin A deficiency [175]. The results showed that encapsulated vitamin A was thermostable during simulated cooking conditions with concomitant longer shelf life when compared to the free vitamin A. In addition, cooked and light-irradiated encapsulated vitamin A was highly bioaccessible compared to the free-treated vitamin [175]. The above studies demonstrate

that encapsulation does not only protect BASs from environmental factors but also enhances their bioavailability and bioaccessibility consequently maximizing absorption and thus exerting health benefits to human.

6. Conclusion

In the context of BASs, encapsulation protects these compounds from degradation and enhances stability, solubility, and bioavailability. It is well documented that many BASs are sensitive to environmental conditions, such as temperature, pH, and light, which can trigger degradation and loss of functional activity. In this article, various methods of BAS encapsulation for food applications were discussed along with their merits and drawbacks. The choice of method depends on the specific application and desired properties of the encapsulated BASs. 3D printing has emerged as a modern trend in BAS encapsulation as it allows for precise and customizable encapsulation of BASs with controlled release properties. Extrusion-based 3D printing is considered cost-effective and scalable method for BAS encapsulation and thus may be used to design personalized functional foods. Encapsulated BASs can be incorporated into inorganic particles and organic-inorganic composites to develop antimicrobial packaging films or nanobiosensors. Inorganic NPs are particularly attractive because of their unique physicochemical properties, including small size and large surface area, which make them ideal candidates for use in antimicrobial films. However, the potential toxicity of some inorganic materials coupled with the lack of transparent and clear nanotechnology regulations limit their application in food encapsulation. Therefore, alternative materials, such as natural and biodegradable polymers, should be explored for safe and effective encapsulation of BASs for food application. Lastly, the various methods of encapsulation enhance bioavailability/bioaccessibility, thus maximizing the absorption potential of encapsulated BASs.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Conceptualization was conducted by D.O.S., A.O.N., N.N.S., P.A., and E.A.N.; D.O.S., A.O.N., N.N.S., P.A., and E.A.N. wrote the original manuscript draft; P.A. and E.A.N. wrote, reviewed, and edited the paper; funding acquisition was conducted by E.A.N. All authors have read and consented to the published version of the manuscript.

Acknowledgments

This work was supported by the Russian Science Foundation (Project No. 21-76-00034). Open access publishing is facilitated by the University of Otago, as part of the Wiley - University of Otago agreement via the Council of Australian University Librarians.

References

[1] M. P. Silva and J. P. Fabi, "Food biopolymers-derived nanogels for encapsulation and delivery of biologically active compounds: a perspective review," *Food Hydrocolloids for Health*, vol. 2, article 100079, 2022.

[2] R. Pangestuti and S. K. Kim, "Biological activities and health benefit effects of natural pigments derived from marine algae," *Journal of Functional Foods*, vol. 3, no. 4, pp. 255–266, 2011.

[3] A. Perrelli, L. Goitre, A. M. Salzano, A. Moglia, A. Scaloni, and S. F. Retta, "Biological activities, health benefits, and therapeutic properties of avenanthramides: from skin protection to prevention and treatment of cerebrovascular diseases," *Oxidative Medicine and Cellular Longevity*, vol. 2018, Article ID 6015351, 17 pages, 2018.

[4] M. H. Alu'datt, M. Alrosan, S. Gammoh et al., "Encapsulation-based technologies for bioactive compounds and their application in the food industry: a roadmap for food-derived functional and health-promoting ingredients," *Food Bioscience*, vol. 50, article 101971, 2022.

[5] M. R. I. Shishir, L. Xie, C. Sun, X. Zheng, and W. Chen, "Advances in micro and nano-encapsulation of bioactive compounds using biopolymer and lipid-based transporters," *Trends in Food Science and Technology*, vol. 78, pp. 34–60, 2018.

[6] Y. Jang and E. Koh, "Characterisation and storage stability of aronia anthocyanins encapsulated with combinations of maltodextrin with carboxymethyl cellulose, gum Arabic, and xanthan gum," *Food Chemistry*, vol. 405, no. Part B, article 135002, 2023.

[7] T. A. Comunian, M. P. Silva, and C. J. F. Souza, "The use of food by-products as a novel for functional foods: their use as ingredients and for the encapsulation process," *Trends in Food Science and Technology*, vol. 108, pp. 269–280, 2021.

[8] R. Iqbal, Z. Mehmood, A. Baig, and N. Khalid, "Formulation and characterization of food grade O/W nanoemulsions encapsulating quercetin and curcumin: insights on enhancing solubility characteristics," *Food and Bioproducts Processing*, vol. 123, pp. 304–311, 2020.

[9] S. Liu, J. Zhang, R. Fu et al., "Improved stability and aqueous solubility of β-carotene via encapsulation in self-assembled bioactive oleanolic acid nanoparticles," *Food Chemistry*, vol. 373, no. Part B, article 131498, 2022.

[10] A. G. Abdel-Razek, M. M. Hassanein, B. Ozçelik, D. A. Baranenko, and T. M. El-Messery, "Omega fatty acid-balanced oil formula and enhancing its oxidative stability by encapsulation with whey protein concentrate," *Food Bioscience*, vol. 50, article 101975, 2022.

[11] C. Drosou, M. Krokida, and C. G. Biliaderis, "Encapsulation of β-carotene into food-grade nanofibers via coaxial electrospinning of hydrocolloids: enhancement of oxidative stability and photoprotection," *Food Hydrocolloids*, vol. 133, p. 107949, 2022.

[12] M. Semenova, A. Antipova, E. Martirosova, D. Zelikina, N. Palmina, and S. Chebotarev, "Essential contributions of food hydrocolloids and phospholipid liposomes to the formation of carriers for controlled delivery of biologically active substances via the gastrointestinal tract," *Food Hydrocolloids*, vol. 120, article 106890, 2021.

[13] S. Boostani and S. M. Jafari, "A comprehensive review on the controlled release of encapsulated food ingredients;

fundamental concepts to design and applications," *Trends in Food Science and Technology*, vol. 109, pp. 303–321, 2021.

[14] Market and Markets, "Food encapsulation market by shell material (lipids, polysaccharides, emulsifiers, proteins), technology (microencapsulation, nanoencapsulation, hybrid encapsulation), application, method, core phase and region - Global Forecast to 2027," 2023, https://www.marketsandmarkets.com/Market-Reports/food-encapsulation-advanced-technologies-and-global-market-68.html.

