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Recent applications of microencapsulation techniques for delivery of functional ingredient in food products: A comprehensive review

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ABSTRACT

The COVID-19 pandemic has resulted in an increased consumer demand for functional foods, mostly due to their potential health benefits. Presently, there is a prevailing trend of incorporating microcapsules that contain functional components into food and beverages in order to develop functional foods. This work aims to present a comprehensive analysis of microencapsulation techniques and their utilization in the food and beverage industry, while also addressing the associated challenges and future possibilities. The review analyzes the manufacturing of functional or modified foods and beverages through various microencapsulation processes. These strategies involve incorporating bioactive compounds and probiotics into microcapsules or nanocapsules. In addition, the study also emphasized the influence of microencapsulation on the sensory characteristics of food, as well as the capacity of functional components to be absorbed and utilized by the body. Moreover, the discussion has highlighted the importance of microencapsulation, commonly used techniques in microencapsulation, the latest advancements in wall materials, and the growing need for functional food. The study concentrated on the difficulties linked to microencapsulation and its potential to be scaled up, and offered practical solutions for these issues. The study determined that microencapsulation of functional chemicals in foods and beverages is an innovative method for safeguarding delicate substances, regulating their release, enhancing sensory characteristics, and improving their bioavailability.

1. Introduction

Over the past few decades, consumers' attitudes towards food have undergone considerable changes as they have come to believe that consuming particular foods might help maintain good health. Several culinary trends have emerged in recent years, especially during the COVID-19 epidemic. Proper diet and nutrition have a crucial role in preserving health and safeguarding against the COVID-19 problem (Galanakis et al., 2020; Vishwakarma et al., 2022). Currently, there is a significant focus on food fortification and the use of functional food ingredients. These approaches have the potential to combat malnutrition and improve the immune system (Olson et al., 2021; Tiozon et al., 2021). Several study and review papers have been published in the past few years about functional foods, functional ingredients, prebiotics, probiotics, and their effectiveness in providing health advantages to consumers (Ballini et al., 2023; Granato et al., 2023; Sarkar et al., 2023). Functional foods lack uniform definitions, although various institutions and international organizations have formulated their own interpretations. Functional foods are dietary products that have the ability to enhance specific physiological responses or reduce the risk of diseases, while along with providing nutrients and energy (Pathan et al., 2024). Functional foods, as defined by the Food and Agriculture Organization (FAO) of the United Nations, are foods that not only contain conventional nutrients but also specific substances that offer potential health advantages beyond basic nutrition (Temple et al., 2022). Mundhe et al. (2022) define functional foods as food products that contain additional substances beyond standard nutrients. These ingredients are specifically chosen to decrease the likelihood of chronic diseases and promote long-term health advantages in the human body.

Functional components, such as purified bioactive compounds, prebiotics, probiotics, concentrated extracts from natural sources, and other similar substances, are added to the food matrix in order to enhance its nutritional and health advantages (Shaikh et al., 2022). Bioactive chemicals are molecules derived from plants or animals that can

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modulate specific physiological responses, perhaps resulting in health advantages (Pateiro et al., 2020). For instance, bioactive substances like polyphenols, essential oils, natural pigments, and others can offer antioxidant, anti-carcinogenic, anti-inflammatory, and antibacterial properties when taken in adequate quantities (Chen et al., 2021; Giaconia et al., 2020). Furthermore, as per the World Health Organization (WHO), a significant 80 % of the global population relies on conventional medicine for their healthcare needs, utilizing various extracts from herbal plants and their bioactive ingredients. In contrast, prebiotics and probiotics are utilized to create a diverse array of functional meals that demonstrate symbiotic and synbiotic relationships. Prebiotics are indigestible substances found in food that promote the growth of helpful microorganisms in the intestines. Probiotics, as defined by the World Health Organization (WHO), are beneficial microbes that, when consumed in specific quantities, offer potential health advantages such as enhancing the gut microbiota and reducing the risk of disease (Davani et al., 2019). Probiotics defend the host against pathogens by limiting the attachment points of mucosal epithelial cells and controlling the immune response, thereby improving the integrity of the intestinal barrier (Fusco et al., 2023). In addition, they control the composition of microorganisms in the digestive system, reduce the negative effects of nutrient intolerances such as lactose intolerance, enhance the absorption of small amounts of essential nutrients, and ease allergic reactions (Roobab et al., 2020). Nevertheless, the effectiveness of these active ingredients relies on their ability to dissolve, penetrate, remain stable, be easily absorbed by the body, and be readily available for use. These characteristics can be affected by various factors such as food processing and storage conditions, as well as the harsh conditions within the gastrointestinal tract (Galanakis et al., 2021).

