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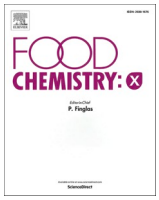

Development of "Smart Foods" for health by nanoencapsulation: Novel technologies and challenges

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ABSTRACT

Importance of nanotechnology may be seen by penetration of its application in diverse areas including the food sector. With investigations and advancements in nanotechnology, based on feedback from these diverse areas, ease, and efficacy are also increasing. The food sector may use nanotechnology to encapsulate smart foods for increased health, wellness, illness prevention, and effective targeted delivery. Such nanoencapsulated targeted delivery systems may further add to the economic and nutritional properties of smart foods like stability, solubility, effectiveness, safeguard against disintegration, permeability, and bioavailability of smart/bioactive substances. But in the way of application, the fabrication of nanomaterials/nanostructures has several challenges which range from figuring out the optimal technique for obtaining them to determining the most suitable form of nanostructure for a bioactive molecule of interest. This review precisely addresses concepts, recent advances in fabrication techniques as well as current challenges/glitches of nanoencapsulation with special reference to smart foods/bioactive components. Since dealing with food materials also raises the quest for safety and regulatory norms a brief overview of the safety and regulatory aspects of nanomaterials/nanoencapsulation is also presented.

1. Introduction

The agricultural productivity as well as nutritive value of food must be increased in order to meet the global food demand and nutritional security. To achieve nutritional security, access to food that is both nutritiously appropriate as well as safe must be guaranteed (Nayak et al., 2021). In this context, smart foods (designed functional/fortified foods with targeted delivery for safe and easy consumption and disease prevention), which have enhanced competence for the transport of the bioactive chemicals they contain (to the target areas), have been sparked by the rising demand towards physical and mental wellness as well as preventing disease via diet and nutrition (Donsì & Ferrari, 2020). Requirement of smart foods with increased nutrients is gaining impetus due to rapid rate of urbanization as well as changing dietary preferences (Nayak et al., 2021). In addition, the consumption of smart foods has provided many health advantages via the triggered, targeted, regulated liberation of bioactive substances together with enhanced cellular uptake in the gastrointestinal tract. The same has potential, to address the problems of inadequate gastric residence time and low permeation inside the gut (Salvia-Trujillo et al. 2017; Araiza-Calahorra, 2018; Fathi et al., 2019; Puttasiddaiah et al., 2022). Traditionally, the inclusion of bioactive substances in foods, such as phytochemicals, micronutrients, and dietary fibers, posed challenges due to issues such as poor miscibility in the food material, unpalatable flavors, and physical/chemical instability in food processing environments like high temperatures, light, oxygen, and so on (Fig. 1(a)) (Donsì, Sessa, & Ferrari, 2015; Donsì, 2018; Fathi et al., 2019). This is further supported by the fact that phenolic substances, which are considered natural antioxidants (used for their therapeutic benefits), may become less bioavailable after interacting with the proteins as well as carbohydrates included in food

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material (Alu'datt et al., 2018; Goyal et al., 2023). Likewise, naturally existing dietary ingredients may have an impact on natural pigments as well, particularly following downstream procedures that harm the product's structure and cause the liberation of acids/enzyme like substances. Such substances may interact with the natural pigments, thereby causing undesirable transformations in the colour (Vinha, Rodrigues, Nunes & Oliveira, 2018; Maleki et al., 2022). In this context, encapsulation seems to be a potent method for overcoming several of the shortcomings described above. Encapsulation facilitates the preservation of a spatiotemporal variety of bioactive substances in their liquid, solid, or gaseous state by encasing them in a safeguarding matrix. Further, encapsulation may increase stability under high-temperature as

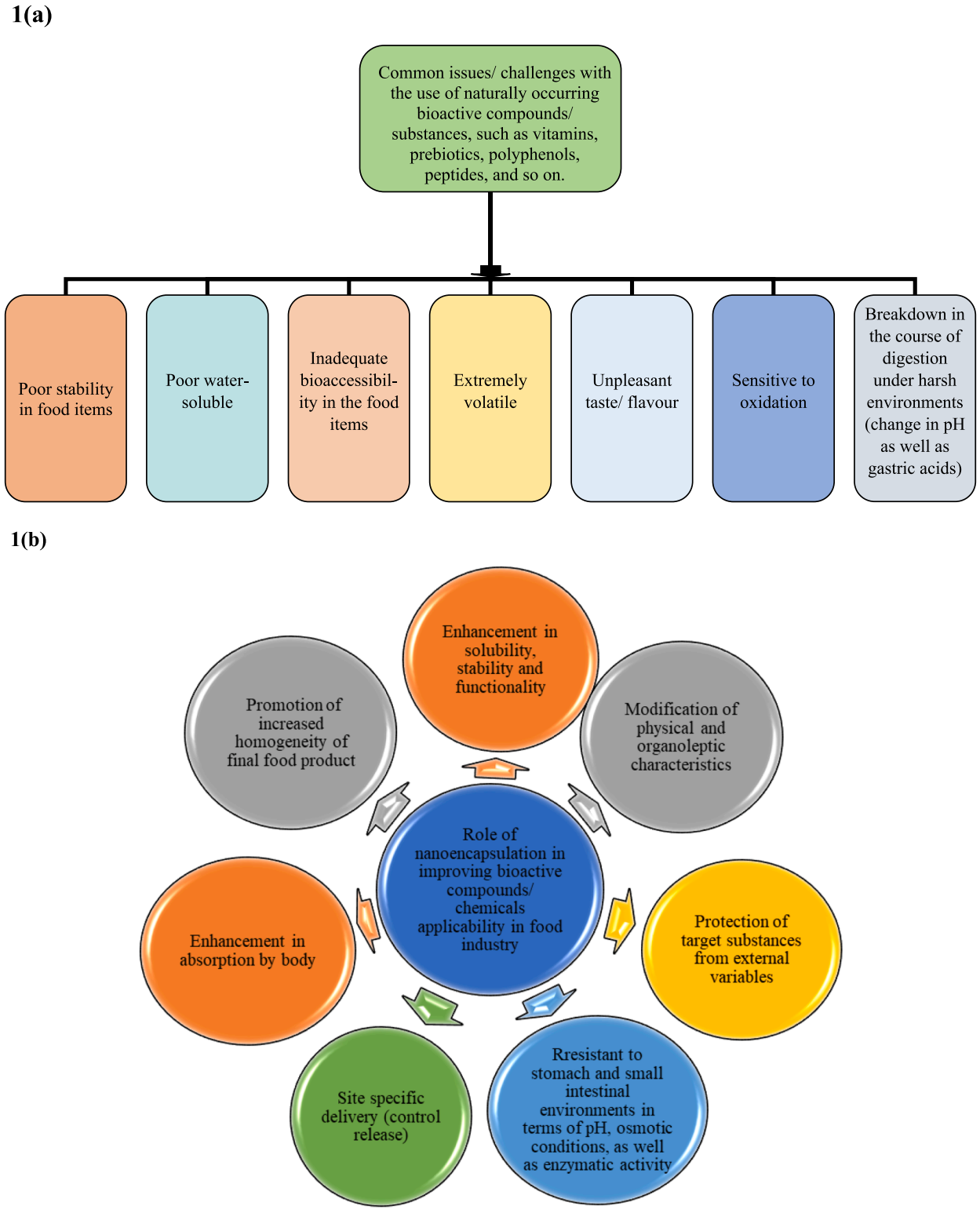

Fig. 1. (a) Problems/issues associated with the exploitation of bioactive substances in the food industry, and (b) Benefits of nanoencapsulation in the food industry/sector.

well as humid environments, thereby enabling the prolonged release of nutrients. It also minimizes unwanted chemical reactions with other components together with safeguarding off-flavors from certain vitamins and minerals (Tomadoni, Fabra, Méndez, Martínez-Abad, & López-Rubio, 2022). Altogether, encapsulation really seems to represent one of the most promising techniques towards protecting fragile/unstable substances from unfavourable conditions or deterioration brought on by oxidative environments (Min, Kim, Lee, & Lee, 2017; Puttasiddaiah et al., 2022).

The majority of substances, which are incorporated into eatable coatings/films are bioactive substances with antibacterial as well as antioxidant characteristics. The common ingredients, which make up the core of the eatable coatings include polyphenols such as anthocyanins, flavonoids, etc., volatile constituents of essential oils such as cinnamon, lemon and so on, natural pigments, vitamins, polypeptides and so on (Zheng et al., 2019; Chen et al., 2022). Besides, improving the characteristics of edible film, bioactive substances in encapsulated films may also makeover the taste profile, shelf life, rate of lipid peroxidation, and other indices of food product quality (Díaz-Montes & Castro-Muñoz, 2021). As far as widely used scales of encapsulation are concerned, there are two forms of encapsulation approaches, i.e., microencapsulation and nanoencapsulation that have been employed often in the food sector to safeguard as well as enhance the valuable characteristics of unstable or sensitive chemicals. The fundamental difference distinguishing microencapsulation from nanoencapsulation hinges upon the dimensions of the particles employed for the encapsulation process. Microencapsulation primarily deals with particles typically falling within the micrometer (μm) range, whereas nanoencapsulation is centered around considerably smaller particles in the nanometer (nm) range (Ayala-Fuentes & Chavez-Santoscoy, 2021). In microencapsulation, minute particles of solid, liquid, or gas find themselves enveloped within a secondary substance, encompassing a size spectrum spanning from 1 to 1000 μm (Dima & Dima, 2015; Lengyel, Kállai-Szabó, Antal, Laki & Antal, 2019; Hogenbom, Jones, Wang, Pickett & Faraone, 2021). This is accomplished using physical processes such as spray drying, fluid bed coating, extrusion, co-extrusion, molecular encapsulation, emulsions, as well as chemical procedures. On the other hand, nanoencapsulation, also known as nanoscale encapsulation, is the loading of bioactive chemicals or components within capsules, which are enclosed in a range of protective substances, where size ranges from 1 to 100 μm (Ayala-Fuentes & Chavez-Santoscoy, 2021; Pateiro et al., 2021). In other words, this method coats the basic, small particles with the wall substance to produce capsules. In contrast to nanoencapsulation, which confines the bioactive components/substances to a cavity surrounded by a special polymer membrane, nano-spheres are matrix systems, where the bioactive constituents are evenly dispersed. To safeguard bioactive chemicals, microencapsulation, as well as nanoencapsulation are used in the pharmaceutical, agricultural, cosmetic, and medical including food or nutraceutical sectors. The intrinsic glitches linked with macro-, as well as microscale encapsulation in delivering bioactive substances, may be addressed by nanoencapsulation technology (Ayala-Fuentes & Chavez-Santoscoy, 2021).

A thorough assessment of the literature revealed that so far, many review articles have been published on the application of nanotechnology in the food industry (Sekhon, 2010; Silva, Cerqueira, & Vicente, 2012; Enescu et al., 2019). Despite many good reviews on such issue, only a few research and review articles are focussed on the nanoencapsulation of smart food or dietary/food components like omega-3 fatty acids, carotenes, vitamins, etc., indicating that this cutting-edge technology is still in its infancy stages (García, Forbe, & Gonzalez, 2010; Fathi, Mozafari, & Mohebbi, 2012; Li et al., 2015; Agarwal et al., 2016; Rawat et al., 2023). Extensive research on food-grade encapsulants is required to facilitate the delivery of preferred bioactive chemicals or components via the food supply (Paredes, Asencio, Manuel, & Allemandi, 2016; Li et al., 2022). Since the challenges in encapsulation are diverse in nature and many, if not all, needs to be addressed for effective smart food delivery, therefore, the focus has been kept on highlighting the development of "Smart Foods" for health by nanoencapsulation in this review. For the benefit of potential authors, emphasis on innovative technologies and trends in this field has also been given, apart from challenges/issues.