[15] Research and Markets, "Food encapsulation market by shell material (lipids, polysaccharides, emulsifiers, proteins), technology (microencapsulation, nanoencapsulation, hybrid encapsulation), application, method, core phase and region - Global Forecast to 2027," 2023, https://www.researchandmarkets.com/reports/5009170/food-encapsulation-market-by-shell-material#product–summary.

[16] M. A. Moreno, M. E. Orqueda, L. G. Gómez-Mascaraque, M. I. Isla, and A. López-Rubio, "Crosslinked electrospun zein-based food packaging coatings containing bioactive chilto fruit extracts," *Food Hydrocolloids*, vol. 95, pp. 496–505, 2019.

[17] P. Paximada, E. Kanavou, E. Apostolidis, and I. G. Mandala, "Encapsulation of catechin in electrosprayed food-grade particles," *Food Hydrocolloids for Health*, vol. 1, article 100021, 2021.

[18] M. Soleimanifar, S. M. Jafari, and E. Assadpour, "Encapsulation of olive leaf phenolics within electrosprayed whey protein nanoparticles; production and characterization," *Food Hydrocolloids*, vol. 101, article 105572, 2020.

[19] C. Jansen-Alves, K. F. Fernandes, M. M. Crizel-Cardozo, F. D. Krumreich, C. D. Borges, and R. C. Zambiazi, "Microencapsulation of propolis in protein matrix using spray drying for application in food systems," *Food and Bioprocess Technology*, vol. 11, no. 7, pp. 1422–1436, 2018.

[20] N. Yekdane and S. A. H. Goli, "Effect of pomegranate juice on characteristics and oxidative stability of microencapsulated pomegranate seed oil using spray drying," *Food and Bioprocess Technology*, vol. 12, no. 9, pp. 1614–1625, 2019.

[21] T. A. Comunian, R. Ravanfar, S. D. Alcaine, and A. Abbaspourrad, "Water-in-oil-in-water emulsion obtained by glass microfluidic device for protection and heat-triggered release of natural pigments," *Food Research International*, vol. 106, pp. 945–951, 2018.

[22] A. Dalmoro, S. Bochicchio, G. Lamberti, P. Bertoncin, B. Janssens, and A. A. Barba, "Micronutrients encapsulation in enhanced nanoliposomal carriers by a novel preparative technology," *RSC Advances*, vol. 9, no. 34, pp. 19800–19812, 2019.

[23] M. V. Vieira, S. M. Oliveira, I. R. Amado et al., "3D printed functional cookies fortified with *Arthrospira platensis*: evaluation of its antioxidant potential and physical-chemical characterization," *Food Hydrocolloids*, vol. 107, article 105893, 2020.

[24] S. Ghasemi, S. M. Jafari, E. Assadpour, and M. Khomeiri, "Nanoencapsulation of D-limonene within nanocarriers produced by pectin-whey protein complexes," *Food Hydrocolloids*, vol. 77, pp. 152–162, 2018.

[25] A. Ruengdech and U. Siripatrawan, "Improving encapsulating efficiency, stability, and antioxidant activity of catechin nanoemulsion using foam mat freeze-drying: the effect of wall material types and concentrations," *Lwt-Food Science and Technology*, vol. 162, article 113478, 2022.

[26] R. Chang, B. Liu, Q. Wang et al., "The encapsulation of lycopene with α-lactalbumin nanotubes to enhance their antioxidant activity, viscosity and colloidal stability in dairy drink," *Food Hydrocolloids*, vol. 131, article 107792, 2022.

[27] W. Lu, R. Cui, B. Zhu et al., "Influence of clove essential oil immobilized in mesoporous silica nanoparticles on the functional properties of poly(lactic acid) biocomposite food packaging film," *Journal of Materials Research and Technology*, vol. 11, pp. 1152–1161, 2021.

[28] X. Zhang, Y. Zhu, L. Fan et al., "Delivery of curcumin by fucoidan-coated mesoporous silica nanoparticles: fabrication, characterization, and in vitro release performance," *International Journal of Biological Macromolecules*, vol. 211, pp. 368–379, 2022.

[29] G. Mishra, B. Dash, and S. Pandey, "Effect of molecular dimension on gallery height, release kinetics and antibacterial activity of Zn–Al layered double hydroxide (LDH) encapsulated with benzoate and its derivatives," *Applied Clay Science*, vol. 181, p. 105230, 2019.

[30] J. N. Saucedo-Zuñiga, S. Sánchez-Valdes, E. Ramírez-Vargas et al., "Controlled release of essential oils using laminar nanoclay and porous halloysite/essential oil composites in a multilayer film reservoir," *Microporous and Mesoporous Materials*, vol. 316, article 110882, 2021.

[31] L. Shi, S. K. Beamer, H. Yang, and J. Jaczynski, "Micro-emulsification/encapsulation of krill oil by complex coacervation with krill protein isolated using isoelectric solubilization/precipitation," *Food Chemistry*, vol. 244, pp. 284–291, 2018.

[32] S. Yang, L. Dai, C. Sun, and Y. Gao, "Characterization of curcumin loaded gliadin-lecithin composite nanoparticles fabricated by antisolvent precipitation in different blending sequences," *Food Hydrocolloids*, vol. 85, no. 17, pp. 185–194, 2018.

[33] H. Rajabi, S. M. Jafari, G. Rajabzadeh, M. Sarfarazi, and S. Sedaghati, "Chitosan-gum Arabic complex nanocarriers for encapsulation of saffron bioactive components," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 578, article 123644, 2019.

[34] C. Dima, E. Assadpour, S. Dima, and S. M. Jafari, "Bioactive-loaded nanocarriers for functional foods: from designing to bioavailability," *Current Opinion in Food Science*, vol. 33, pp. 21–29, 2020.

[35] B. Kumar and K. Smita, "Scope of nanotechnology in nutraceuticals," in *In Nanotechnology Applications in Food: Flavor, Stability, Nutrition and Safety*, pp. 43–63, Elsevier Inc, 2017.

[36] E. Assadpour and S. M. Jafari, "Nanoencapsulation: techniques and developments for food applications," *Nanomaterials for Food Applications*, vol. 1, pp. 35–61, 2019.