Emerging technologies are implemented in the food production chain to facilitate the delivery and regulation of functional ingredients at the desired location, safeguarding them from unfavorable environmental factors including light, oxygen, temperature, and pH. Microencapsulation is the process of enclosing small particles or droplets in a homogeneous or heterogeneous matrix to protect them from the external environment and to regulate their release (Pittia et al., 2021). This coating ensures safe delivery and allows for controlled release at the desired location (Huang et al., 2023). The objective of this technology is to limit the responsiveness of functional ingredients to the external environment, hence limiting degradation and alteration of the capsule properties. This enables improved handling and masks the undesirable taste and scent. Many food companies are incorporating innovative technology into the production of functional foods to suit the worldwide demand.

This study seeks to offer a thorough examination of the latest advancements in foods and beverages containing various functional components through the use of microencapsulation. Additionally, it attempts to explore the impact of microencapsulation on the bioaccessibility, bioavailability, and sensory characteristics of these food products. Moreover, this review paper examines the difficulties associated with microencapsulation and its incorporation in the food sector, along with viable remedies for these obstacles. Furthermore, this text briefly covers popular methods of encapsulation, as well as the advancements in wall materials in recent times and the growing market for functional meals.

2. Functional ingredient

Nowadays, different additives are intentionally added to foods and beverages to serve other functions rather than only as a source of nutrition for the host. According to Galanakis et al. (2021), functional ingredients are substances that provide health benefits such as neutralizing free radicals, preventing cell damage, improving gut microbiota, and reducing non-communicable diseases like cancer, diabetes, heart disease, and so on. Bioactive compounds (polyphenols, anthocyanins, flavonoids, tannins, carotenoids, antioxidants, organic acids, proteins, polysaccharides, essential oils, etc.) from plant extracts, fruits, and vegetables by products, prebiotics, probiotics and their secondary metabolites, plant fiber, vitamins, minerals, natural pigments, natural flavors, and so on, are incorporated in food products to enrich their physiochemical, phytochemical, and sensory properties (Fathi et al., 2022; El-Kader et al., 2020). Around 3000 essential oils (EOs) are discovered by the scientific community; however, the USA Food and Drug Administration (FDA) has defined only 300 EOs and oleoresins as Generally Regarded as Safe (GRAS) in Code of Federal Regulations Title 21 (Baptista et al., 2020; Guo et al., 2021). Food powder made from Cornelian cherry anthocyanins, lactic acid bacteria, and inulin provides anti-proliferative action against human colon cancer cells (Enache et al., 2022). Probiotic bacteria, such as *Lactobacillus, Lactococcus, Enterococcus, Streptococcus*, and *Bifidobacterium*, have beneficial effects on our body. These effects include enhancing the functioning of the intestinal mucosa's barrier, maintaining a healthy balance of intestinal bacteria, reducing inflammation, promoting the growth of beneficial bacteria, alleviating gastrointestinal discomfort, preventing diarrhea, and inhibiting the proliferation of harmful pathogens (Rahman et, al., 2023). Various techniques have been devised to extract functional components for use in formulating functional foods and beverages, which eventually provide benefits to the consumer.

3. Microencapsulation

Microencapsulation is a process through which a small amount of active ingredient or functional ingredient is entrapped within a capsule using other materials and these materials are referred as encapsulants (Vivek et al., 2023). The prime objective is to protect functional ingredients from physical or chemical stresses such as temperature, pH, humidity, acid, toxic substances etc. The encapsulant also referred as wall material or coating material or shell capsules can be of single constituent or a mixture of several ingredient belonging to different classes for example carbohydrates, proteins, lipids, waxes etc., soluble in aqueous or other solvent with ability to exhibit phase transition (Choudhury et al., 2021). Microencapsulation depends on several factors, 1) properties of core material. 2) properties of encapsulant, 3) interaction between core material, encapsulant and environment, 4) core to encapsualant ratio, 5) stability of core material in microcapsule and food matrix, 6) release mechanism of core material (Huang et al., 2023). Due to advancement of technology, nanoencapsulation has emerged as novel encapsulation technology. The nanoparticles exhibited enhanced characteristics including increased surface area, greater solubility, and improved bioavailability, as well as an enhanced release mechanism attributed to their subcellular size (Alu'datt et al., 2022).