2. Nanoencapsulation

The term 'nanoencapsulation' illustrates the possible uses of material that is enclosed at nanoscale sizes encompassing films, coatings, layers, or even simple microdispersions. The nanoparticle (nano-P)-based encapsulation strategy offers greater encapsulation-friendly characteristics. Nanoparticles (nano-Ps) release bioactive substances more effectively and with improved encapsulation-related features (Fig. 1(b).) Additionally, the transport of substances to a variety of tissues inside the organism is directly impacted by particle size. Intriguingly, it is reported that only nano-Ps may effectively enter certain cell lines, which provide nano-Ps an edge over bigger microparticles, which have a much-reduced absorption rate (Price & Patel, 2023). Nano-Ps might also increase the compatibility of the food matrix, extending the shelf life as well as the bioavailability of the food items (Pradhan et al., 2015; Cunha et al., 2020). It is said to be bioavailable, when a material or medicine is fully available for its targeted biological destination. As an example, Fig. 2(a) depicts the factors that contribute to the lower bioaccessibility of bioactive substances/chemicals like flavonoids. In particular, nanoencapsulation yields particles with a size below 100 nm. The encapsulated particles can be further categorized into three groups: nanocapsules (with a size of less than 0.2 μm), microcapsules (ranging from 0.2 to 5000 μm), and macrocapsules (measuring less than 5000 μm) (Berkland, Kipper, Narasimhan, Kim, & Pack, 2004; Jafari, 2017; Pateiro et al., 2021). The uniformity that nanoencapsulation gives, which leads to improved efficiency and acceptable physical and chemical characteristics, is one of the key advantages of using it. This method is a desirable substitute for redesigning smart food ingredients that can significantly affect the processability, bioavailability, and stability of bioactive components (Mahmoud, Ali, & Amin, 2018; Human, de Beer, van der Rijst, Aucamp, & Joubert, 2019).

The appropriate and effective encapsulation process is dependent upon the core material as well as the required final product attributes (Dias et al., 2017; Sivanathan et al., 2020). It should be emphasized that carrier formulation has a significant impact on final characteristics, encapsulation effectiveness, as well as liberation of entrapped component. Water solubility, shelf life, as well as bioavailability are among the key characteristics governed by carrier makeup. As particle size as well as type (hydrophilic or lipophilic) are important parameters in controlling these features, nanoencapsulation caters to more regulation by lowering particle size (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013; Chaudhari, Singh, Das, & Dubey, 2021). Substances that are hydrophilic dissolve in water but not in lipids/organic solvents. Bioactive substances such as ascorbic acid, polyphenols, and so on are some nanoencapsulated hydrophilic bioactive substances/chemicals, for example. On the other hand, lipophilic substances are soluble in lipids and organic solvents but not in water. Lycopene, β-carotene, lutein, etc., are some important lipophilic nutrients. The rate, as well as the mechanism, of release from a polymer matrix system, are determined by the dissolution of the bioactive components. Hydrophilic substances liberate at a greater speed, and their kinetics are regulated by the proper amalgamation of diffusion as well as erosion processes. Lipophilic substances typically cause partial liberation because of poor solubility as well as slow rates of dissolving through an erosion process (Kumar and Kumar, 2001; Varma, Kaushal, Garg, & Garg, 2004; Kuang, Oliveira, & Crean, 2010; Falsafi et al., 2022). In addition, hydrophilic substances have poor permeability and can merely be absorbed through active transport, while lipophilic substances are extremely permeable through the gut by active transport as well as facilitated diffusion (Acosta, 2009; Salah et al., 2020). Overall, the main goal of nanosized delivery methods is to

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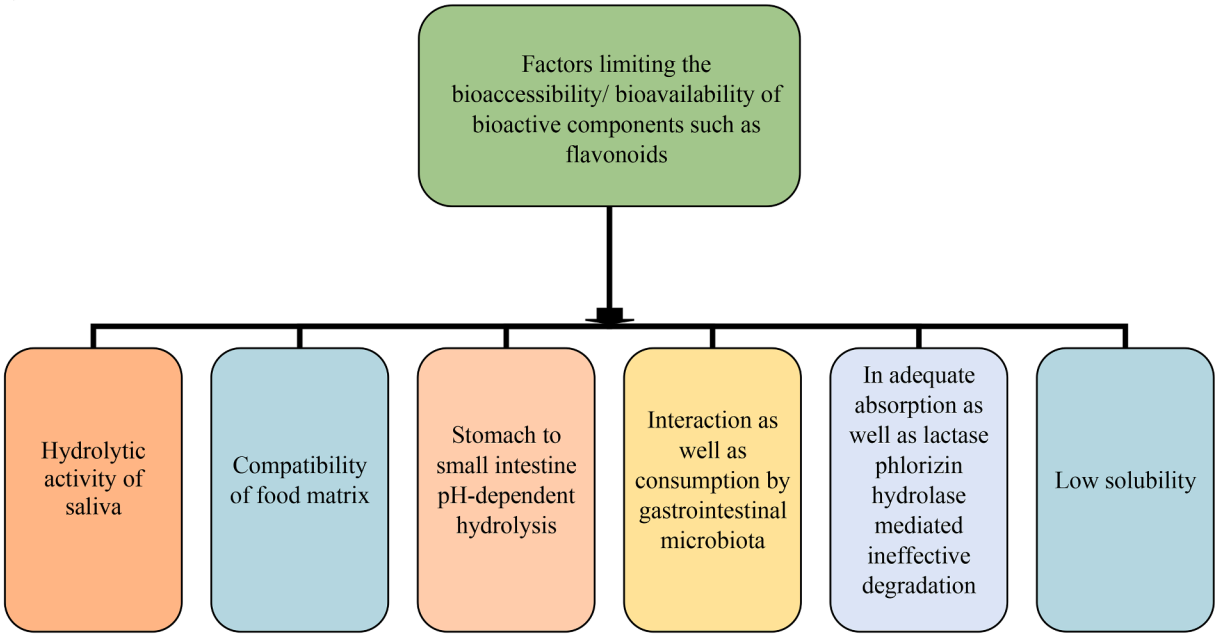

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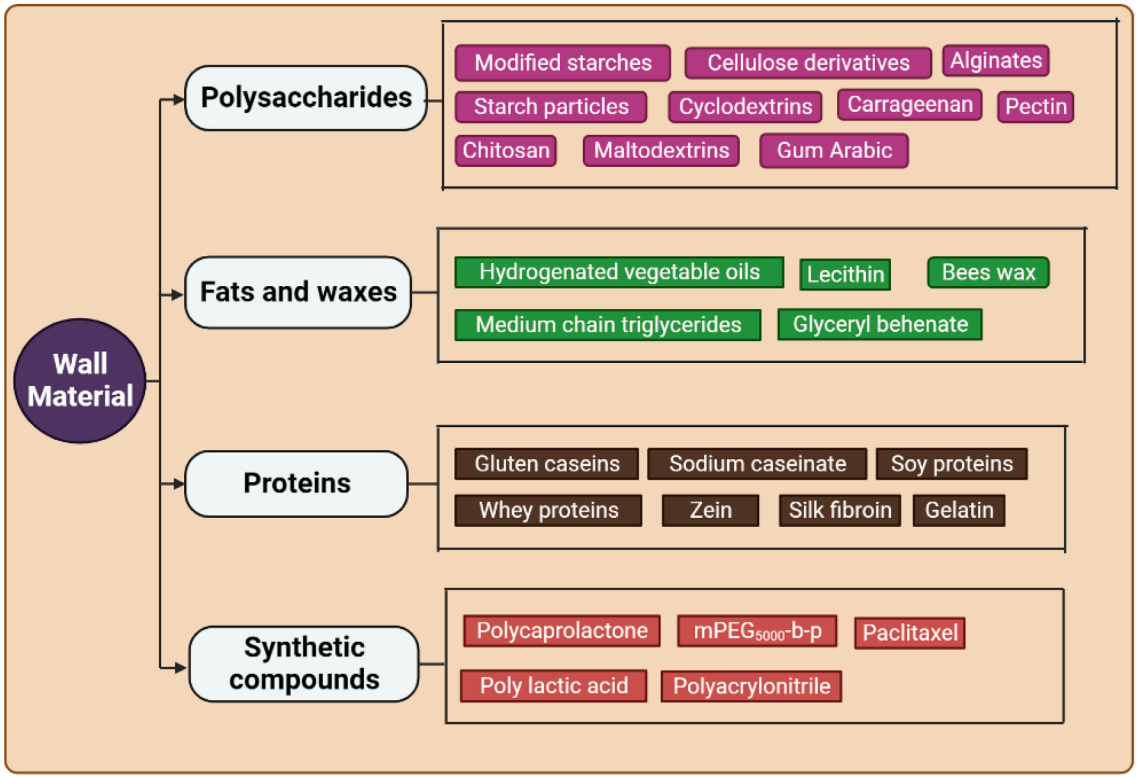

Fig. 2. (a) A list of the variables responsible for limited bioaccessibility of bioactive components/chemicals like flavonoids, and (b) An outline of the polymeric wall materials that are often used in the food industry.

enhance the digestion, release, as well as absorption of bioactive substances that are chemically unstable or lipophilic in nature. It is worth mentioning here that for the body's physiological processes, these traits of bioactive substances are crucial (Jones, Caballero, & Davidov-Pardo, 2019). For instance, structural lipids have been investigated as carriers of healthy components employed for the prevention of cholesterol transportation from the digestive tract to the circulation (Dingman, 2008; Van et al., 2022). Further review of available literature suggest that the solid-lipid nanoparticles, liposomes, biopolymers, colloids, emulsions, and nanofibers have all shown unquestionable efficacy as

carriers of functional substances (Abbas, Saleh, Mohamed, & MohdAzhan, 2009; Gorantla et al., 2022). Table 1 shows an overview of commonly consumable bioactive substances (core ingredients) that can be nanoencapsulated.

3. Nanoencapsulation coating/wall materials

Encapsulation is the process of encasing microscopic particles or droplets in a covering to produce capsules. Nanocapsules are tiny spheres surrounded by a homogeneous wall and used in different sectors. In the food sector, the wall materials used as encapsulating systems are composed of polysaccharides, lipids, waxes, protein molecules, as well as safe synthetic substances. Mainly, polysaccharides as well as protein molecules make up the majority of the wall materials employed as encapsulating systems in the food sector. The reason behind their use is that such biopolymeric substances are acceptable for human consumption, harmless, as well as their interaction characteristics enable the entrapment of many kinds of bioactive substances. The substance inside the nanocapsule is known as the core, internal phase, or fill, whereas the wall is known as the shell, coating, or membrane. The wall material of the nanocapsules is developed to fulfill a particular function based on the use. Hence, the wall material is the most important aspect of any nanocapsule as it is critical in the fabrication of nanocapsules for preserving bioactive substances/food components from external conditions. Further, the wall material must be unreactive to the core active constituents, stabilize the core substance/component, film-forming, flexible, flavourless, non-hygroscopic, having modest viscosity, cost-effective, dissolvable in an aqueous environment/solvent. In addition, the covering can be flexible, fragile, tough as well as thin, with the ability to regulate liberation at a precise site in particular environments (Vijeth, Heggannavar, & Kariduraganavar, 2019). Furthermore, the coating wrapped around the food material must be made properly and there should not be any form of leakage, which are typical safety precautions to consider while developing nano-capsules. The vast variety of natural and synthetic polymers must be considered when choosing a coating substance that eventually focuses on the properties that will be required to create the final product. The best coating materials for encapsulation might have superior strength as well as durability together with strong rheological properties at increasing concentrations. The coating material should be capable of holding as well as sealing the active constituent inside its structure throughout processing as well as long-term storage (Tahir et al., 2021). Fig. 2(b) shows an overview of the polymeric wall materials typically utilized in the food industry.

Amongst polymeric wall materials, the frequently employed polysaccharides in various applications encompass chitosan, pectins, maltodextrins, corn syrup solids, acacia gums (commonly known as gum Arabic), starch, maltodextrins, and β-cyclodextrins. These carbohydrates are favored due to their noteworthy properties, including non-toxicity, robust stability, biodegradability, and bioadhesibility, rendering them valuable components for delivery systems (De Souza Simões, Madalena, Pinheiro, Teixeira, Vicente, & Ramos, 2017). Their thermal resilience is especially pivotal, rendering them apt as carriers for safeguarding heat-sensitive compounds during elevated-temperature food processing, thus presenting an intriguing and advantageous alternative that surpasses the capabilities of lipid- or protein-based materials (Fathi, Martín, & McClements, 2014). On the other hand, lipids, commonly referred to as either oils or fats, are categorized based on their physical state at room temperature, whether they exist as liquids or solids. Additionally, these compounds can be classified into nonpolar forms like cholesterol or triacylglycerol and polar forms such as phospholipids, resulting in significant variations in their solubility and functional characteristics. Lipid-based delivery systems offer numerous advantages, including the ability to encapsulate bioactive compounds with varying solubility profiles. Notably, these systems excel in safeguarding unstable molecules with high hydrophobicity from degradation, thereby enhancing their stability during storage (De Souza Simões, Madalena, Pinheiro, Teixeira, Vicente, & Ramos, 2017). Examples of lipid carriers commonly utilized in such delivery systems encompass beeswax, vegetable oils, lecithin, and medium-chain triglycerides as detailed previously (Jafari, 2017). Likewise, proteins represent a class of biological macromolecules composed of amino acid units covalently linked through peptide bonds. These amino acids exhibit diversity in their structural properties, classified into categories such as aliphatic, aromatic, charged (positively or negatively charged), or polar, based on the characteristics of their side groups. Proteins employed extensively in the food manufacturing industry can be sourced from botanical origins, including soy and zein, or from animal sources, encompassing casein, egg, and whey proteins. Another method for obtaining proteins is through hydrolysis. Proteins hold notable significance in terms of dietary value and offer a multitude of functional attributes. These functionalities include the ability to form gels, act as emulsifiers, and bind water effectively. Remarkably, proteins exhibit versatility, enabling the creation of various structural forms such as particles, films, fibers, tubules, and hydrogels. This structural diversity presents opportunities for encapsulating both hydrophobic and hydrophilic bioactive components within these protein-based matrices. Furthermore, proteins are

Table 1
Common food bioactive substances/smart components (core compounds) that may be nanoencapsulated.