[37] T. Borel and C. M. Sabliov, "Nanodelivery of bioactive components for food applications: types of delivery systems, properties, and their effect on ADME profiles and toxicity of nanoparticles," *Annual Review of Food Science and Technology*, vol. 5, no. 1, pp. 197–213, 2014.

[38] M. A. Colín-Cruz, D. J. Pimentel-González, H. Carrillo-Navas, J. Alvarez-Ramírez, and A. Y. Guadarrama-Lezama, "Co-encapsulation of bioactive compounds from blackberry juice and probiotic bacteria in biopolymeric matrices," *Lwt-Food Science and Technology*, vol. 110, pp. 94–101, 2019.

[39] J. K. S. Andrade, M. Denadai, G. R. S. Andrade et al., "Development and characterization of microencapsules containing spray dried powder obtained from Brazilian brown, green and red propolis," *Food Research International*, vol. 109, pp. 278–287, 2018.

[40] Y. Gao, X. Li, Y. Xie et al., "Encapsulation of bitter peptides in diphasic gel double emulsions: bitterness masking, sustained release and digestion stability," *Food Research International*, vol. 162, no. Part B, article 112205, 2022.

[41] J. B. Pires, L. M. Fonseca, T. J. Siebeneichler et al., "Curcumin encapsulation in capsules and fibers of potato starch by electrospraying and electrospinning: thermal resistance and antioxidant activity," *Food Research International*, vol. 162, no. Part B, article 112111, 2022.

[42] O. P. Bamidele, A. Amiri-Rigi, and M. N. Emmambux, "Encapsulation of ascorbyl palmitate in corn starch matrix by extrusion cooking: release behavior and antioxidant activity," *Food Chemistry*, vol. 399, article 133981, 2023.

[43] A. Granja, I. Frias, A. R. Neves, M. Pinheiro, and S. Reis, "Therapeutic potential of epigallocatechin gallate nanodelivery systems," *BioMed Research International*, vol. 2017, Article ID 5813793, 15 pages, 2017.

[44] A. Mohammadi, S. M. Jafari, A. S. Mahoonak, and M. Ghorbani, "Liposomal/nanoliposomal encapsulation of food-relevant enzymes and their application in the food industry," *Food and Bioprocess Technology*, vol. 14, no. 1, pp. 23–38, 2021.

[45] S. Rathee, V. Nayak, K. R. Singh, and A. Ojha, "Nanofortification of vitamin B-complex in food matrix: need, regulations, and prospects," *Food Chemistry: Molecular Sciences*, vol. 4, no. 2, article 100100, 2022.

[46] A. Rezaei, M. Fathi, and S. M. Jafari, "Nanoencapsulation of hydrophobic and low-soluble food bioactive compounds within different nanocarriers," *Food Hydrocolloids*, vol. 88, pp. 146–162, 2019.

[47] F. A. Nobari Azar, A. Pezeshki, B. Ghanbarzadeh, H. Hamishehkar, and M. Mohammadi, "Nanostructured lipid carriers: promising delivery systems for encapsulation of food ingredients," *Journal of Agriculture and Food Research*, vol. 2, article 100084, 2020.

[48] Y. Guo, D. Qiao, S. Zhao, B. Zhang, and F. Xie, "Starch-based materials encapsulating food ingredients: recent advances in fabrication methods and applications," *Carbohydrate Polymers*, vol. 270, article 118358, 2021.

[49] Y. Weng, S. Ranaweera, D. Zou et al., "Improved enzyme thermal stability, loading and bioavailability using alginate encapsulation," *Food Hydrocolloids*, vol. 137, article 108385, 2023.

[50] Z. Yang, C. Guan, C. Zhou et al., "Amphiphilic chitosan/carboxymethyl gellan gum composite films enriched with mustard essential oil for mango preservation," *Carbohydrate Polymers*, vol. 300, article 120290, 2023.

[51] M. Usman, C. Zhang, P. J. Patil et al., "Potential applications of hydrophobically modified inulin as an active ingredient in functional foods and drugs - a review," *Carbohydrate Polymers*, vol. 252, article 117176, 2021.

[52] X. L. Li, W. J. Liu, B. C. Xu, B. Zhang, W. Wang, and D. L. Su, "OSA-linear dextrin enhances the compactness of pea protein isolate nanoparticles: increase of high internal phase emulsions stability," *Food Chemistry*, vol. 404, no. Part A, article 134590, 2023.

[53] C. Guo, J. Yin, and D. Chen, "Co-encapsulation of curcumin and resveratrol into novel nutraceutical hyalurosomes nano-food delivery system based on oligo-hyaluronic acid-curcumin polymer," *Carbohydrate Polymers*, vol. 181, pp. 1033–1037, 2018.

[54] E. O. Mensah, O. N. Kanwugu, P. K. Panda, and P. Adadi, "Marine fucoidans: structural, extraction, biological activities and their applications in the food industry," *Food Hydrocolloids*, vol. 142, article 108784, 2023.

[55] Z. Ren, X. Li, F. Ma et al., "Oil-in-water emulsions prepared using high-pressure homogenisation with *Dioscorea opposita* mucilage and food-grade polysaccharides: guar gum, xanthan gum, and pectin," *Lwt*, vol. 162, article 113468, 2022.

[56] Q. Xiao, H. Weng, G. Chen, and A. Xiao, "Preparation and characterization of octenyl succinic anhydride modified agarose derivative," *Food Chemistry*, vol. 279, pp. 30–39, 2019.

[57] C. Ai, H. Meng, J. Lin, X. Tang, and X. Guo, "Emulsification properties of alkaline soluble polysaccharide from sugar beet pulp: effect of acetylation and methoxylation," *Food Hydrocolloids*, vol. 124, article 107361, 2022.

[58] Q. Xiao, G. Chen, and A. Xiao, "Preparation, characterization, and emulsification properties of agarose fatty acid derivatives with different hydrophobic chains," *International Journal of Biological Macromolecules*, vol. 141, pp. 906–918, 2019.

[59] M. N. Sithole, Y. E. Choonara, L. C. du Toit, P. Kumar, and V. Pillay, "A review of semi-synthetic biopolymer complexes: modified polysaccharide nano-carriers for enhancement of oral drug bioavailability," *Pharmaceutical Development and Technology*, vol. 22, no. 2, pp. 283–295, 2017.