4. Necessity for microencapsulation

Microencapsulation refers to a technique used to isolate tiny particles using a thin layer of polymer matrix that is applied to shield the particles from the external environment and to allow controlled release for enhancing their effectiveness (Vivek et al., 2023). Microcapsules encapsulate bioactive chemicals to shield them against heat, oxygen, humidity, light, and various other environmental variables (Calderón et al., 2022). Moreover, microencapsulation serves as a protective barrier that regulates the release, solubility, transportation, and bioavailability of bio extracts. It also conceals their undesirable taste and scent (Calderón et al., 2022). The thermal stability of sulforaphane, an isothiocyanate derived from glucoraphanin, was improved by microencapsulation using gum arabic. The encapsulation efficiency was measured at 65 % (Zambrano et al., 2023). Furthermore, the utilization of maltodextrin for microencapsulating Chilean papaya waste extract, specifically the seeds and skin, resulted in an increased concentration of phenolic and flavonoid compounds, as well as notable antioxidant properties, as compared to the non-encapsulated extract (Fuentes et al., 2023). The incorporation of emulsified microcapsules containing mulberry polyphenol using gum arabic in dried minced pork slices extended the durability and effectiveness of polyphenols by preventing oxidation reactions and simultaneously improving the color, as compared to unencapsulated mulberry polyphenol. This indicates that the anthocyanins and other compounds present in the extract were protected from the light and heat exposure during meat processing (Xu et al., 2019). A study conducted by Cherif et al. (2022) demonstrates that essential fatty acids are highly vulnerable to heat treatment in comparison to other fatty acids. The concentration of essential fatty acids reduces significantly when exposed to temperatures above 210 °C, and heat treatment also speeds up the synthesis of trans fatty acids. Many bacteria have the ability to degrade fatty acids, utilizing them as an exclusive source of resources to support their growth. As an illustration, E. coli breaks down fatty acids using the β-oxidation pathway, resulting in the production of acetyl CoA and the reduced forms of NADH and FADH cofactors (Pavoncello et al., 2022). Microencapsulation is used to improve the stability of fatty acids, specifically omega-3, −6, and −9, by reducing oxidation and extending their shelf life (Vargas et al., 2020). In addition, linoleic acid is prone to undergo free radical oxidation by molecular oxygen, a process known as autoxidation, which leads to the creation of its esters (Müller et al., 2023). Conversely, the survivability of probiotics is primarily affected by factors such as the moisture content of the food matrix, water activity, temperature, acidity, pH level, nutritional makeup, and inhibitory chemicals. Most lactic acid bacteria (LAB), such as *Lactobacillus* strains, are adapted to moderate temperatures and can only survive below 50 °C. However, several LAB species have the ability to withstand high temperatures ranging from 45 to 80 °C (Aguinaga et al., 2022). For probiotic rich food to be successful, it should include a bacterial count of 8 to 9 log CFU/g before it is consumed. This ensures that a minimum of 6–7 log CFU/g enters the colon for therapeutic benefits. Nevertheless, numerous probiotics have difficulties in preserving substantial quantities as a result of variables such as the acidic nature (pH 2) of stomach juice and exposure to oxygen (Rahman et al., 2023). Mustafa et al. (2019) conducted a study to examine how different pH levels (2.5, 4.0, and 5.5) affect the survival of L. *casei* in pomegranate juice. The results showed that variations in pH had a detrimental impact on the growth of the probiotic, especially at pH values of 2.5 and 5.5. The stability of probiotics in a product can be significantly improved by microencapsulating them using freeze drying with whey protein isolate and fructoligosaccharides. This method was found to increase the bacteria stability over a 30-day storage period at 4 °C. The log CFU/g values for L. *acidophilus* and L. *casei* were $\geq$ 8.57 and $\geq$ 7.61, respectively, compared to free cells (Massounga et al., 2019). In a study conducted by Kumar et al. (2023b), it was found that L. *plantarum* MTCC 25,432, when encapsulated with a dual coating material, showed significantly higher survival rates at pH 2.0 (6.8 log CFU) and pH 3.0 (7.1 log CFU) during a 120-minute incubation period in simulated gastric and intestinal fluid conditions. In comparison, free cells had much lower survival rates (2.01 log CFU and 2.2 log CFU).

5. Common microencapsulation techniques

The categorization of microencapsulation methods is based on the mechanism of microparticle formation. These techniques can be classified into three groups: chemical (involving molecular fusion through complexation and interfacial polymerization), physical (including extrusion, spray drying, fluidized-bed coating, and freeze drying), and physicochemical (involving organic phase separation, coacervation, emulsion system, and liposome formation) (Huang et al., 2023). Various techniques and combinations of techniques are used for encapsulation; however, some are widely used in the food processing sector to create functional meals. The subsequent paragraphs provide a concise description of the commonly employed microencapsulation techniques.