No.	Bioactive chemicals/substances	Encapuslation strategy	Uses of their encapsulation	References
1.	Phenolic compounds like Quercetin, tea catechins, folic acid, thymol, resveratrol, anthocyanins	Freeze-drying, spray-drying, and microwave-drying	Target delivery, enhancement of their antioxidant and other functional capabilities, inclusion of new beneficial characteristics	Grgić et al., (2020), Pateiro et al., (2021)
2.	Essential fatty acids like (DHA, linolenic acid	Spray drying	Stabilization, improved solubility, reduced volatility, lower dosages, and a positive effect on the sensory quality of the final product	Geranpour et al., (2020), Pateiro et al., (2021)
3.	Vitamins like Vitamin D_3, vitamin B_9, vitamin B_2, riboflavin, thiamine	Spray drying and solvent evaporation	Defending against oxidation	Mujica-Álvarez et al., (2020), Pateiro et al., (2021)
4.	Carotenoids like tomato lycopene and crocins	Freeze-drying nanodispersion and nanoemulsion	Stabilization, effective controlled release, and increased industrial use (as colourants and antioxidants)	Saini et al., (2022), Pateiro et al., (2021)
5.	Peptides and enzymes like natural dipeptides and nisin	Nanoliposomes and Spray drying	Enhanced antioxidant and/or antibacterial effects, improved absorption	Pateiro et al., (2021), Aguilar-Toalá et al., (2022)
6.	Probiotics and prebiotics like *L* Lactobacillus *casei*, *L. reuteri*, Bifidobacterium *bifidum*, *B. breve,* Streptococcus *thermophilus,* fructooligosaccharides, lactulose, and galactooligosaccharides	Emulsification	Increased viability, gastrointestinal health promotion, and appropriate inclusion in the food product	Pateiro et al., (2021), Rajam & Subramanian (2022)
7.	Others such as minerals, colorants, flavors,buffers, micronutrients)	Nanoemulsion, nanoliposome	Improvements to the food system's homogeneity, regulated release, flavour, taste, and/or texture	Pateiro et al., (2021), Soni et al. (2022)

generally regarded as natural, biodegradable, and safe carriers for delivery systems (De Souza Simões, Madalena, Pinheiro, Teixeira, Vicente, & Ramos, 2017). Their inherent biocompatibility and the fact that they break down into harmless components within the body make them highly suitable for applications in drug delivery and food technology (Pateiro et al., 2021). However, synthetic compounds like polyvinyl alcohol and polyacrylamide present noteworthy advantages in the context of nanoencapsulation, particularly for smart foods and bioactive compounds. For instance, polyvinyl alcohol demonstrates properties of biodegradability, non-toxicity, and biocompatibility, rendering it highly suitable for various encapsulation applications. On the other hand, polyacrylamide is recognized for its exceptional stability, contributing to its appeal as a choice material for encapsulation strategies (Gaaz, Sulong, Akhtar, Kadhum, Mohamad, & Al-Amiery, 2015; Barbălată-Mândru, Serbezeanu, Butnaru, Rîmbu, Enache, & Aflori, 2022). These inherent attributes arise from the unique characteristics of these synthetic compounds, positioning them as valuable contenders in encapsulation methodologies across diverse industries, including the realms of food science and pharmaceuticals.

4. Discharge/liberation mechanisms in controlled release systems

The discharge mechanisms of the matrix's core material influence the release profile of bioactives. For the same reason, a precise understanding of bioavailability, as well as bioaccessibility, may help to grasp release ideas better. Bioaccessibility is defined as the proportion of active substances liberated from their main site in food into the digestive system for luminal absorption (Jafari & McClements, 2017; Jalali-Jivan et al., 2022). On the other hand, bioavailability is defined as the fraction of ingested substances that reach the cardiovascular system and thus are available for biological functions (Flores & Kong, 2017; Arshad et al., 2021). Liberation/discharge might be instant (release occurs rapidly after use) or modified (release occurs either over a long period of time after use or at a precise location inside the body) (Perrie & Rades, 2012; Ghezzi et al., 2021). The controlled release systems are a subset of modified-release systems that are designed to reach a specified dosage/amount regardless of target site circumstances. In another sense, controlled release systems point toward uniformity throughout the release/liberation, which signifies that the bioactive substances are delivered in a predetermined profile over a predetermined time period (Perrie & Rades, 2012; Yadav et al., 2022). Furthermore, the liberation mechanisms involve the processes or circumstances that influence how quickly a bioactive substance is discharged or delivered (Boostani & Jafari, 2021). There are some typical release mechanisms for the controlled release, which are given below:

4.1. Osmosis-mediated liberation mechanism

The osmosis release mechanism shares similarities with the swelling release mechanism, also known as solvent-activated release. In this scenario, the carrier system gradually absorbs the solvent over time, causing it to swell until it reaches a point of structural compromise. Eventually, the carrier swells to the extent that it initiates cracks or fractures in the coating material (Boostani & Jafari, 2020). This mode of transport is predominantly characterized by convection rather than diffusion. Thus, when an exceptionally selective water-permeable carrier with minute orifices, which is also resistant to the encapsulated compounds, encounters an aqueous medium, it undergoes water absorption, leading to the generation of osmotic pressure and subsequent release (Boostani & Jafari, 2020; Fredenberg, Wahlgren, Reslow, & Axelsson, 2011).

4.2. Erosion based liberation mechanism

The erosion mechanism can be categorized into two distinct groups: surface erosion (characterized by degradation occurring solely in the outer layer of the carrier) and bulk erosion (degradation extends throughout the entire carrier structure). The concept of erosion, in essence, is defined as the release phenomenon occurring in the absence of transport events, primarily due to carrier dissolution (McClements, 2015). It is important to emphasize that erosion as the mass loss of the polymer, initiates only when the degradation products of the polymer diffuse into the release environment, a concept reinforced by prior research (Fredenberg, Wahlgren, Reslow, & Axelsson, 2011; Jafari, Katouzian, Rajabi, & Ganje, 2017). The nature of the release mechanism, whether surface or bulk, is intricately linked to the erosion rate at the point of occurrence, which in turn, is influenced by factors related to the carrier and the surrounding conditions. Moreover, the formation of pores resulting from the erosion process can augment the diffusion rate of bioactive compounds. However, when diffusion surpasses erosion in terms of speed, the release process is predominantly erosion-controlled. Conversely, when erosion outpaces diffusion, the release mechanism becomes primarily diffusion-controlled (Boostani & Jafari, 2020). This delicate interplay between erosion and diffusion kinetics underscores the complex nature of controlled release systems.

4.3. Diffusion mediated liberation mechanism

The predominant mechanism governing controlled release (CR) systems is diffusion, making it the most influential mechanism (McClements, 2015). Diffusion, in this context, refers to the stochastic movement of bioactive molecules guided by a potential chemical gradient, typically described in terms of a concentration gradient (Fredenberg, Wahlgren, Reslow, & Axelsson, 2011). As it fundamentally dictates the migration of bioactives from within the carriers to their exterior, diffusion can be considered a critical rate-limiting step in the release process. The rate of diffusion is contingent upon the solubility and permeability characteristics of the bioactive compounds. Furthermore, the nature of the carrier material plays a significant role, with diffusion being slowest in solids and fastest in gases (Boostani & Jafari, 2020). Additionally, it's worth noting that during the diffusion process, the encapsulation system can either remain relatively stable or undergo changes. These changes may include swelling, shrinkage, erosion, and fragmentation events, which can impact the overall release kinetics (McClements, 2015).

4.4. Solubilization-based liberation mechanism

In this context, when the carrier is exposed to specific environments, particularly those that are thermodynamically compatible, it facilitates the release of bioactives into the adjacent surroundings (McClements, 2015). Among various mechanisms of CR, solubilization-based CR systems are considered the most straightforward to design. Typically, solubilization is envisioned to commence from the external surface and progress inward within the carrier system (Jafari, Katouzian, Rajabi, & Ganje, 2017). Broadly, two categories of CR-solubilization systems can be delineated: (i) Encapsulation-solubilization CR systems: In this scenario, food ingredients are encapsulated within materials that gently dissolve. Consequently, the rate of solubilization is chiefly governed by the solubility characteristics of the food ingredients and the intrinsic properties of the carrier material, and (ii) Matrix-solubilization CR systems: In these systems, bioactives are homogenously distributed throughout the carrier material, thereby influencing the dissolution rate. However, distinguishing between the solubilization mechanism and the diffusion mechanism can often be challenging. This challenge arises because the solvent can participate in both erosion and swelling processes, potentially augmenting the overall diffusion rate (Boostani & Jafari, 2020; McClements, 2015). These dissolution-based CR systems hold significant potential in various applications due to their relative simplicity in design. Nevertheless, a thorough understanding of the intricate interplay between dissolution, diffusion, and carrier matrix properties is vital for optimizing their performance in controlled release

applications.

4.5. Swelling based liberation mechanism

In this case, the liberation of substances from the encapsulation system is a consequence of solvent absorption, leading to an expansion of the encapsulation material. The pace at which these substances are released is influenced by two factors: the rate of material expansion and the duration it takes for the food components to disperse through the expanded system (McClements, 2015). The enlargement of the polymeric systems can be intentionally manipulated by introducing nutrients or other ingredients with osmotic properties, which facilitate the entry of solvent into the carrier material. The mechanism of release through swelling can be carefully controlled by choosing an appropriate polymeric matrix and managing external conditions such as temperature and pH (Boostani & Jafari, 2020).