[60] R. Cazorla-Luna, A. Martín-Illana, F. Notario-Pérez, R. Ruiz-Caro, and M. D. Veiga, "Naturally occurring polyelectrolytes and their use for the development of complex-based mucoadhesive drug delivery systems: an overview," *Polymers*, vol. 13, no. 14, 2021.

[61] F. Astutiningsih, S. Anggrahini, A. Fitriani, and S. Supriyadi, "Optimization of saffron essential oil nanoparticles using chitosan-Arabic gum complex nanocarrier with ionic gelation method," *International Journal of Food Science*, vol. 2022, Article ID 4035033, 14 pages, 2022.

[62] S. A. Fioramonti, A. C. Rubiolo, and L. G. Santiago, "Characterisation of freeze-dried flaxseed oil microcapsules obtained by multilayer emulsions," *Powder Technology*, vol. 319, pp. 238–244, 2017.

[63] L. G. Gómez-Mascaraque and A. López-Rubio, "Protein-based emulsion electrosprayed micro- and submicroparticles for the encapsulation and stabilization of thermosensitive hydrophobic bioactives," *Journal of Colloid and Interface Science*, vol. 465, pp. 259–270, 2016.

[64] Y. Zhang, Y. Guo, F. Liu, and Y. Luo, "Recent development of egg protein fractions and individual proteins as encapsulant materials for delivery of bioactives," *Food Chemistry*, vol. 403, article 134353, 2023.

[65] Y. Cao, H. Xiao, W. Zheng et al., "Green synthesis of environmentally benign collagen fibers-derived hierarchically structured amphiphilic composite fibers for high-flux dual separation of emulsion," *Journal of Environmental Chemical Engineering*, vol. 10, no. 1, article 107067, 2022.

[66] S. Salimiraad, S. Safaeian, A. A. Basti, A. Khanjari, and R. M. Nadoushan, "Characterization of novel probiotic nanocomposite films based on nano chitosan/nano cellulose/gelatin

for the preservation of fresh chicken fillets," *Lwt*, vol. 162, article 113429, 2022.

[67] L. Dai, C. Sun, R. Li, L. Mao, F. Liu, and Y. Gao, "Structural characterization, formation mechanism and stability of curcumin in zein-lecithin composite nanoparticles fabricated by antisolvent co-precipitation," *Food Chemistry*, vol. 237, pp. 1163–1171, 2017.

[68] Y. Wan, J. Li, J. Ma et al., "Fixing zein at the fibrillar carboxymethyl cellulose toward an amphiphilic nano-network," *Food Chemistry*, vol. 398, article 133862, 2023.

[69] A. Jain, D. Thakur, G. Ghoshal, O. P. Katare, and U. S. Shivhare, "Characterization of microcapsulated β-carotene formed by complex coacervation using casein and gum tragacanth," *International Journal of Biological Macromolecules*, vol. 87, pp. 101–113, 2016.

[70] F. Plati and A. Paraskevopoulou, "Hemp protein isolate: gum Arabic complex coacervates as a means for oregano essential oil encapsulation. Comparison with whey protein isolate: gum Arabic system," *Food Hydrocolloids*, vol. 136, article 108284, 2023.

[71] R. Pérez-Masiá, J. M. Lagaron, and A. López-Rubio, "Development and optimization of novel encapsulation structures of interest in functional foods through electrospraying," *Food and Bioprocess Technology*, vol. 7, no. 11, pp. 3236–3245, 2014.

[72] D. Baiocco, J. A. Preece, and Z. Zhang, "Microcapsules with a fungal chitosan-gum Arabic-maltodextrin shell to encapsulate health-beneficial peppermint oil," *Food Hydrocolloids for Health*, vol. 1, article 100016, 2021.

[73] L. Yang, X. Cao, A. Gai et al., "Chitosan/guar gum nanoparticles to stabilize Pickering emulsion for astaxanthin encapsulation," *LWT-Food Science and Technology*, vol. 165, article 113727, 2022.

[74] W. Shen, M. Yan, S. Wu et al., "Chitosan nanoparticles embedded with curcumin and its application in pork antioxidant edible coating," *International Journal of Biological Macromolecules*, vol. 204, pp. 410–418, 2022.

[75] K. Liu, X. L. Kong, Q. M. Li, H. L. Zhang, X. Q. Zha, and J. P. Luo, "Stability and bioavailability of vitamin D_3 encapsulated in composite gels of whey protein isolate and lotus root amylopectin," *Carbohydrate Polymers*, vol. 227, article 115337, 2020.

[76] Q. Guo, J. Tang, S. Li et al., "*Lactobacillus plantarum* 21805 encapsulated by whey protein isolate and dextran conjugate for enhanced viability," *International Journal of Biological Macromolecules*, vol. 216, pp. 124–131, 2022.

[77] D. Lin, A. L. Kelly, and S. Miao, "The impact of pH on mechanical properties, storage stability and digestion of alginate-based and soy protein isolate-stabilized emulsion gel beads with encapsulated lycopene," *Food Chemistry*, vol. 372, article 131262, 2022.

[78] V. Miranda-Linares, D. Quintanar-Guerrero, A. Del Real, and M. L. Zambrano-Zaragoza, "Spray-drying method for the encapsulation of a functionalized ingredient in alginate-pectin nano- and microparticles loaded with distinct natural actives: stability and antioxidant effect," *Food Hydrocolloids*, vol. 101, article 105560, 2020.

[79] E. Kurtulbaş, R. Albarri, M. Torun, and S. Şahin, "Encapsulation of *Moringa oleifera* leaf extract in chitosan-coated alginate microbeads produced by ionic gelation," *Food Bioscience*, vol. 50, article 102158, 2022.

[80] S. Manocha, S. Dhiman, A. S. Grewal, and K. Guarve, "Nanotechnology: an approach to overcome bioavailability challenges of nutraceuticals," *Journal of Drug Delivery Science and Technology*, vol. 72, article 103418, 2022.