5.1. Extrusion technology

Extrusion is a highly utilized method for encapsulation because it is cost-effective, offers operational flexibility, avoids the use of toxic solvents, and, most importantly, extends the shelf life of bioactive chemicals by preventing oxidation (Petkova et al., 2022). This method is frequently employed for volatile and thermo-sensitive bioactive chemicals. In this process, the active ingredients are combined with a hydrocolloid solution and then forced through a nozzle into a curing solution. This results in the formation of microcapsules (Mehta et al., 2022; Agriopoulou et al., 2023). The size of the beads is determined by various factors, such as the diameter of the nozzle, the distance that exists between the nozzle and the curing solution, and the level of concentration of the hydrocolloid solutions (Rodrigues et al., 2020; Piñón et al., 2020). The extrusion process commonly utilizes sodium alginate, carrageenan, starches, gelatin, cellulose derivatives, waxes, gum acacia, and polyethylene glycol as wall materials to create beads with diameters ranging from 0.1 to 5 mm (Timilsena et al., 2020). Technological advancements have resulted in modifications to dripping equipment, giving rise to various extrusion techniques such as electrostatic extrusion, jet extrusion with a vibrating nozzle, coaxial airflow extrusion, and extrusion with rotational automizer discs (Fangmeier et al., 2019).

5.2. Coacervation method

The coacervation process is widely used for the creation of microcapsules or nanoparticles. The approach operates based on the principle of phase separation, in which one or more hydrocolloids in a polymeric solution form a protective layer around the active ingredient that is suspended in the same solution. (El-Kader et al., 2020). Phase separation is accomplished by modifying the surface energy of the core and wall material by adjusting process parameters such as pH, temperature, composition, etc. (Cittadini et al., 2022). During the following phase, the coating substance is solidified through the application of heat, cross-linking, or the removal of solvents. The microcapsules are acquired using centrifugation or filtering, followed by washing in specific solvents and subsequent drying using conventional procedures such as spray drying, freeze drying, or fluidized bed drying (Cittadini et al., 2022). The procedure is categorized into two groups: simple coacervation and complex coacervation. In the process of simple coacervation, a single polymer is used and is separated by adding an electrolyte, removing the solvent with a water-miscible substance, or changing the temperature. On the other hand, complex coacervation involves two polymers with opposite charges, such as proteins (positively charged) and polysaccharides (negatively charged) (Timilsena et al., 2020). Both strategies operate based on the same fundamental premise, but the process of separating phases is achieved using distinct approaches. The coacervation process utilizes several wall materials, with gelatin and gram arabic being the predominant combination. However, in recent times, whey protein isolates, bovine serum albumin, lactoferrin, and other substitutes have been increasingly used in place of gelatin Eratte et al. (2014). Complex coacervation is effective because it does not involve complex equipment, high maintenance costs, and efficient particle size control; however, the process is very complex to industrially scale up, and final products are less stable, and it needs additional processes, e.g., spray drying or freeze drying, to improve the storage durability, which eventually increases the cost of final products (Nezamdoost et al., 2024).

5.3. Spray drying method

Spray drying is a widely used technique for microencapsulation of useful ingredients. The approach is versatile, economically robust, has excellent efficiency in encapsulation, and can be employed for large-scale continuous manufacturing (Santos et al., 2020). Spray drying operates by combining functional chemicals with coating materials to create a suspension. This suspension is then sprayed through a nozzle into a hot air chamber at temperatures ranging from 150 to 300 °C. The resulting mixture forms dry powders (Maroof et al., 2022; Mohammed et al., 2020). The spray drying process yields a product with particle sizes ranging from 10 to 185 μm, which is a significant benefit. This is advantageous since adding powdered substances to food products does not alter their mouthfeel (Meena et al., 2023; Singh et al., 2022). Typically, in the food business, the feed used in the spray drying process is in the form of a liquid including water. Therefore, it is necessary for the wall materials to be able to dissolve in water (Gómez et al., 2018). Typically, coating ingredients in spray drying often consist of low molecular weight compounds such as gelatin, maltodextrin, whey protein isolates, and gum acacia (Domínguez et al., 2021). The spray drying process comes with several disadvantages, such as high capital cost, viscosity of suspension, particle size control, and high processing temperature; however, new designs are developed to mitigate these problems, such as nano-spray drying, which is used to have better particle size control, whereas vacuum spray drying is introduced to reduce the loss of active ingredients through the use of low processing temperature (Piñón et al., 2020; Binesh et al., 2023). Furthermore, different protective agents are used to reduce the viability loss of probiotics, e.g., low melting point fats, which absorb a significant amount of heat during the drying process (Meena et al., 2023; Liu et al., 2019).