4.6. Fragmentation mediated liberation mechanism

Whenever subjected to various environmental conditions like pressure, shearing forces, shifts in pH, and enzymatic activities, the carrier may undergo cracking or breakage. As a consequence of this, the constituents of the food are set free using a fragmentation mechanism (Boostani & Jafari, 2020). The pace at which these constituents are

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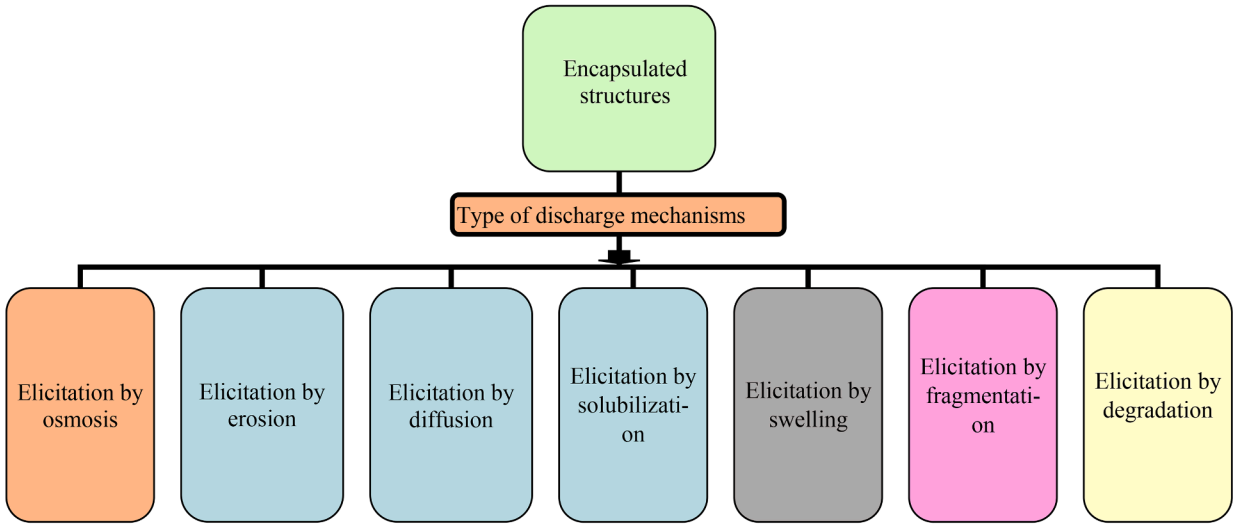

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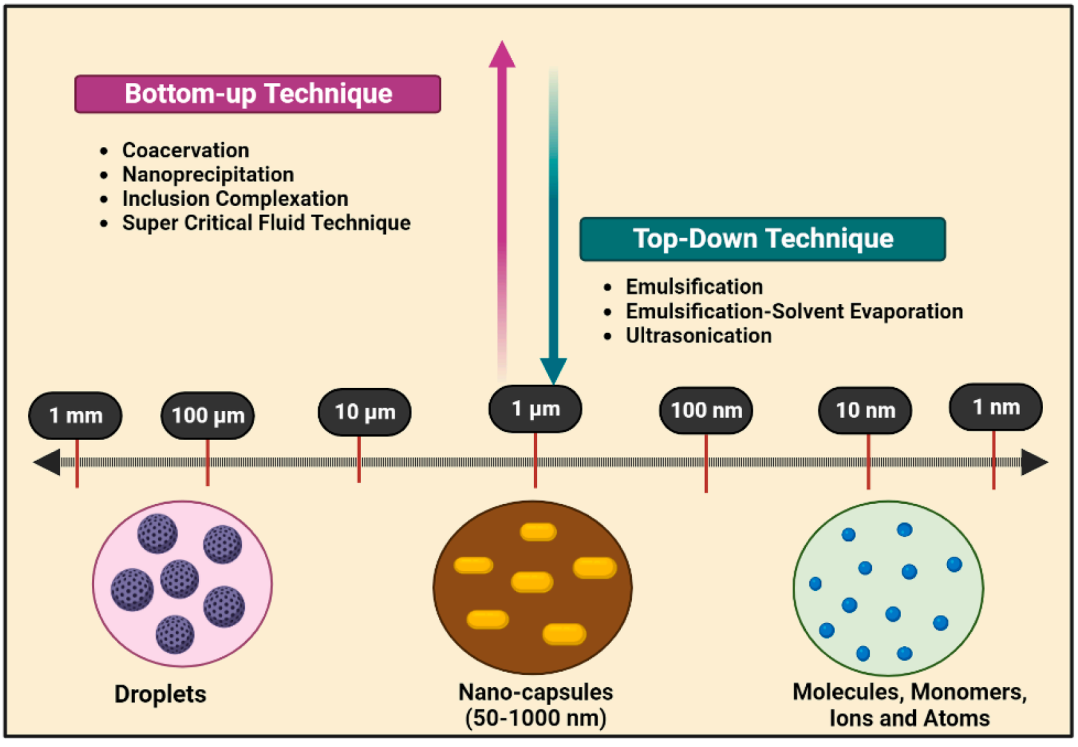


Fig. 3. (a) Liberation/discharge mechanism of bioactive substances/from enclosed/encapsulated structures, and (b) Different approaches for nanoencapsulation.

released is governed by the attributes that define the breakage of the encapsulation system, including the stress experienced at the point of rupture. Additionally, the configuration and dimensions of the resultant fragments also have the potential to impact the release rate significantly. The bioactive elements are anticipated to exit the fragments through an assortment of release mechanisms, encompassing diffusion, dissolution, and erosion. Notably, due to the formation of smaller fragments and the subsequent amplification in exposed surface area, faster rates of release typically come into play (McClements in 2015).

4.7. Degradation mediated liberation mechanism

This process involves the degradation or erosion of a polymer system, whether it's a complex mixture or a uniform structure. This leads to the liberation of the integrated components, dispersed throughout the carrier matrix. These occurrences encompass the gradual cleavage of molecular chains, driven by biological mechanisms and/or microorganisms, (McClements in 2015). Within the realm of the first category of biodegradable substances (i), the carrier's outer surface experiences a diminishing effect over time, inducing a decline in the release kinetics. This stems from a situation where a larger proportion of central compounds finds itself enclosed within the inner layers rather than the outer ones. As for the second category (ii), biodegradable agents exhibit a progressive breakdown during their initial phases. However, as subsequent stages unfold, self-catalytic phenomena come into play, hastening the degradation process significantly. Consequently, a substantial portion disintegrates within a relatively compact timeframe. In the context of hydrophobic polymers, heterogeneous erosion prevails, while hydrophilic polymers tend to undergo homogeneous erosion. The occurrence of heterogeneous erosion aligns more favorably with controlled release designs, as it facilitates a consistent release profile that isn't contingent solely upon the encapsulated substances (Boostani & Jafari, 2020).

The convergence of CR systems and encapsulation technologies paves the way for the creation of next-generation smart foods. Understanding the discharge and liberation mechanisms governing these systems is instrumental in the design, formulation, and commercialization of intelligent food products aimed at improving health and well-being. As research in this field continues to evolve, the potential benefits of CR systems in smart food development are expected to expand, offering consumers novel ways to achieve their nutritional goals and maintain a healthier lifestyle. Fig. 3(a) summarizes the various liberation mechanisms that allow the bioactive substances in the films or coatings to be released into the intended food product.

5. Techniques and innovations in nanoencapsulation

The encapsulation methods as well as delivery approaches have been shown to modify physical and chemical parameters such as the size of particle/distribution, surface area, shape, dissolution, and encapsulation efficiency together with discharging mechanisms. Consequently, it becomes even more critical to choose a suitable encapsulation approach that relies on the prerequisite size, physicochemical characteristics, core material type, as well as wall material. Approaches for attaining nanoencapsulation are often more complicated than those for producing micro-encapsulation. This is primarily due to the greater challenging nature of producing capsules at the nanoscale (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013; Sivanathan et al., 2020). Several approaches for nanoencapsulation have been developed as well as employed as revealed in Fig. 3(b). There are two main methods of fabricating nanocapsules, i.e., top-down as well as bottom-up. The 'top-down' strategy entails the exploitation of specific technologies that enable a decrease in size as well as structural shaping for the intended use of nanomaterials. The 'bottom-up' technique, in contrast, increases the size of the particles. Coacervation, as well as nanoprecipitation, are instances of bottom-up approaches, whereas emulsification falls under the top-down method, as detailed previously (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013; Kırımlıoğlu, 2023). It is possible to encapsulate a variety of hydrophilic as well as lipophilic bioactive substances/smart foods using these nanoencapsulation methods. The hydrophilic, as well as lipophilic substances, have been encapsulated by emulsification, coacervation, as well as the supercritical fluid approaches (McClements, Decker, Park, & Weiss, 2009; Chong, Yunus, Abdullah, Choong, & Spotar, 2009; Leong, Wooster, Kentish, & Ashokkumar, 2009; Awuchi et al., 2022). Lipophilic substances, on the other hand, are mainly processed via inclusion complexation, emulsification-solvent evaporation, and nanoprecipitation methods (Reis, Neufeld, Ribeiro, & Veiga, 2006; Prajapati et al., 2023). Several encapsulation strategies have been suggested in the literature, but none of them can be regarded as standard or appropriate for the encapsulation of all physiologically bioactive substances (Jia, Dumont, & Orsat, 2016). The optimum technique, nevertheless, might be chosen based on the characteristics of the core (drug or food matrix) as well as encapsulating substances together with their molecular weight, polarity, solubility and particle size distribution, etc. So far, several techniques have been established for microencapsulation. But, the strategy for nanoencapsulation is more complicated compared to microencapsulation (Shishir, Xie, Sun, Zheng, & Chen, 2018). In Industries, usually nanoencapsulation of substances is based on a top-down method, even though this generally necessitates higher temperatures owing to the high-energy shear rates used in encapsulation. Future advancements in nanotechnology are predicted to result in more widespread use, as the bottom-up strategy for nanoencapsulation becomes a potential choice (Aguilar et al., 2018). The following section briefly summarises the utmost widely employed encapsulation strategies.

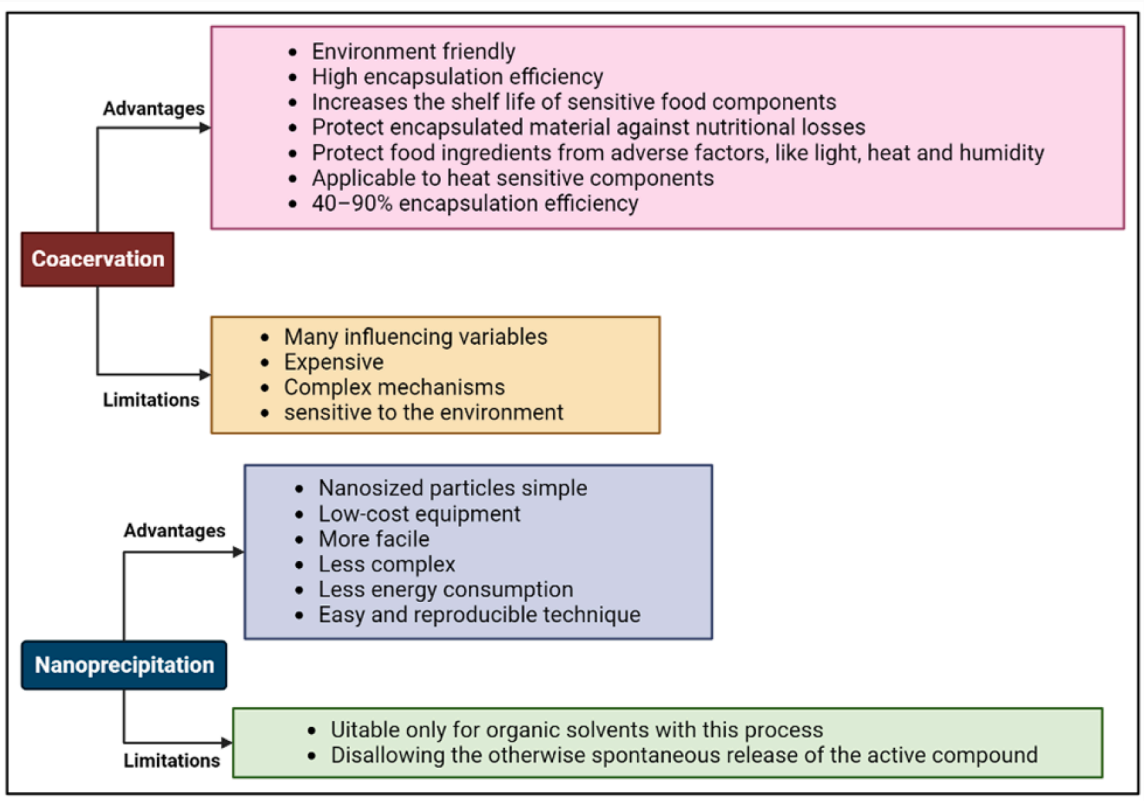
5.1. Coacervation

Coacervation is a process in which aggregate formation takes place by fusion of colloidal particles. During this process the separated hydrocolloids from the primary solution tend to agglomerate into a separate liquid phase. It's worth noting that coacervation may not be considered the most innovative technology for nanoencapsulation in the context of smart foods. However, it might be considered innovative if applied in novel ways or combined with other advanced technologies to create unique encapsulation solutions. It is responsible for the phase separation of a single or amalgamation of polyelectrolytes from a solution as well as the consequent deposition of the freshly formed coacervate phase around the bioactive substances. Cross-linkers such as transglutaminase or glutaraldehyde may be utilized to improve the durability and robustness of coacervate (Zuidam & Shimoni, 2010; Tahir et al., 2021). This method may be categorized as simple coacervation (just one kind of polymer) or complicated coacervation depending on the number of polymer types employed (two or more kinds of polymeric substance). The kind of biopolymeric substance together with its molar mass, flexibility, charge, pH, ionic strength, concentration as well as proportion of biopolymeric substance, are only a few of the many factors that affect how intensely the biopolymers interact and the form of a complex that develops as a consequence (McClements & Rao, 2011; Samrot et al., 2020). Because of the extremely greater cargos possible up to 99 %, and the feasible consequences of controlled release, reliant on mechanical pressure, temperature, and continuing liberation, coacervation is a unique and intriguing encapsulating innovation. The main challenge with this technique is the commercialization of coacervated food constituents due to the usage of cross-linking, which must be used in accordance with the country's regulations and guidelines. It is worth mentioning that a great number of appropriate enzymes for cross-linking are presently being explored (Anandharamakrishnan, 2014; Ai et al., 2023). The experienced drawback is that the resultant capsules have a susceptibility to aggregate and are not stable under aqueous conditions and the method is not very cost effective as well as pH-sensitive (Fang & Bhandari, 2010; Munin & Edwards-Lévy, 2011; De, Mahata, & Kim,

2022). The advantages and disadvantages of the coacervation approach are shown in Fig. 4(a).