[81] S. Punia, K. S. Sandhu, M. Kaur, and A. K. Siroha, "Nanotechnology: a successful approach to improve nutraceutical bioavailability," in *Nanobiotechnology in Bioformulations*, Nanotechnology in the Life Sciences, R. Prasad, V. Kumar, M. Kumar, and D. Choudhary, Eds., Springer, Cham, 2019.

[82] D. J. Mcclements, H. Xiao, and P. Demokritou, "Physicochemical and colloidal aspects of food matrix effects on gastrointestinal fate of ingested inorganic nanoparticles," *Advances in Colloid and Interface Science*, vol. 246, pp. 165–180, 2017.

[83] A. Manuja, B. Kumar, R. Kumar et al., "Metal/metal oxide nanoparticles: toxicity concerns associated with their physical state and remediation for biomedical applications," *Toxicology Reports*, vol. 8, pp. 1970–1978, 2021.

[84] Y. Zhu, C. Li, H. Cui, and L. Lin, "Encapsulation strategies to enhance the antibacterial properties of essential oils in food system," *Food Control*, vol. 123, article 107856, 2021.

[85] J. Fraczyk, M. Walczak, L. Szymanski et al., "Carbon nanotubes functionalized with folic acid attached via biomimetic peptide linker," *Nanomedicine*, vol. 12, no. 18, pp. 2161–2182, 2017.

[86] J. C. Bonilla, F. Bozkurt, S. Ansari, N. Sozer, and J. L. Kokini, "Applications of quantum dots in food science and biology," *Trends in Food Science and Technology*, vol. 53, pp. 75–89, 2016.

[87] G. Jing, L. Yang, H. Wang, J. Niu, Y. Li, and S. Wang, "Interference of layered double hydroxide nanoparticles with pathways for biomedical applications," *Advanced Drug Delivery Reviews*, vol. 188, p. 114451, 2022.

[88] F. Mustafa and S. Andreescu, "Nanotechnology-based approaches for food sensing and packaging applications," *RSC Advances*, vol. 10, no. 33, pp. 19309–19336, 2020.

[89] R. Chawla, S. Sivakumar, and H. Kaur, "Antimicrobial edible films in food packaging: current scenario and recent nanotechnological advancements- a review," *Carbohydrate Polymer Technologies and Applications*, vol. 2, p. 100024, 2021.

[90] A. S. Prasad, Y. Wang, X. Li et al., "Investigating the effect of surface modification on the dispersion process of polymer nanocomposites," *Nano*, vol. 6, no. 3, pp. 111–124, 2020.

[91] D. Massella, E. Celasco, F. Salaün, A. Ferri, and A. A. Barresi, "Overcoming the limits of flash nanoprecipitation: effective loading of hydrophilic drug into polymeric nanoparticles with controlled structure," *Polymers*, vol. 10, no. 10, p. 1092, 2018.

[92] V. I. Sousa, J. F. Parente, J. F. Marques, M. A. Forte, and C. J. Tavares, "Microencapsulation of essential oils: a review," *Polymers*, vol. 14, no. 9, p. 1730, 2022.

[93] D. S. Tupuna, K. Paese, S. S. Guterres, A. Jablonski, S. H. Flôres, and A. de Oliveira Rios, "Encapsulation efficiency and thermal stability of norbixin microencapsulated by spray-drying using different combinations of wall materials," *Industrial Crops and Products*, vol. 111, pp. 846–855, 2018.

[94] K. Anil and D. Roshan, "Functional food market by ingredient. Retrieved from functional food market by ingredient website," 2020, https://www.alliedmarketresearch.com/functional-food-market.

[95] Z. Yin, T. Zheng, C. T. Ho, Q. Huang, Q. Wu, and M. Zhang, "Improving the stability and bioavailability of tea polyphenols by encapsulations: a review," *Food Science and Human Wellness*, vol. 11, no. 3, pp. 537–556, 2022.

[96] S. Zhang, W. Jiang, Z. Zhang, Y. Zhu, L. Wang, and J. Fu, "A nanoparticle/oil double epigallocatechin gallate-loaded Pickering emulsion: stable and delivery characteristics," *Lwt-Food Science and Technology*, vol. 130, article 109369, 2020.

[97] P. Adadi, N. V. Barakova, and E. F. Krivoshapkina, "Selected methods of extracting carotenoids, characterization, and health concerns: a review," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 24, pp. 5925–5947, 2018.

[98] P. Adadi and N. V. Barakova, "Application of surface response methodology for an enzyme-assisted extraction of carotenoids," *Journal of Microbiology, Biotechnology and Food Sciences*, vol. 9, no. 2, pp. 195–203, 2019.

[99] D. Rajanna, H. A. Pushpadass, F. M. E. Emerald, N. V. Padaki, and B. S. Nath, "Nanoencapsulation of casein-derived peptides within electrospun nanofibres," *Journal of the Science of Food and Agriculture*, vol. 102, no. 4, pp. 1684–1698, 2022.

[100] A. Alehosseini, B. Ghorani, M. Sarabi-Jamab, and N. Tucker, "Principles of electrospraying: a new approach in protection of bioactive compounds in foods," *Critical Reviews in Food Science and Nutrition*, vol. 58, no. 14, pp. 2346–2363, 2018.

[101] H. Huang, Y. Song, Y. Zhang et al., "Electrospun nanofibers: current progress and applications in food systems," *Journal of Agricultural and Food Chemistry*, vol. 70, no. 5, pp. 1391–1409, 2022.

[102] A. López-Córdoba, J. M. Lagarón, and S. Goyanes, "Fabrication of electrospun and electrosprayed carriers for the delivery of bioactive food ingredients," *Encyclopedia of Food Chemistry*, vol. 1, pp. 733–739, 2019.

[103] J. Xue, T. Wu, Y. Dai, and Y. Xia, "Electrospinning and electrospun nanofibers: methods, materials, and applications," *Chemical Reviews*, vol. 119, no. 8, pp. 5298–5415, 2019.

[104] E. T. Stace, P. A. Mouthuy, A. J. Carr, and H. C. Ye, "Biomaterials: electrospinning," in *In Comprehensive Biotechnology*, vol. 5Elsevier, Third edition, 2019.

[105] V. Amal Nath, R. Vijayakumar, M. M. Leena, J. A. Moses, and C. Anandharamakrishnan, "Co-electrospun-electrosprayed ethyl cellulose-gelatin nanocomposite pH-sensitive membrane for food quality applications," *Food Chemistry*, vol. 394, p. 133420, 2022.