5.4. Emulsification technology

Emulsification encapsulation technology involves combining the functional ingredient with an organic solvent and a wall material. This mixture is then emulsified in either oil or water, with the addition of stabilizing agents or surfactants to create an emulsion (Choudhury et al., 2021). During the subsequent phase, the polymer wall is created around the core material while the organic solvent evaporates. Emulsions can be categorized into two groups: simple emulsions, such as water in oil or oil in water emulsions, and multiple emulsions, which can have a single core or numerous cores (Mudrić et al., 2019). Moreover, emulsion can be prepared through two methods: one involves the use of high energy, such as ultrasound or high pressure homogenizer, to mix the oil and water phases, while the other utilizes low energy methods like phase inversion temperature, membrane emulsification, and spontaneous emulsification (Yakdhane et al., 2021). This method is appropriate for enclosing enzymes, essential oils, vitamins, probiotics, and other substances. Additionally, the system can be adjusted to be used on a wide scale (Vivek et al., 2023; Mehta et al., 2022). Nevertheless, the exorbitant expense of stabilizing agents, emulsifiers, surfactants, and vegetable oils, together with the inconsistent size and form of microcapsules, are the primary drawbacks of emulsification technology.

Various emulsions consisting of alginate-chitosan, carrageenan-locust bean gum, sodium-alginate, alginate-starch, calcium-alginate, and cellulose acetate phthalate were used to encapsulate probiotics in order to enhance their survival rates in simulated gastrointestinal conditions (Razavi et al., 2021; Vivek et al., 2023). Nano-encapsulation is a technology that has recently been developed in the field of encapsulation techniques employing emulsions. This process involves drying emulsions using either a spray dryer or a freeze dryer (El-Kader et al., 2020). Nevertheless, this sophisticated technology is accompanied by several notable constraints, primarily concerning the stability of emulsions. Additionally, it necessitates a substantial amount of energy due to the utilization of intense agitation methods such as high-shear stirring, high-speed or high-pressure homogenizers, ultrasonicators, or microfluidizers for the creation of nanoemulsions (Cittadini et al., 2022; Yakdhane et al., 2021).

5.5. Freeze drying or lyophilization method

Freeze drying is a well-established method in the field of encapsulation, with extensive research conducted over several years, making it a reliable and widely used technique compared to other procedures. The process described is a form of dehydration that utilizes sublimation, where a frozen solvent is extracted under vacuum circumstances. This is then followed by grinding to create a powdered form (Pudziuvelyte et al., 2020; Estupiñan et al., 2020; Todorović et al., 2022). The sublimation process is influenced by the nature of the freeze-dried product, namely the pressure and temperature conditions. Typically, the pressure ranges from 0.05 to 0.1 mBar, while the temperature ranges from −50 °C to −30 °C (Vivek et al., 2023). The approach is straightforward and highly adaptable, offering a significant advantage over existing methods due to its ability to operate at lower temperatures. This makes it ideal for preserving the integrity of heat-sensitive functional components such polyphenols and probiotics (Estupiñan et al., 2020). Moreover, the reduced moisture content confers a benefit to freeze-dried microcapsules, as they may be easily integrated into food products (Todorović et al., 2022). Probiotics such as L. *acidophilus*, L. *rhamnosus*, and *Lactococcus lactis* showed improved stability following freeze drying and storage (Moayyedi et, al., 2018; Shu et, al., 2018; Archacka et, al., 2019). In addition, freeze-dried powder obtained through this method exhibited superior solubility, Carr index, Hausner ratio, loading capacity, oxidation stability, and controlled release of active ingredients. However, it is important to note that this process is time-consuming and significantly costlier compared to alternative drying methods (Pudziuvelyte et al., 2020; Muhoza et al., 2023).