The structural integrity and antioxidant properties of zein and potato starches are heavily influenced by the pH of their environment. However, the stability of anthocyanins, which are compounds with antioxidant properties, has primarily been observed in acidic conditions, limiting their effective encapsulation to low pH levels. In light of this challenge, Farnad and Farhadi (2023) conducted a comprehensive investigation. They sought to encapsulate anthocyanins extracted from *Rosa damascena* mill L. (used as a model compound) within zein, starch,

4 (a)



4 (b)

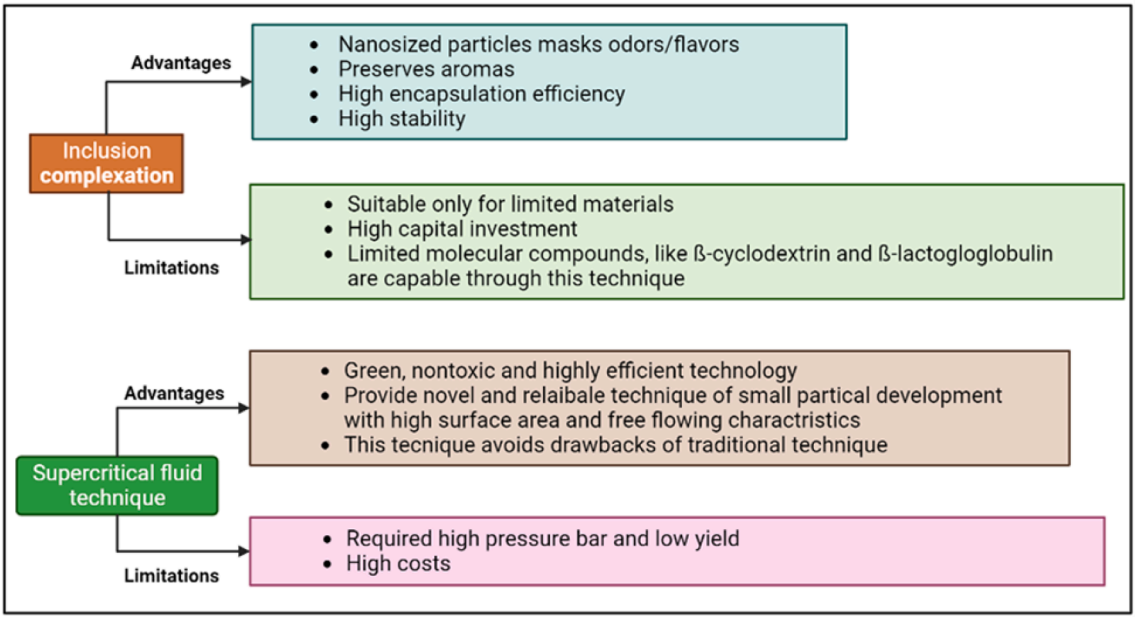


Fig. 4. Various benefits as well as shortcomings of (a) coacervation as well as nanoprecipitation techniques, and (b) inclusion complexation and supercritical fluid strategies.

and various combinations of these two using both simple and complex coacervation methods. The primary objective was to identify new conditions that could enhance anthocyanin preservation and improve the antioxidant properties of zein and potato starches. The results revealed that the zein/starch/anthocyanin nanocapsules exhibited notably high levels of antioxidant activity and encapsulation efficiency. Additionally, the maximum antioxidant activity was achieved with zein/starch nanocapsules (excluding anthocyanin) at pH 2 and 8, correspondingly. Furthermore, the size of the zein nanocapsules was observed to decrease significantly within the range of 50 to 175 nm following the encapsulation of anthocyanin at pH 8. This size reduction is particularly advantageous for potential drug delivery applications. Importantly, the prepared nanocapsules exhibited a remarkable capacity for scavenging free radicals, highlighting their potential as potent antioxidants. Similarly, food-grade proteins are a suitable material for creating nanoparticles and microparticles due to several advantages, including their digestibility, cost-effectiveness, and ability to interact effectively with various compounds and nutrients. In light of these attributes, Penalva, Esparza, Agüeros, Gonzalez-Navarro, Gonzalez-Ferrero, and Irache (2015) conducted a study with the aim of preparing and characterizing casein nanoparticles for the oral delivery of folic acid. These nanoparticles were synthesized through a coacervation process, with stabilization achieved using either lysine or arginine, and subsequently dried through spray-drying. Additionally, certain batches underwent an additional treatment with high hydrostatic pressure before drying to assess its impact on the resulting carriers. The resultant nanoparticles exhibited an average size of approximately 150 nm, containing around 25 μg of folic acid per milligram of nanoparticle. In vitro release studies revealed that the casein nanoparticles functioned as gastro-resistant devices, releasing folic acid only under simulated intestinal conditions. In a pharmacokinetic study, laboratory animals were orally administered a single dose of 1 mg/kg of folic acid. Animals treated with folic acid-loaded casein nanoparticles exhibited notably higher serum levels compared to those receiving an aqueous solution of the vitamin. Consequently, the oral bioavailability of folic acid when administered in the form of casein nanoparticles was calculated to be approximately 52 %, a 50 % improvement over the traditional aqueous solution. Regrettably, the application of high hydrostatic pressure to the casein nanoparticles did not alter the release profile of the vitamin or its oral bioavailability.

5.2. Solvent displacement/nanoprecipitation

The solvent displacement/nanoprecipitation method is considered innovative for the encapsulation of smart foods for health because it offers precise control, protection, and improved delivery of bioactive compounds, along with other benefits that contribute to the development of healthier and more appealing food products. In this method (which is also called nanoprecipitation), the organic internal phase together with the dissolved polymeric substance, drug as well as organic solvent spontaneously emulsifies into the aqueous exterior phase. It takes account of polymeric substance precipitation from an organic solution as well as organic solvent diffusion in an aqueous media (Stella, Marengo, & Arpicco, 2017). This approach is said to be capable of producing both nanospheres as well as nanocapsules. Moreover, eco-friendly polymeric substances like poly (alkylcyanoacrylate), polycaprolactone, and so on are often employed (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013; Nabipour, & Hu, 2020). Fig. 4(a) demonstrates the benefits and limitations of nanoprecipitation.

Picrorhiza kurroa root and rhizome extract are recognized as valuable nutraceuticals for promoting healthy liver function. However, the major hepatoprotective compounds within this extract, namely picrosides I and II, suffer from limited intestinal absorption and poor bioavailability due to their low solubility in water. Considering this, Jia, Dumont, and Orsat (2016) carried out investigation in order to enhance the bioavailability of these bioactive molecules, a nanoformulation of the *P. kurroa* extract was developed using biodegradable PLA nanoparticles based on pluronic-F-68 copolymer via the nanoprecipitation method. This method exhibited a notable encapsulation efficiency, specifically 60.1 % for picroside I and 67.2 % for picroside II. Analysis of the particle size, both hydrodynamic (determined by zeta size) and actual (observed through TEM), demonstrated uniformly spherical nanoparticles with sizes of 174 nm and 154 nm, respectively. Furthermore, this formulation displayed an initial burst release, followed by a sustained release over a period of 27 and 210 h, correspondingly. Consequently, the nanoformulation of this traditional herbal extract offers a nutraceutical product with added value, improving hepato-protection by increasing intestinal absorption and bioavailability.

5.3. Inclusion complexation

Inclusion complexation offers a promising approach towards nanoencapsulation of smart foods for health due to its ability to improve bioavailability, protect bioactives, enable controlled release, mask undesirable tastes, provide formulation flexibility, allow for targeted delivery, and potentially reduce environmental impact. These advantages make it an innovative and valuable technology in the development of functional foods designed to promote health and well-being. Inclusion complexation is the term used to describe the encapsulation of a supramolecular association of a ligand (the ingredient that is being enclosed) into a substrate that has a cavity in it (the material that makes up the shell). This is accomplished through hydrogen bonds, the van der Waals force, or an entropy-driven hydrophobic effect. This method is mostly used to encapsulate volatile organic compounds, like vitamins as well as essential oils, with the intention of keeping the unpleasant taste, fragrance, and odour under check. However, this technique can only be used to encapsulate a small number of specific molecules (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013; Nabipour, & Hu, 2020). In Fig. 4(b), the advantages and disadvantages of the inclusion complexation approach are emphasized.

In a study carried out by Wang, Luo, & Peng, (2018), a subfraction of spiral dextrin (SD-40) was obtained through enzymatic debranching and gradient ethanol precipitation. This SD-40 exhibited the ability to form inclusion complexes with vitamin E (VE) and soy isoflavone (SIO), categorized as V-type inclusion complexes. The confirmation of these complexes was established through analytical techniques including Fourier transform-infrared spectroscopy, atomic force microscopy, and differential scanning calorimetry. To explore the behavior of these inclusion complexes in a simulated gastrointestinal environment, an in vitro gastrointestinal model was employed. The study aimed to investigate the breakdown of these complexes and the release patterns of bioactive compounds. The results of this investigation revealed that both inclusion complexes demonstrated controlled and sustained release behaviors during the digestive process. Notably, it was observed that the SD-40/VE inclusion complex exhibited superior stability and possessed a stronger antioxidant capacity when compared to the SD-40/SIO inclusion complex. The release kinetics of VE and SIO from the inclusion complexes in the stomach were evaluated using both first and zero order models, while the release in the intestine was described using the first order model.

5.4. Supercritical fluid method

The supercritical fluid method is considered innovative for nanoencapsulation of smart foods due to its ability to encapsulate a wide range of compounds efficiently, its mild processing conditions, sustainability benefits, and its potential to enhance the properties and bioavailability of encapsulated materials. These advantages make it a promising technology in various industries seeking advanced encapsulation solutions. A supercritical fluid (CF) can either be used as a liquid or a gas over its thermodynamic critical point of temperature as well as pressure. The CF has characteristics that fall amongst liquids and gases

like low viscosity, high dissolving power, higher diffusabilities, and so on above the critical point. A variety of substances, including carbon dioxide, water, propane, nitrogen, and others, may be raised to a supercritical state. Carbon dioxide (CO_2) is employed as an alternative to solvents in a wide-range of chemical as well as industrial processes because it is cheap, abundant, and has characteristics that fall between various gases and liquids. Above its critical temperature (31 °C) and pressure (73.8 bar), CO_2 is in the supercritical state and exhibits viscosities and densities that are similar to those of gases and liquids, respectively. Supercritical CO_2 is an exceptionally adjustable, adaptable, and preferential solvent due to its ability to vary with changes in temperature and pressure as well as its density, viscosity, and dielectric characteristics (Gomes, Santos, & Meireles, 2012; Siril, & Türk, 2020). In a method analogous to spray drying, supercritical fluids are utilized to encapsulate thermolabile substances. In this approach, the bioactive chemical, as well as polymeric material, are dissolved in a supercritical fluid and expanded via a nozzle. The supercritical fluid then evaporates during the spraying operation, resulting in the ultimate precipitation of solute particles. Due to its low critical temperature as well as little usage of organic solvent, this approach has been frequently employed (Pohlmann, Schaffazick, Creczynski-Pasa, & Guterres, 2010; Franco, & De Marco, 2021). Fig. 4(b) illustrates the benefits and limitations of supercritical fluid technique.