[106] J. S. Moreno, P. Dima, I. S. Chronakis, and A. C. Mendes, "Electrosprayed ethyl cellulose core-shell microcapsules for the encapsulation of probiotics," *Pharmaceutics*, vol. 14, no. 1, 2021.

[107] J. Wang, J. A. Jansen, and F. Yang, "Electrospraying: possibilities and challenges of engineering carriers for biomedical applications - a mini review," *Frontiers in Chemistry*, vol. 7, pp. 1–9, 2019.

[108] P. Sagitha, C. R. Reshmi, O. Manaf, S. P. Sundaran, K. Juraij, and A. Sujith, "Development of nanocomposite membranes by electrospun nanofibrous materials," in *Nanocomposite Membranes for Water and Gas Separation*, pp. 199–218, Elsevier, 2020.

[109] K. Khoshakhlagh, A. Koocheki, M. Mohebbi, and A. Allafchian, "Development and characterization of electrosprayed *Alyssum homolocarpum* seed gum nanoparticles for encapsulation of D-limonene," *Journal of Colloid and Interface Science*, vol. 490, pp. 562–575, 2017.

[110] F. Fareed, F. Saeed, M. Afzaal et al., "Fabrication of electrospun gum Arabic–polyvinyl alcohol blend nanofibers for improved viability of the probiotic," *Journal of Food Science and Technology*, vol. 59, no. 12, pp. 4812–4821, 2022.

[111] A. P. R. Charles, R. Mu, T. Z. Jin et al., "Application of yellow mustard mucilage and starch in nanoencapsulation of thymol and carvacrol by emulsion electrospray," *Carbohydrate Polymers*, vol. 298, p. 120148, 2022.

[112] N. K. Mohammed, C. P. Tan, Y. A. Manap, B. J. Muhialdin, and A. S. M. Hussin, "Spray drying for the encapsulation of oils—a review," *Molecules*, vol. 25, no. 17, p. 3873, 2020.

[113] A. Gharsallaoui, G. Roudaut, O. Chambin, A. Voilley, and R. Saurel, "Applications of spray-drying in microencapsulation of food ingredients: an overview," *Food Research International*, vol. 40, no. 9, pp. 1107–1121, 2007.

[114] H. Bao, H. H. Ding, A. P. R. Charles et al., "Application of yellow mustard mucilage in encapsulation of essential oils and polyphenols using spray drying," *Food Hydrocolloids*, vol. 143, p. 108815, 2023.

[115] S. P. Moulik, A. K. Rakshit, A. Pan, and B. Naskar, "An overview of coacervates: the special disperse state of amphiphilic and polymeric materials in solution," *Colloids and Interfaces*, vol. 6, no. 3, p. 45, 2022.

[116] A. Napiórkowska and M. Kurek, "Coacervation as a novel method of microencapsulation of essential oils—a review," *Molecules*, vol. 27, no. 16, p. 5142, 2022.

[117] A. B. Tomé Constantino and E. E. Garcia-Rojas, "Microencapsulation of betanin by complex coacervation of carboxymethylcellulose and amaranth protein isolate for application in edible gelatin films," *Food Hydrocolloids*, vol. 133, p. 107956, 2022.

[118] Y. Yuan, Z. Y. Kong, Y. E. Sun, Q. Z. Zeng, and X. Q. Yang, "Complex coacervation of soy protein with chitosan: constructing antioxidant microcapsule for algal oil delivery," *Lwt-Food Science and Technology*, vol. 75, pp. 171–179, 2017.

[119] S. Kandasamy and R. Naveen, "A review on the encapsulation of bioactive components using spray-drying and freeze-drying techniques," *Journal of Food Process Engineering*, vol. 45, no. 8, pp. 1–14, 2022.

[120] F. Saeed, M. Afzaal, A. Ahmad et al., "Enhanced viability of microencapsulated lyophilized probiotics under in vitro simulated gastrointestinal conditions," *Journal of Food Processing and Preservation*, vol. 46, no. 5, 2022.

[121] G. Bonat Celli and A. Abbaspourrad, "Tailoring delivery system functionality using microfluidics," *Annual Review of Food Science and Technology*, vol. 9, no. 1, pp. 481–501, 2018.

[122] C. J. Hsiao, J. F. Lin, H. Y. Wen et al., "Enhancement of the stability of chlorophyll using chlorophyll-encapsulated polycaprolactone microparticles based on droplet microfluidics," *Food Chemistry*, vol. 306, p. 125300, 2020.

[123] A. S. Opalski, T. S. Kaminski, and P. Garstecki, "Droplet microfluidics as a tool for the generation of granular matters and functional emulsions," *Kona Powder and Particle Journal*, vol. 36, pp. 50–71, 2019.

[124] S. He, N. Joseph, X. Luo, and C. Raston, "Continuous flow thin film microfluidic mediated nano-encapsulation of fish oil," *Lwt-Food Science and Technology*, vol. 103, pp. 88–93, 2019.

[125] L. Kong, R. Chen, X. Wang et al., "Controlled co-precipitation of biocompatible colorant-loaded nanoparticles by microfluidics for natural color drinks," *Lab on a Chip*, vol. 19, no. 12, pp. 2089–2095, 2019.

[126] T. A. Comunian, R. Ravanfar, M. J. Selig, and A. Abbaspourrad, "Influence of the protein type on the stability of fish oil in water emulsion obtained by glass microfluidic device," *Food Hydrocolloids*, vol. 77, pp. 96–106, 2018.

[127] A. Ofner, I. Mattich, M. Hagander et al., "Controlled massive encapsulation via tandem step emulsification in glass," *Advanced Functional Materials*, vol. 29, no. 4, pp. 1–9, 2019.

[128] S. C. S. R. de Moura, G. N. Schettini, A. O. Garcia, D. A. Gallina, I. D. Alvim, and M. D. Hubinger, "Stability of *Hibiscus* extract encapsulated by ionic gelation incorporated in yogurt," *Food and Bioprocess Technology*, vol. 12, no. 9, pp. 1500–1515, 2019.