5.6. Super critical fluid (SCF) assisted encapsulation technique

The pharmaceutical sector extensively employs SCF encapsulation for the advancement of drug delivery systems. Typically, in the context of SCF (supercritical fluid) applications, carbon dioxide (CO_2) is preferred due to its non-toxic, cost-effective, non-flammable, ecologically friendly nature, and its wide availability in very pure form from various sources (Klettenhammer et al., 2021). When CO_2 is exposed to temperatures above 31 °C and pressures above 73.8 bar, it undergoes a phase transition into the supercritical state. In this condition, CO_2 exhibits gas-like viscosities and liquid-like densities (Tahir et al., 2021; Yousefi et al., 2021). SCF-CO_2 can be classified into various categories, including solvent, anti-solvent, solute, co-solvent, extractor, atomization, or drying medium, depending on its role in the encapsulation approach employed (Klettenhammer et al., 2021). In the rapid expansion of supercritical solutions (RESS) technique, as described by Soh et al. (2019), active ingredients and coating material are combined with a supercritical fluid (SCF) acting as a solvent. The SCF is then rapidly expanded or depressurized, causing the coating material to lose its solvent and form microcapsules by depositing the active ingredients. In contrast, SC—CO_2 functions as an antisolvent in the supercritical antisolvent (SAS) approach. This involves blending active chemicals and polymers in an organic solvent, which is subsequently sprayed into SCF-CO_2. The SCF-CO_2 process rapidly eliminates the organic solvent, resulting in supersaturation and the subsequent precipitation of microcapsules. In addition, there are several techniques that can be employed employing supercritical fluid (SCF), such as supercritical aided atomization (SAA), supercritical phase inversion, supercritical antisolvent fractionation (SAF), and supercritical solvent impregnation (SSI). When compared to other methods of microencapsulation, SCF has a notable advantage: it does not require the use of hazardous solvents, and, critically, it eliminates the requirement for a separation stage in the process (Martín et al., 2012; Chakravarty et al., 2019). An inherent issue with RESS and SAS microencapsulation is the tendency of polymers to undergo plasticization upon exposure to SCF, as noted by Park et al. (2021). Additional issues encompass the solubility of the bioactive component in the solvents, the accessibility of solvents and carrier materials that meet food grade standards, and other related factors (Klettenhammer et al., 2020).

5.7. Fluidized bed coating

Fluidized bed coating is a mechanical method that was initially created for the pharmaceutical business. It involves spraying a protective agent onto the surface of solid particles. Nowadays, this process is commonly used in the food industry to produce functional food (Song et al., 2023). The primary application of this technique is for sensitive materials or water-soluble solids, especially those with a low pH. In this process, a wall material is sprayed onto a fluidized bed of powder to create coated particles (Agriopoulou et al., 2023). The entire procedure can be categorized into three phases. In the initial phase, the particle to be coated is made to flow like a fluid in the air stream. Subsequently, the wall material is applied onto the particle surface using a nozzle. Finally, the wall material adheres to the particle surface as its solvent evaporates upon contact with hot air.

The optimization of the coating process relies on several operational parameters, including humidity, coating feed rate, spray pressure, and temperature, all of which are crucial factors in this process (Shah et al., 2022). Strasser et al. (2009) conducted a study in which cellulose was used to encapsulate Enterococcus faecium IFANo.045 and L. plantarum IFANo.278 by fluidized bed coating. The method is adaptable and can be expanded to accommodate large-scale manufacturing, such as in the case of commercial dry yeast production (Barajas et al., 2023; Rajam et al., 2022). Nevertheless, there are certain disadvantages linked to this method, such as the substantial expense of the equipment and, notably, the elevated temperature, which might potentially lead to oxidation of sensitive substances or the deterioration of bioactive substances and probiotics (Soni et al., 2023).

5.8. Ionic gelation method

Ionic gelation is a method used to create microparticles or nanoparticles by exploiting the electrostatic contact between charges of opposite polarity. This interaction leads to a separation of the liquid into a polymer-rich gel phase and a polymer-poor liquid phase (Hoang et al., 2022). Hydrophilic polymers such as sodium alginate, gelatin, and chitosan are commonly employed as raw materials in the process of ionic gelation (Su et al., 2023). Hydrogel beads are often formed by adding drops of a solution comprising polymers and active substances into a water-based solution that contains cationic polyelectrolytes (Sacco et al., 2021). The viscosity of the initial mixture, surface tension, dynamic interactions between droplets and the matrix fluid, polymer concentration, and molecular weight of the polymer are important factors that influence the size and shape of beads (Gadziński et al., 2023). This technique does not require the utilization of organic solvents or elevated temperatures and offers significant benefits, including excellent stability, affordability, effective sustained release of hydrogels, and encapsulation efficiency that can reach up to 99 % (Koop et al., 2022). The formation of nano particles by cross linking chitosan and tripolyphosphate for the purpose of encapsulating quercetin and myricetin shown a significant retention capacity of 82 % and 89 % respectively, as well as improved stability (Trindade et al., 2021). Nevertheless, the ionic gelation approach is hindered by challenges such as limited control over particle size, expensive equipment requirements, specific storage conditions, and complexities in scaling up production (Koop et al., 2022).