Chaves, Baldino, Pinho, & Reverchon (2022) conducted a study focusing on the utilization of nanoliposomes as a targeted delivery system for two vital nutraceutical compounds, curcumin and vitamin D3 (VD3), known for their significant roles in human health. The researchers prepared vesicles using varying ratios of hydrogenated and non-hydrogenated phospholipids sourced from soy and egg-yolk. To generate these nanoliposomes, they employed a supercritical CO_2-assisted process with operating conditions set at 40 °C and 100 bar, using a water flow rate of 10 mL/min. The morphology and stability of the nanoliposomes were assessed through scanning electron microscopy and dynamic light scattering. Additionally, the encapsulation efficiency and release kinetics of the biomolecules were determined using a UV/Vis spectrophotometer. The study also delved into investigating antioxidant activity and the resilience of the nanoliposomes under stress-induced conditions. Key findings from the study included nanoliposome diameters ranging from 128 to 228 nm, with encapsulation efficiencies of up to 95 % for curcumin and 74 % for VD_3. Notably, the incorporation of 30 % w/w of saturated phospholipids in the initial formulation led to an increase in vesicle size, subsequently enhancing the encapsulation efficiency of both biomolecules. The study also revealed that the antioxidant activity of curcumin remained intact after processing, and the nanovesicles co-loaded with these compounds exhibited robust stability when subjected to various stress conditions. In another study conducted by (Aredo, Passalacqua, Pratavieira, & de Oliveira, 2019), the creation of lycopene-loaded hydrolyzed collagen (LLHC) particles through the process of supercritical CO_2 impregnation has been investigated. To achieve this, a mixture consisting of 9.09 g of hydrolyzed collagen powder and 0.91 g of lycopene was introduced into an autoclave. This mixture was then exposed to supercritical CO_2 at varying pressures of 150 and 250 bar and temperatures of 50 and 60 °C, all while being agitated at 1250 rotations per minute for a duration of 45 min. At the higher temperature of 60 °C under both 150 and 250 bar pressures, the mixture exhibited a viscoelastic behavior, transforming into a cohesive mass. In contrast, at 50 °C, again under both 150 and 250 bar pressures, lycopene was successfully incorporated into the physical structure of the hydrolyzed collagen powder particles. Notably, LLHC particles generated at 150 bar and 50 °C exhibited surface fissures when compared to those produced at 250 bar and 50 °C. These fissures seemed to facilitate potential electrostatic interactions and led to improved impregnation and even distribution of lycopene within the particles. Consequently, based on these findings, it is recommended that the optimal conditions for LLHC particle formation involve supercritical CO_2 impregnation at 150 bar and 50 °C. This particular combination yields LLHC particles with desirable characteristics, making it the preferred choice for this process.

5.5. Emulsification

Innovation often comes from improvements and adaptations of existing technologies. Researchers and industries continue to refine and optimize emulsification processes, making them more efficient and suitable for various applications. Hence, while emulsification may not be considered the newest or most cutting-edge encapsulation method, it still plays a significant role in many industries and can be innovative in its own right when used in novel ways or combined with other techniques. Two immiscible solvents/liquids like water and oil are amalgamated/mixed by a process known as emulsification, and the resultant product like water-in-oil or oil-in-water is known as an emulsion (Fang & Bhandari, 2010; Singh, Kapila, Ganesan, & Rangarajan, 2022). In this approach, the entire lipid unites into the watery medium in the manner of small droplets that are distributed into the continuous phase. In addition to constituents, the size of the droplet may also be influenced by fabricating strategy and the kind of emulsion together with various other factors (Solans & Solé, 2012; Adil, & Onaizi, 2022). The nanoemulsion characteristically has limited size distribution, with particle sizes between 20 and 200 nm (Solans, Izquierdo, Nolla, Azemar, & Garcia-Celmaet, 2005; McClements, 2011; Choi & McClements, 2020). Several studies have shown that the majority of water-in-oil or oil-in-water nano-emulsions are being fabricated via high-energy emulsification or dispersion. Further, the investigation of nanoemulsion preparation, condensation as well as low-energy emulsification has been shown to be more productive (Helgeson, 2016; Kundu, Arora, Gu, Kumar, & Mishra, 2019). As a non-equilibrium system, a nanoemulsion cannot be produced rapidly. It is primarily formed using high-energy techniques involving various mechanical tools together with ultrasound, high-shear stirrers, and high-pressure homogenizers. These procedures are fairly simple in which the high-energy involvement leads to reduced droplet size. In contrast to nanoparticle formation, where a huge amount of energy is required, a minimal amount of energy is needed in the simple emulsification process (Uluata, Decker, & McClements, 2016; Choudhary, Kaur, & Kaur, 2023). It's interesting to note that, low-energy emulsification procedures, which use the system's intrinsic chemical energy, produce smaller particle sizes than high-energy emulsification. A simple stirring motion with a minimal extent of energy is needed to produce the minute particle size (Solans & Solé, 2012; Liu et al., 2019). It has also been shown that high-energy procedures allow for the formation of nanoemulsions at greater oil-to-surfactant ratios over low-energy approaches (Yang, Marshall-Breton, Leser, Sher, & McClements, 2012; Saffarionpour, 2019). Further, this kind of encapsulation necessitates the use of an emulsifier for emulsion stability. If the encapsulated bioactive substances are dried following emulsification, they might be in liquid or powder form (Fang & Bhandari, 2010; Comunian et al., 2020). This type of encapsulation is appropriate for oil-soluble substances such as carotenoids, plant sterols, and dietary lipids. There are two types of emulsions: nanoemulsions and double emulsions (Fang & Bhandari, 2010; Jia, Dumont, & Orsat, 2016; Sneha & Kumar 2022). Fig. 5(a) depicts the benefits and shortcomings of the emulsification technology.

Curcumin and piperine were examined by Bolat, Islek, Demir, Yilmaz, Sahin, & Ucisik (2020) as potential treatments for colorectal cancer using a nanoemulsion-based technology. Both curcumin and piperine were found to be water-insoluble, making their dissolution in water difficult. They were also observed to be sensitive to factors such as light, heat, and the presence of iron ions, which could lead to their degradation. To enhance the solubility and delivery of these compounds, a nanoemulsion was employed. This nanoemulsion allowed for the controlled release of curcumin and piperine, with 40 % of the curcumin and 7.5 % of the piperine being released after 72 h. This controlled release is important for sustaining their therapeutic effects over time.

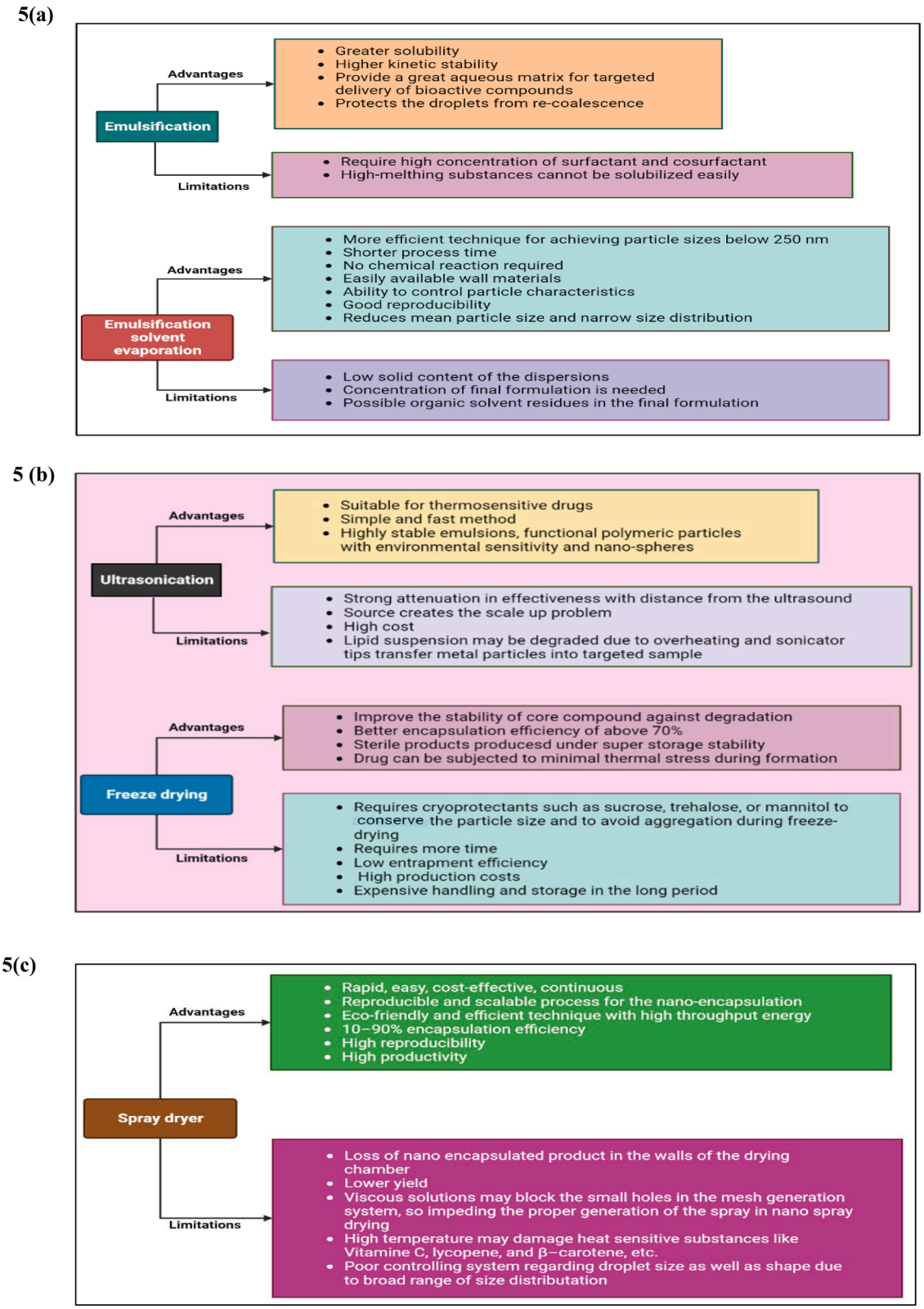


Fig. 5. The advantages and disadvantages of (a) emulsification as well as emulsification-solvent evaporation techniques, (b) ultrasonication as well as freeze-drying/lyophilization strategies, and (c) spray drying process.

The primary focus of this research was to assess the anticancer activity of curcumin in combination with piperine, using this nanoemulsion-based approach. Specifically, the study aimed to enhance the effectiveness of curcumin in combating colorectal cancer, as demonstrated in the HCT116 colorectal cancer model. In another study conducted by Lv, Zhang, Tan, Zhang, & McClements (2019) the efficacy of emulsification of Vitamin E was investigated. Vitamin E is a water-insoluble compound that is known to be sensitive to various factors including oxygen, light, and pH levels. The researchers developed oil-in-water emulsions to improve the bioaccessibility of vitamin E. The bioaccessibility of these

emulsions was found to be in the range of 65 % to 85 %, indicating that a significant proportion of vitamin E became available for absorption by the body. Additionally, the study demonstrated that these vitamin E-fortified emulsions exhibited prolonged stability under storage. This suggests that the emulsions were able to maintain their vitamin E content over time, which is important for preserving the nutritional value of products containing vitamin E.

5.6. Emulsification–solvent evaporation

The emulsification-solvent evaporation method is considered an improvisation for the encapsulation of smart foods. The emulsification-solvent evaporation technique is a variant of the solvent-evaporation method. The polymer solution is turned into an aqueous phase by emulsification, and the polymeric solvent is evaporated to cause the polymeric material to precipitate as nanospheres (Kumari, Yadav, & Yadav, 2010; Demina et al., 2021). The drug is evenly distributed throughout the polymer matrix network. Fine-tuning the stir rate, kind/quantity of dispersion agent, and the viscosity of organic/aqueous phases including temperature may all be used to regulate the size of the capsules (He et al., 2018). Furthermore, this technology proved to be the most efficient for achieving particle sizes less than 250 nm (Chen, Li, Zhang, & Li, 2019). This technology primarily employs polymeric materials like poly(lactide-*co*-glycolide), poly (hydroxybutyrate), and so on (Iqbal, Valour, Fessi, & Elaissari, 2015). Fig. 5(a) represents the benefits and drawbacks of the emulsification-solvent evaporation procedure. Furthermore, Shaikh, Ankola, Beniwal, Singh, & Kumar (2009) conducted an investigation, where curcumin underwent a process known as emulsion-diffusion-evaporation, coupled with lyophilization, resulting in the formation of nanoparticles measuring 264 nm. This process achieved an impressive 77 % efficiency and loaded 15 % of the active compound. These nanoparticles exhibited excellent stability over a period of three months and notably, provided nine times higher bioavailability compared to non-nanoparticle formulations.