[129] H. N. Pradeep and C. A. Nayak, "Enhanced stability of C-phycocyanin colorant by extrusion encapsulation," *Journal of Food Science and Technology*, vol. 56, no. 10, pp. 4526–4534, 2019.

[130] I. Alemzadeh, M. Hajiabbas, H. Pakzad, S. Sajadi Dehkordi, and A. Vossoughi, "Encapsulation of food components and bioactive ingredients and targeted release," *International Journal of Engineering*, vol. 33, no. 1, pp. 1–11, 2020.

[131] V. Dadwal, S. Bhatt, R. Joshi, and M. Gupta, "Development and characterization of controlled released polyphenol rich micro-encapsulate of Murraya koenigii bark extract," *Journal of Food Processing and Preservation*, vol. 44, no. 5, 2020.

[132] E. H. J. Kim, D. Paredes, L. Motoi et al., "Dynamic flavor perception of encapsulated flavors in a soft chewable matrix," *Food Research International*, vol. 123, pp. 241–250, 2019.

[133] F. Garavand, S. Rahaee, N. Vahedikia, and S. M. Jafari, "Different techniques for extraction and micro/nanoencapsulation of saffron bioactive ingredients," *Trends in Food Science and Technology*, vol. 89, pp. 26–44, 2019.

[134] M. P. Silva, F. L. Tulini, E. Martins, M. Penning, C. S. Fávaro-Trindade, and D. Poncelet, "Comparison of extrusion and co-extrusion encapsulation techniques to protect *Lactobacillus acidophilus* LA3 in simulated gastrointestinal fluids," *LWT-Food Science and Technology*, vol. 89, pp. 392–399, 2018.

[135] I. Yasmin, M. Saeed, I. Pasha, and M. A. Zia, "Development of whey protein concentrate-pectin-alginate based delivery system to improve survival of *B. longum* BL-05 in simulated gastrointestinal conditions," *Probiotics and Antimicrobial Proteins*, vol. 11, no. 2, pp. 413–426, 2019.

[136] G. Frakolaki, M. Katsouli, V. Giannou, and C. Tzia, "Novel encapsulation approach for *Bifidobacterium subsp*. lactis (BB-12) viability enhancement through its incorporation into a double emulsion prior to the extrusion process," *Science and Technology*, vol. 130, p. 109671, 2020.

[137] M. Fangmeier, D. N. Lehn, M. J. Maciel, and C. F. Volken de Souza, "Encapsulation of bioactive ingredients by extrusion with vibrating technology: advantages and challenges," *Food and Bioprocess Technology*, vol. 12, no. 9, pp. 1472–1486, 2019.

[138] V. Vancauwenberghe, V. Baiye Mfortaw Mbong, E. Vanstreels, P. Verboven, J. Lammertyn, and B. Nicolai, "3D printing of plant tissue for innovative food manufacturing: encapsulation of alive plant cells into pectin based bio-ink," *Journal of Food Engineering*, vol. 263, pp. 454–464, 2019.

[139] M. K. Gupta, F. Meng, B. N. Johnson et al., "3D printed programmable release capsules," *Nano Letters*, vol. 15, no. 8, pp. 5321–5329, 2015.

[140] C. P. Radtke, N. Hillebrandt, and J. Hubbuch, "The biomaker: an entry-level bioprinting device for biotechnological applications," *Journal of Chemical Technology & Biotechnology*, vol. 93, no. 3, pp. 792–799, 2018.

[141] F. U. Din, W. Aman, I. Ullah et al., "Effective use of nanocarriers as drug delivery systems for the treatment of selected tumors," *International Journal of Nanomedicine*, vol. 12, pp. 7291–7309, 2017.

[142] C. Fuciños, M. Míguez, P. Fuciños, L. M. Pastrana, M. L. Rúa, and A. A. Vicente, "Creating functional nanostructures: encapsulation of caffeine into α-lactalbumin nanotubes," *Innovative Food Science and Emerging Technologies*, vol. 40, pp. 10–17, 2017.

[143] J. Zhang, M. Liu, and Z. Zeng, "The antisolvent coprecipitation method for enhanced bioavailability of poorly water-soluble drugs," *International Journal of Pharmaceutics*, vol. 626, p. 122043, 2022.

[144] L. N. Carli, J. S. Crespo, and R. S. Mauler, "PHBV nanocomposites based on organomodified montmorillonite and halloysite: the effect of clay type on the morphology and thermal and mechanical properties," *Composites Part A: Applied Science and Manufacturing*, vol. 42, no. 11, pp. 1601–1608, 2011.

[145] M. S. Gasser, "Inorganic layered double hydroxides as ascorbic acid (vitamin C) delivery system-intercalation and their controlled release properties," *Colloids and Surfaces B: Biointerfaces*, vol. 73, no. 1, pp. 103–109, 2009.

[146] S. J. Choi and Y. R. Kim, "Bioinspired layered nanoclays for nutraceutical delivery system," *ACS Symposium Series*, vol. 1143, pp. 207–220, 2013.

[147] M. Türker, S. M. Selimoğlu, and H. Taşpınar-Demir, "Chapter 12- waste (water) to feed protein: effluent characteristics, protein recovery, and single-cell protein production from food industry waste streams," in *Clean Energy and Resource Recovery*, A. An, V. Tyagi, M. Kumar, and Z. Cetecioglu, Eds., pp. 201–244, Elsevier, 2022.

[148] I. R. Ariyarathna and D. Nedra Karunaratne, "Use of chickpea protein for encapsulation of folate to enhance nutritional potency and stability," *Food and Bioproducts Processing*, vol. 95, pp. 76–82, 2015.

[149] I. R. Ariyarathna and D. N. Karunaratne, "Microencapsulation stabilizes curcumin for efficient delivery in food applications," *Food Packaging and Shelf Life*, vol. 10, pp. 79–86, 2016.

[150] C. Liu, B. Xu, D. J. McClements et al., "Properties of curcumin-loaded zein-tea saponin nanoparticles prepared by antisolvent co-precipitation and precipitation," *Food Chemistry*, vol. 391, p. 133224, 2022.

[151] C. Beck, S. V. Dalvi, and R. N. Dave, "Controlled liquid antisolvent precipitation using a rapid mixing device," *Chemical Engineering Science*, vol. 65, no. 21, pp. 5669–5675, 2010.