6. Microencapsulation of bioactive compounds

Bioactive compounds are substances included in food products derived from plants or animals that have physiological effects beyond their basic nutritional functions (Arruda et al., 2022). Various categories of biologically active substances, including carotenoids, polyphenols, antioxidants, essential oils, flavors, and others, are used into food and drinks to enhance their sensory attributes and provide nutritional and health advantages (Kumar et al., 2023a). These substances can be obtained from various food sources such as fruits, vegetables, seaweeds, fish, and herbs. In order to improve their stability, bioavailability, and shelf life when added to food, they are microencapsulated. (Alu'datt et al., 2022; Jaime et al., 2021). In a study, the phenolic compounds of ciriguela peel were extracted using ultrasound and then encapsulated using spray drying and freeze drying. This process led to an increased quantity of phenolic and flavonoid compounds, which remained stable even after three months of storage at 7 °C. The microencapsulated samples showed no significant variation in their content compared to the lyophilized ones (Silva et al., 2023b). In another study, the process of microencapsulation was employed to protect propolis and bee honey by using various wall materials (tara gum, maltodextrin, and modified native potato starch) and spray drying. The results indicated that modified starch was more effective than maltodextrin in terms of encapsulation, as it provided better core protection and higher release kinetics of phenolic compounds (ranging from 8.13 to 12.58 mg GAE/g between 7 and 13 h) (Ligarda et, al., 2023).

The study conducted by Meira et al. (2023) shown that β-carotene was encapsulated using freeze drying using the leftover proteins derived from beer waste. The resulting microparticles showed a bioaccessibility of 84.1 % and provided exceptional protection against thermal degradation. The thermostability of microcapsules containing anthocyanin was found to be higher at temperatures of 60 and 80 °C, and they also exhibited improved resistance against pH levels of 7 and 11, in comparison to free anthocyanin Zhang et al. (2024). The sap of Croton lechleri bark, known as Dragon's blood sap (DBS), was encapsulated using electrospraying assisted by pressurized gas technology (EAPG) with whey protein concentrate and zein. This encapsulation process resulted in an increase in oxidative stability for the encapsulated DBS compared to the free DBS when exposed to ultraviolet light (Escobar et al., 2023). Soiklom et al. (2024) developed anthocyanin-rich gel beads by modifying the ionotropic gelation technique using colored rice. These gel beads effectively reduced the release of anthocyanins and phenolics in simulated gastric conditions, while enhancing their release in the intestines. As a result, the bioavailability of the active ingredient was improved. A separate study conducted by Crozatti et al. (2023) demonstrated that the thermal and light stability of microencapsulated anthocyanin from juçara palm fruit was enhanced when combined with maltodextrin and beta-cyclodextrin. Furthermore, this combination also increased the color intensity across a wide range of pH levels. The antioxidant activity of natural dye extracts from Spirulina platensis, dragon fruit peel, and pumpkin skin increased when they were encapsulated with various coating materials. The IC_{50} values for antioxidant activity increased to 4026.96 ppm, 2403.71 ppm, and 4327.92 ppm from their original values of 2164.75 ppm, 688.91 ppm, and 1025.62 ppm, respectively (Handayani et al., 2023). Table 1 shows microencapsulation of bioactive compounds using different encapsulation techniques, binding materials, and their effect on developed foods and beverages.

7. Microencapsulation of probiotics

Probiotics are widely utilized components in the creation of functional food owing to their considerable potential for promoting health advantages (Hamad et al., 2022). In order to ensure the effectiveness of the health benefits, it is crucial to maintain a substantial quantity of probiotic bacteria, specifically around 6–7 log CFU/g, over the ingestion period (Rahman et al., 2024). Microencapsulation enhances the viability of probiotics under challenging conditions encountered during manufacturing, handling, storage, and the hostile gastrointestinal environment (Sbehat et al., 2022). The viability of freeze-dried microcapsules containing *Bifidobacterium bifidum* R0071 and *Bifidobacterium breve* M-16 V, along with pectin and 0.5 % bovine milk osteopontin (OPN), was shown to be over 10^6 CFU/g after undergoing simulated infant digestion. In contrast, capsules without OPN only had 10^3 CFU/g of viable cells (Huang et al., 2024). Table 2 shows microencapsulation of

Table 1
Microencapsulation of bioactive compounds using different encapsulation techniques, binding materials, and their effect on developed foods and beverages.