5.7. Ultrasonication

Ultrasonication represents a pioneering technological approach for the precise execution of nanoencapsulation processes. Leveraging the phenomenon of high-frequency sound wave propagation within a liquid medium, ultrasonication harnesses mechanical forces to enable nanoscale encapsulation, thereby offering a novel and advanced methodology for achieving this intricate task. In order to produce ultrafine emulsions, ultrasonication exploits ultrasonic waves as part of its emulsification process. It aids in breaking up clumps as well as dispersing solid particles in a liquid media (Shamsara, Muhidinov, Jafari, Bobokalonov, Jonmurodov, Taghvaei, et al., 2015; Ahmed, Bhattacharya, & Ali, 2022). To link a new functional group, the molecular boundary layer that surrounds dispersed particles must be removed since it is often connected to the particle surface. Using Hielscher ultrasound technology, the pressure created by sonication helps to overcome the van der Waal's forces of attraction as well as takes the functional components to the surface of the particles, where they are trapped by the wall material contained in the solution (Rosli, Hasham, & Aziz, 2015; Tahir et al., 2021). The ultrasonication method employs higher-intensity waves, shear forces, temperature, as well as pressure to modify the characteristics of treated particles (Shanmugam & Ashokkumar, 2017). Nevertheless, the primary advantages of this technology are reduced energy requirement as well as emulsifier utilization, smaller particle size, low polydispersity, along with improved stability of nanoemulsions (Li & Chiang, 2012). The benefits along with shortcomings of the ultrasonication process are revealed in Fig. 5(b).

In a study conducted by Khatib, Varidi, Mohebbi, Varidi & Hosseini (2020), the investigation focused on the substitution of nitrite with hop components in the preparation of cooked beef-sausage (CBS). To achieve this, they developed lupulon-xanthohumol loaded nanoliposomes (L-X-NL) using an ultrasonication process under optimized conditions (specifically, a sonication time of 10.8 min, a power level of 72.7 W, and a lecithin concentration of 140 mg/mL). The release of lupulon and xanthohumol into the liquid meat extract adhered to the Rigter-Peppus model. Various samples of CBS, comprising 60 % meat, were produced by supplementing them with different ratios of nitrite and L-X-NL. To assess the safety of these CBS samples, microbial analysis and measurement of lipid oxidation were conducted. Remarkably, the formulated CBS, containing 30 ppm of nitrite and 150 ppm of L-X-NL, remained microbiologically safe even after 30 days of storage at 4 °C. Furthermore, it was observed that the presence of L-X-NL had the beneficial effect of delaying oxidation. Importantly, the addition of L-X-NL did not compromise the sensory attributes of the final product. However, it should be noted that nitrite was still crucial for achieving the desired coloration of the CBS. In light of these findings, it is recommended that nitrite be partially reduced in the CBS formulation, with up to a 50 % reduction, and replaced with L-X-NL, which demonstrates promise as a novel preservative. Likewise, Ahmad et al. (2018) conducted a comprehensive investigation into the nano-encapsulation of catechin within starch nanoparticles. This pioneering study involved the creation of innovative starch-based nanoparticles derived from three distinct sources: horse chestnut (HSC), water chestnut (WSC), and lotus stem (LSC). The primary objective was to enhance the encapsulation efficiency of catechin hydrate while reducing the size of the starch particles to the nano-scale. This was achieved through ultrasonication treatment at a frequency of 40 KHz for a duration of 30 min, utilizing a fixed probe sonicator. The 30 min sonication process was conducted in 5 min intervals to prevent excessive heating. Subsequently, the resulting solution underwent freezing at −18 °C followed by lyophilization, employing a freeze dryer (Telstar-Cryodos, Spain) to yield finely powdered catechin-encapsulated nanoparticles. The average particle sizes of the nanoparticles derived from HSC, WSC, and LSC were determined to be 322.7, 559.2, and 615.6 nm, respectively, with corresponding encapsulation efficiencies of 59.09, 48.30, and 55.00 %. To gain insights into the structural, physical, and thermal properties of these nanoparticles, various analytical techniques were employed, including Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), and differential scanning calorimetry (DSC). SEM images confirmed the formation of capsules with entrapped catechin, while FTIR spectra revealed characteristic peaks at 3475, 1650, 1383, 1148, 1083, and 790 cm^{-1}, indicative of successful catechin encapsulation within the starch nanoparticles without any discernible interactions. XRD analysis demonstrated a loss of crystallinity following the encapsulation process. Furthermore, the study found that a higher content of catechin in intestinal juice ensured a controlled release within the intestine. Importantly, bioactive properties were observed to be retained at a higher level in encapsulated catechin compared to its free counterpart during in-vitro digestion. This suggests the potential for improved bioavailability and controlled release of catechin when encapsulated within these starch-based nanoparticles, which could have significant implications for various applications in the field of pharmaceuticals and functional foods.

5.8. Freeze-drying/lyophilization

While freeze-drying/lyophilization is not a new technology, it remains a valuable and relevant tool in the encapsulation of smart foods for health due to its ability to preserve nutritional value, maintain sensory properties, and protect sensitive ingredients. Innovations in its application and integration with other technologies contribute to the development of innovative health-focused food products. The material is first frozen in the lyophilization/freeze-drying approach so that the frozen water may move straight from the solid stage to the gas stage. Almost all heat-sensitive materials/bioactive substances as well as scents/aromas are dehydrated by lyophilization.The process of lyophilization involves freezing, sublimation (primary drying), desorption

(secondary drying), and storage as the last steps before the material is stabilized. This technique produces high-quality products that are readily reconstituted and have an extended lifespan (Anandharamakrishnan, Rielly, & Stapley, 2010; Ray, Raychaudhuri, & Chakraborty, 2016). The primary drawbacks of lyophilization are the lengthy processing time (about 20 h or more), open porous structure along with higher consumption of energy. Usually, lyophilization is utilized for separating nanoparticles in conjunction with other fabrication procedures. Another concern associated with freeze-drying is the formation of pores as a result of the ice sublimation process. Furthermore, this method is often used to eliminate water from nanocapsules without affecting their structure or form. In terms of reducing pore size as well as drying time, the spray-freeze drying approach may be a better alternative than the traditional freeze-drying method (Anandharamakrishnan, 2014; Tahir et al., 2021).

The lyophilization plays a crucial part in revealing superior encapsulation effectiveness as well as stability of nanocapsules through their advantageous drying process. This method is increasingly useful for the nanoencapsulation of bioactive food substances that are sensitive to heat characteristics of formulated nano-Ps in the course of lyophilization are also dependent on the emulsification techniques or other encapsulating techniques used to transform the droplets into nanostructures. It is pertinent to mention that cryoprotectants like mannitol, sucrose, etc., may stop nano-Ps agglomeration throughout drying. Various recent researchers have used polymeric substances like chitosan, etc., as a wall material for encapsulation (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013; Raza, Khalil, Ayub, & Banat, 2020). The benefits and drawbacks of the lyophilization/freeze-drying strategy are shown in Fig. 5(b).

Fish oil, known for its omega-3 fatty acids crucial for human health, faces challenges due to susceptibility to oxidation during food processing and storage. To safeguard its integrity, Moghadam, Pourahmad Mortazavi, Davoodi, and Azizinezhad (2019) explored nanoencapsulation via freeze-drying. Gum arabic (GA) was selected as the nanoencapsulating material, while tween 80 served as the emulsifier. The process involved creating a water-in-oil (W/O) emulsion through sonication, where 6 % fish oil was dispersed within aqueous solutions containing 20 and 25 % total wall material. Sonication transpired at 24 kHz for 120 s. Subsequent freeze-drying led to nanocapsules incorporation into probiotic fermented milk, wherein their impact was evaluated. Results revealed that nanoparticles encapsulated with 25 % gum arabic and 4 % emulsifier exhibited the highest encapsulation efficiency (EE) at 87.17 % and the lowest surface oil content of 31.66 mg/100 kg. Introducing nanoencapsulated fish oil into fermented milk significantly enhanced Lactobacillus plantarum viability, as well as the levels of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). The fermented milk containing fish oil nanoencapsulated with 25 % wall material and 4 % emulsifier displayed the highest probiotic bacterial count at 8.41 Log CFU/mL, along with the lowest peroxide value of 0.57 mEq/kg. Additionally, this sample exhibited the highest EPA and DHA concentrations. Importantly, the utilization of nanoencapsulated fish oil did not negatively impact the overall acceptance of the fermented milk. As a result, this approach holds promise for fortifying low-fat probiotic fermented milk with enhanced nutritional benefits.

5.9. Spray drying

It's important to note that while spray drying may not be considered the most innovative encapsulation technology. Its perceived lack of innovation in some cases should not overshadow its practical utility in various industries. The perception of innovation often depends on the specific needs of a given industry, product, or application. Therefore, ongoing research and development efforts may continue to improve and innovate within the spray drying field, making it more competitive with newer technologies. Spray drying is a quick, easy-going, economical, flexible, as well as uninterrupted processing technique employed to create a dry powder from aqueous systems with the highest degree of product repeatability (Sosnik & Seremeta, 2015; Rezvankhah, Emam-Djomeh, & Askari, 2020). These devices sprinkle liquid formulations into a heated air compartment using a fixed, small atomizer. These sprinkled droplets are removed from the solution in the drying chamber, encouraging the expulsion of solid particles into the air stream, which are subsequently recovered. Despite many advantages, this technique is not free from disadvantages and the biggest disadvantage of typical spray drying on a lab level is their lower processing output. As a result, BÜCHI Labortechnik AG invented a nano-spray drier in 2009 to address this issue while also improving spray drying on a submicron level (Lee, Heng, Ng, Chan, & Tan, 2011; Jafari, Arpagaus, Cerqueira & Samborska, 2021). With its high effectiveness, conventional spray drying can quickly transform aqueous solutions into finer powder particles. The rapid drying method is suited for even sensitive bioactive substances/components without any substantial disrupting effect (Jafari, Fathi, & Mandala 2015; Rezvankhah, Emam-Djomeh, & Askari, 2020). With the intention of nanoencapsulation, nano-spray drying has been employed in a wide range of investigations including the development of functional foods, cosmetics, as well as medicines (Esfanjani & Jafari, 2016; Ouarga et al., 2022). Fig. (c) shows the benefits and limitations of spray drying technique.

Veneranda, Hu, Wang, Luo, Castro, Madariaga (2018) conducted an investigation, where three food polymers, namely zein, sodium caseinate (NaCas), and pectin, were utilized as the matrix for the development of colloidal complex nanoparticles designed to encapsulate eugenol. A complexation process induced by heat and pH was meticulously optimized by adjusting polymer concentrations, the loading percentage of eugenol, and pH conditions. This optimization aimed to achieve the production of small, uniformly distributed, and stable complex nanoparticles. During the heating process, it was observed that the pH conditions had a substantial impact on the properties of the resulting nanoparticles. The smallest and most uniform complex nanoparticles were obtained when the heating process occurred at pH 6.6, which corresponds to the isoelectric point of zein. Sodium caseinate (NaCas) played a pivotal role in ensuring the desired stability of the complex nanoparticles during storage and spray drying processes. The formation of the complex structure was elucidated by Fourier transform infrared spectroscopy, revealing that both hydrophobic and electrostatic interactions acted as the driving forces behind this process. Furthermore, an innovative technique involving nano spray drying was employed to transform the colloidal nanoparticles into fine powder particles. This transformation facilitated long-term storage in powder form, enhancing their potential applications within the food industry. Under the optimal preparation conditions and formulation, eugenol-loaded complex nanoparticles were successfully synthesized, characterized by their size, which measured 140 nm, spherical shape, and uniform size distribution. The structural integrity of these nanoparticles was confirmed through scanning and transmission electron microscopy analyses.