[152] Y. Dong, W. K. Ng, J. Hu, S. Shen, and R. B. H. Tan, "A continuous and highly effective static mixing process for antisolvent precipitation of nanoparticles of poorly water-soluble drugs," *International Journal of Pharmaceutics*, vol. 386, no. 1–2, pp. 256–261, 2010.

[153] S. Pedroso-Santana and N. Fleitas-Salazar, "Ionotropic gelation method in the synthesis of nanoparticles/microparticles

for biomedical purposes," *Polymer International*, vol. 69, no. 5, pp. 443–447, 2020.

[154] E. Henao, E. Delgado, H. Contreras, and G. Quintana, "Polyelectrolyte complexation versus ionotropic gelation for chitosan-based hydrogels with carboxymethylcellulose, carboxymethyl starch, and alginic acid," *International Journal of Chemical Engineering*, vol. 2018, Article ID 3137167, 12 pages, 2018.

[155] S. A. Algharib, A. Dawood, K. Zhou et al., "Preparation of chitosan nanoparticles by ionotropic gelation technique: effects of formulation parameters and in vitro characterization," *Journal of Molecular Structure*, vol. 1252, p. 132129, 2022.

[156] R. Pérez-Masiá, J. M. Lagaron, and A. Lopez-Rubio, "Morphology and stability of edible lycopene-containing micro- and nanocapsules produced through electrospraying and spray drying," *Food and Bioprocess Technology*, vol. 8, no. 2, pp. 459–470, 2015.

[157] R. Penalva, I. Esparza, M. Agüeros, C. J. Gonzalez-Navarro, C. Gonzalez-Ferrero, and J. M. Irache, "Casein nanoparticles as carriers for the oral delivery of folic acid," *Food Hydrocolloids*, vol. 44, pp. 399–406, 2015.

[158] M. Abdollahi, M. Rezaei, and G. Farzi, "A novel active bionanocomposite film incorporating rosemary essential oil and nanoclay into chitosan," *Journal of Food Engineering*, vol. 111, no. 2, pp. 343–350, 2012.

[159] M. Alboofetileh, M. Rezaei, H. Hosseini, and M. Abdollahi, "Antimicrobial activity of alginate/clay nanocomposite films enriched with essential oils against three common foodborne pathogens," *Food Control*, vol. 36, no. 1, pp. 1–7, 2014.

[160] D. Sonin, E. Pochkaeva, S. Zhuravskii et al., "Biological safety and biodistribution of chitosan nanoparticles," *Nanomaterials*, vol. 10, no. 4, p. 810, 2020.

[161] A. Manzoor, A. H. Dar, V. K. Pandey et al., "Recent insights into polysaccharide-based hydrogels and their potential applications in food sector: a review," *International Journal of Biological Macromolecules*, vol. 213, pp. 987–1006, 2022.

[162] Z. Zhu, S. Jiang, Y. Liu et al., "Micro or nano: evaluation of biosafety and biopotency of magnesium metal organic framework-74 with different particle sizes," *Nano Research*, vol. 13, no. 2, pp. 511–526, 2020.

[163] A. Damato, F. Vianello, E. Novelli et al., "Comprehensive review on the interactions of clay minerals with animal physiology and production," *Frontiers in Veterinary Science*, vol. 9, 2022.

[164] W. Xu, K. Tamarov, L. Fan et al., "Scalable synthesis of biodegradable black mesoporous silicon nanoparticles for highly efficient photothermal therapy," *ACS Applied Materials and Interfaces*, vol. 10, no. 28, pp. 23529–23538, 2018.

[165] D. Nath, R. Santhosh, K. Pal, and P. Sarkar, "Nanoclay-based active food packaging systems: a review," *Food Packaging and Shelf Life*, vol. 31, article 100803, 2022.

[166] S. Liang, S. Xu, D. Zhang, J. He, and M. Chu, "Reproductive toxicity of nanoscale graphene oxide in male mice," *Nanotoxicology*, vol. 9, no. 1, pp. 92–105, 2015.

[167] A. Skovmand, A. Jacobsen Lauvås, P. Christensen, U. Vogel, K. Sørig Hougaard, and S. Goericke-Pesch, "Pulmonary exposure to carbonaceous nanomaterials and sperm quality," *Particle and Fibre Toxicology*, vol. 15, no. 1, pp. 10–12, 2018.

[168] M. Szmidt, E. Sawosz, K. Urbańska et al., "Toxicity of different forms of graphene in a chicken embryo model," *Environmental Science and Pollution Research*, vol. 23, no. 19, pp. 19940–19948, 2016.

[169] O. Farshad, R. Heidari, M. J. Zamiri et al., "Spermatotoxic effects of single-walled and multi-walled carbon nanotubes on male mice," *Frontiers in Veterinary Science*, vol. 7, p. 591558, 2020.

[170] O. Akhavan, E. Ghaderi, E. Hashemi, and E. Akbari, "Dose-dependent effects of nanoscale graphene oxide on reproduction capability of mammals," *Carbon*, vol. 95, pp. 309–317, 2015.

[171] P. Adadi, N. V. Barakova, K. Y. Muravyov, and E. F. Krivoshapkina, "Designing selenium functional foods and beverages: a review," *Food Research International*, vol. 120, pp. 708–725, 2019.

[172] J. Grgić, G. Šelo, M. Planinić, M. Tišma, and A. Bucić-Kojić, "Role of the encapsulation in bioavailability of phenolic compounds," *Antioxidants*, vol. 9, no. 10, p. 923, 2020.

[173] S. Peng, Z. Li, L. Zou, W. Liu, C. Liu, and D. J. McClements, "Enhancement of curcumin bioavailability by encapsulation in sophorolipid-coated nanoparticles: an in vitro and in vivo study," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 6, pp. 1488–1497, 2018.

[174] S. Y. Koo, K. T. Hwang, S. Hwang et al., "Nanoencapsulation enhances the bioavailability of fucoxanthin in microalga *Phaeodactylum tricornutum* extract," *Food Chemistry*, vol. 403, p. 134348, 2023.

[175] W. Tang, J. Zhuang, A. C. Anselmo et al., "Enhanced stability and clinical absorption of a form of encapsulated vitamin A for food fortification," *Proceedings of the National Academy of Sciences*, vol. 119, no. 51, article e2211534119, 2022.