6. Challenges and perspective in nanoencapsulation

The newest and most distinctive technique is encapsulation. It opens up new possibilities as well as aids in resolving issues that the food together with pharmaceutical industries were facing. Encapsulation technology has shown to be a boon in the field of edible films as it incorporates several bioactive substances/components that are precisely released/delivered at specific places to enhance food durability, taste, colour, and texture throughout processing and storage. There is currently a little/very limited knowledge of the formulation of different nanoencapsulation technologies together with their commercial implementation. There is no widely usable single procedure that can be employed for all kinds of core substances. It is also because each core and use require a unique design approach. Further, the food processing sector must handle a variety of issues related to the storage as well as

stability of encapsulated bioactive components/smart foods. Altogether, the commercialization of encapsulation technology is, however, hampered by technical difficulties (Adel, Ibrahim, El-Shafei, & Al-Shemy, 2019). For instance, high-temperature involving techniques like spray drying has the potential of destroying flavourful, delicate substances like vitamin C, beta-carotene, lycopene, and anthocyanins together with other colours. Dry particles in the dryers could adhere to the walls and are not retrieved, which might result in a decreased product yield (Kanwate, Ballari, & Kudre, 2019). The solubility of the bioactive substances/constituents that are encapsulated, the kind of wall material, the heat sensitivity along with the presence of additional substances should be taken into account. Freeze drying is a good method for dehydrating heat-sensitive materials, but it takes a long time to accomplish. In addition, this technique exploits a vacuum pump to achieve the necessary lower pressure, which results in greater energy costs. Likewise, nanoemulsions have numerous intrinsic benefits for the food sector, including ease of manufacture, greater loading capacity, creaming resistance, as well as optical clarity (Salvia-Trujillo, Soliva-Fortuny, Rojas-Graü, McClements, & Martín-Belloso, 2017; Fernandez-Avila, Hebishy, Donsì, Arranz, & Trujillo, 2019), nevertheless, they lack regulation on the liberation of the encapsulated bioactive substances. The core or shell of the nanoemulsion may add structural complexity for higher functionality. For instance, solid-lipid nano-Ps, also known as nanoemulsions with a core composed of crystalline biocompatible lipids, aid in enhancing the payload's protection against breakdown as well as enable regulated liberation/discharge, and focused delivery, including increased bioavailability (Donsì, Sessa, & Ferrari, 2013; Wen, Chen, & Chen, 2018; da Silva Santos, Badan Ribeiro, & Andrade Santana, 2019). The nanostructured lipid carriers, which are composed of partly crystallized lipid droplets have been speculated as the next generation of solid-lipid nano-Ps. This is because the core of these nanostructured lipid carriers has a lesser organized crystalline or completely amorphous framework, which enhances the stabilization as well as loading potential of the particles together with ability for customized discharge characteristics (Naseri, Valizadeh, & Zakeri-Milani, 2015; Wen, Chen, & Chen, 2018). In addition, the cost efficacy is further impacted by maintenance costs together with the need for special tools or equipment.

The kind of edible coating materials employed is another crucial issue in nanoencapsulation. As polysaccharide-based films are hydrophilic in nature, they are ineffective as water hindrances and may cause dehydration (Dehghani, Hosseini, & Regenstein, 2018). In addition, protein molecule coatings have a more limited range of uses over other polymeric substances owing to their being hydrophilic as well as weak in mechanical properties. Even though hydrophobic nature, lipid-based coatings can be susceptible to rancidity, and their waxy texture as well as flavour are also significant limitations (Jeevahan, Chandrasekaran, Durairaj, Mageshwaran, & Joseph, 2017; Chaudhary, Thakur, Kajla, Thakur, & Punia, 2021). Likewise, synthetic compounds, while offering several advantages, do exhibit certain drawbacks that need to be considered. These limitations include issues related to toxicity, stability, and susceptibility to chemical modification. For instance, polyvinyl alcohol (PVA) is known to exhibit reduced stability under certain conditions, and it can be prone to chemical modifications that may impact its intended function. Additionally, polyacrylamide, another synthetic compound, is associated with concerns regarding its potential toxicity (Gaaz, Sulong, Akhtar, Kadhum, Mohamad, & Al-Amiery, 2015; Barbălată-Mândru, Serbezeanu, Butnaru, Rîmbu, Enache, & Aflori, 2022).

The majority of bioactive substances including smart foods are supplied orally. Therefore, designing biocompatible as well as biologically degradable nano-Ps that reduce their digestion, absorption, and metabolism in the body before reaching the intended tissues is a significant problem. Enzymes in the digestive system may break down several biodegradable components in the nano-Ps. Although nano-Ps in their intact formulations can preserve the encapsulated bioactive component/substance payload, gut digestion can alter the integrity, properties, and pharmacokinetics of nano-Ps, thereby reducing their potential to safeguard (Wang et al., 2014). In this context, the research must concentrate not only on creating nanGoktaso-Ps that bypass stomach digestion but also reach circulation unaltered. Some of the important research objectives involve functionalizing the nano-P surface to prolong their blood circulation period intended for sustainable delivery and/or target delivery to the proper tissues (Goktas et al., 2020).

Several nanosystems or nanoencapsulations may have harmful consequences after being administered. Toxicology is often associated with particle size as well as the shape of nanosystems as these characteristics may result in unintended penetration of nanosystems into non-intended regions. Furthermore, because of their size, they may cause oxidative stress, inflammation, or DNA damage, resulting in tissue damage along with cell death. As a result, studies of their toxicity are also necessary (Paolino et al., 2021). In terms of surface properties of the nanocarriers or nanoencapsulation, precisely the surface charge, these systems can generate greater toxicity if they are positively charged because of increased cellular interaction as well as internalization (Podila & Brown, 2013; Sánchez, Mejía & Orozco, 2020). To begin with, a precise physicochemical characterization of the nanosystems is a critical step in postulating their application as supplemental foods.

Concerning the capacity of certain bioactive components/substances to boost gastrointestinal absorption of a given substance, the inclusion of enhancers in their structure can also improve gut barrier permeability to potentially harmful agents such as allergens, toxins, as well as germs (Maher, Mrsny, & Brayden, 2016). As a result, the damage should be reversible and remedied rapidly, and a thorough examination of the barrier repair process is required (Cristiano et al., 2020).

A different factor to consider in the course of the investigational stages is the potential immunotoxicity generated by various nanosystem components that may function as antigens like antibody fragments or peptides (Renukuntla, Vadlapudi, Patel, Boddu, & Mitra, 2013; Feng, Xu, Li, Song, Ding & Chen, 2019). Looking into the above-mentioned limitations/challenges, the conclusion made by Paolino et al. (2021) appears adequate that the lack of standards, as well as established methodologies/guidelines for toxicity research, makes comparing the findings of *in-vitro* and *in-vivo* investigations problematic.

The concept of "perspective" is essential when considering the application of nanoencapsulation technology in the food and pharmaceutical industries. Nanoencapsulation, a novel and distinct technique, holds immense potential for addressing challenges faced by these industries. It involves precisely enclosing smart food ingredients/bioactive substances within protective shells, enabling targeted release to enhance aspects of food such as durability, taste, color, and texture during processing and storage. However, realizing its full potential requires addressing aforementioned technical challenges, ensuring safety, and developing standardized methodologies for toxicity assessment through rigorous research. As this technology continues to evolve, it has the potential to revolutionize both the food and pharmaceutical industries, offering new ways to improve product quality, stability, and bioavailability.

7. Safety and regulatory aspects

The majority of the discussion over the safe application of nanotechnology in the food industry has centered on the ambiguities as well as the unavailability of toxicological evidence. In the current scenario, the supportable data or any general conclusion on whether nanotechnology-derived food/food contact materials are safe or even more harmful compared to their conventional counterparts seems inadequate. Most of the scientific committees that have assessed nanotechnology uses found that, although consumers are expected to gain an advantage from this breakthrough, new information, data, and evidence together with new measuring methodologies may be required to guarantee that the safety of nanotechnology-based products is appropriately

evaluated (Nickols-Richardson, 2007; Li et al., 2009; Sekhon, 2010; Cockburn et al., 2012). In other words, regulatory measures are required so as to control the possible dangers brought on through the exploitation of nanotechnology in the food sector (Singh, 2018). However, there is no worldwide regulation governing the regulatory implications of nanomaterials in the food sector. Most nations currently lack precise laws for assessing the danger of encapsulated nanoproducts. The lack of uniformity in information interchange across nations is a potential threat to human health as well as ecology, and it can hinder the global marketing of novel as well as advantageous products (Shishir, Xie, Sun, Zheng, & Chen 2018). In the recent past, European Union rules mandated that any food component or substance developed through nanotechnological tools be subjected to a safety evaluation before being approved for application (Rauscher, Rasmussen, & Sokull-Klüttgen, 2017). Furthermore, as per regulation 258/97 in the United States, a nanomaterial shall be regarded as "fresh food" if it is employed as a main component (Gallocchio, Belluco, & Ricci, 2015). Once the term "food additive" is employed in line with European Commission Regulation No. 1333/2008, it is not essentially applicable to the nano-form. In this context, the nanosystem needs inspection as a distinct additive, and should thereby be assessed as a new, harmless substance before being put in the market (European Commission, 2008). The European Food Safety Authority has issued its risk assessment guidelines for the use of nanosciences/nanotechnologies in the food chain. Although it provides a systematic approach for carrying out nanomaterial safety evaluation in food and feed, it also emphasizes the requirement for more investigation to evaluate the safety of nanomaterials, characterize them, as well as assess their response (European Food Safety Authority, 2018).**

The most usual pathway for nano-Ps to enter the stomach is via food/drink consumption. The consumer-safety concerns of nanotechnology used in food have been intrinsically associated with the physical and chemical characteristics of the nano-Ps, as well as the probability cum degree of exposure from nanofood consumption. Nanoparticles have much bigger surface areas with increased reactivity together with remarkably distinct physical, chemical and biological characteristics than their normal counterparts (Chaudhry et al., 2008; Pourmadadi et al., 2022). Owing to the improved reactivity of nano-Ps, it is very feasible that when an innocuous nano-Ps is introduced into food, it will be transformed into a dangerous form or vice versa. Furthermore, the lack of knowledge on the possible toxicity, behaviour, bioavailability, biodistribution, and bioaccumulation of nanomaterials has prevented the adoption of international laws (Huang, Mei, Chen, & Wang, 2018). It has also been reported that long-term nano-P contact may induce oxidative stress in human cells, kidney as well as liver/DNA damage (Naseer, Srivastava, Qadri, Faridi, Islam, & Younis, 2018). Inhalation as well as permeation via the dermal tissue into persons working in nanotechnology factories is thought to be quite frequent (Youssef, 2013; Aziz et al., 2023).

A further advanced investigation in toxicity is required in order to guarantee the safety of nano-formed delivery systems, since the safety of nanodelivery systems for usage in the food industry is unclear (Puttaiahsiddaiah et al., 2022). More research is required to address the drawbacks of nanoencapsulation practices, upgrade current methodologies, formulations, encapsulation systems, fulfilling marketing requirements as well as investigating the use of nano-products in food/gastrointestinal systems including their commercial scale fabrication. Investigations must also focus on the use of nanocarriers for bioactive substances in food/biological systems, investigating how these substances affect cell survival as well as how they are absorbed, distributed, metabolized, and excreted by humans together with other living things (Shishir, Xie, Sun, Zheng, & Chen, 2018). The potential for nanoencapsulating bioactive substances stresses the requirement for their global regulation to enable their safety usage as well as commercialization. This pattern is supported by several studies documenting the positive impacts of nanostructured bioactive substances, and they suggest a potential future line of investigation (Bazana, Codevilla, & de Menezes, 2019).

8. Conclusion

The concept of smart foods for health, driven by nanoencapsulation technology, represents an innovative approach. It introduces new avenues and tackles challenges within the realms of both the food and pharmaceutical industries. Nanoencapsulation technology stands as a game-changer, particularly in the domain of edible films. It enables the integration of a multitude of smart food and bioactive components, strategically releasing them in precise locations. This precision greatly enhances the stability, flavor, color, and texture of food products throughout their processing and storage phases. Further, this technology showcases its ability by serving as a means to deliver smart and bioactive substances in a tailored and targeted manner. This not only enhances food safety but also extends the shelf life of products. Despite its immense potential, the widespread commercialization of nanoencapsulation faces certain challenges. To harness its full potential in the development of sustainable, active, and cost-effective edible films, several obstacles need to be addressed. These include refining the fabrication process, making it cost-efficient, achieving controlled release of bioactive substances within food items, and standardizing the characteristics of edible films. Therefore, comprehensive research remains imperative to unlock all possible applications of nanoencapsulation technology. In addition, before products incorporating this technology can reach the market, safety concerns related to the consumption of nanomaterials in food must be rigorously evaluated. It is crucial to establish standardized testing protocols for assessing the impact of nanomaterials. In this direction, regulatory frameworks should be put in place to alleviate consumer concerns and bolster acceptance. In conclusion, when harnessed responsibly and with a focus on addressing these challenges, nanoencapsulation technology holds the promise of a brighter future, not only for the advancement of edible coatings but also for the entire food industry. However, achieving this potential will necessitate continued research, rigorous safety considerations, and a commitment to regulatory standards to ensure its successful implementation and commercialization.

Declaration of Competing 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.

Data availability

Data will be made available on request.

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