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
Tradescantia zebrina leaves	Bioactive extract	Maltodextrin	Spray drying	Yogurt	The L* and a* values of yogurt samples rose when microparticles were added. A significant amount of bioactive compounds were present despite the decrease in TPC (142.94 to 100.21 mg GAE/g), DPPH activity (175.99 to 94.80 μm TE/g), and anthocyanin (0.047 to 0.027 mg C3G/g) after in vitro digestion.	Feihrmann et al. (2024)
Peanut skins	Phenolic extract	Maltodextrin, Carboxymethyl cellulose and Soy lecithin	Freeze drying	Soymilk	The samples containing free and encapsulated extracts exhibited diminished levels of bacterial proliferation, rancid taste, hydroperoxides, hexanal, and sweetness in comparison to the control sample. Unlike the microencapsulated sample, the free sample showed higher phenol content (819.72 mg gallic acid equivalents per liter) and greater antioxidant activity (64.66 % DPPH inhibition).	Larrauri et al. (2023)
Encosta do Caparaó property, Castelo-ES, Brazil	Green coffee extract	Polydextrose and Inulin	Freeze drying and spray drying	Dairy Beverage	Microcapsules enhanced the TPC (3.05–3.42 mg GAE/mL) and DPPH activity (12.89–14.56 μmol Trolox/mL) of dairy beverages compared to the control (2.20 mg GAE/mL and 11.31 μmol Trolox/mL). Furthermore, around 90 % recovery of phenolic and antioxidant compounds was observed after in vitro gastrointestinal digestion.	Carmo et al. (2022)
Ceder Natural Vegetable Oil Co. Ltd, Jiangxi province, China	Thyme essential oil	Gum arabic	Vacuum-freeze drying	Mutton patties	Heat loss for TPC was 21.12 % for the microcapsules, whereas the value was 33.31 % for free extract. Mutton patties with microencapsulated oil had a TPC of 0.49 g GAE/kg (highest), compared to free essential oil (0.32 g GAE/kg).	Yu et al. (2023)
Cornelian cherry, Red cabbage, and Chokeberry	Anthocyanin extracts	Inulin and maltodextrin	Spray drying	Bread	Breads with red cabbage extracts had the highest anthocyanins (5.39–6.56 mg/g DW); however, the value decreased following each stage of in vitro digestion. The FRAP activity of enriched breads exhibited a substantial increase following the application of extracts. The bread's FRAP antioxidant capacity ranged to 25.21 from 13.84 μmol TE/g DW, and its capacity to reduce $Fe3+$ ions.	Czubaszek et al. (2023)
Chagalapoli (Ardisia compressa K.) fruit	Anthocyanin extract of fruit pulp	Maltodextrin and Capsul®	Spray drying	Isotonic beverage	Compared to the samples kept at 25 °C, the anthocyanin retention was higher in the beverages at 4 °C. But, at 25 °C, the stability of encapsulated anthocyanin was lower than samples with free extract.	Antonio-Gómez et al. (2023)
Pink guava	Pink guava pulp colorant	Mucilage of Opuntia ficus-indica (OFI) and aloe vera (AV)	Spray drying	Yogurt	The carotenoid content of Yogurt with pink guava pulp microcapsule increased by approximately 7.2 times and antioxidant capacity by 6.6 times relative to the control. When yogurt with microcapsules was stored in the dark at 4 °C for 25	Otálora et al. (2022)

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Table 1 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
					days, it displayed superior color stability as compared to the sample that had E110 artificial dye.	
Black Carrot	Anthocyanin extract	Gum arabic and maltodextrin	Freeze drying	Ice cream	The highest amount of anthocyanin (143.21 mg/100 g) and phenolic (545.38 mg GAE/ 100 g) was observed in ice cream enriched with 9 % microencapsulated anthocyanins powder. Throughout the storage (60 days), the ice cream's quality attributes remained acceptable.	Shamshad et al. (2023)
Sigma-Aldrich (St. Louis, USA)	Beta-carotent (β-C)	Lactoferrin (LF) and Amaranth carboxymethyl starch cellulose (CMS)	Complex coacervation	Gummy candies	At pH = 5, CMS/LF complex coacervates generated 98 % encapsulation efficiency. The microcapsules had a spherical shape with strong thermal and photolytic stability. When β-C microcapsules were added to gummy sweets, the hardness was lowered and 22 % bioaccessibility was made possible.	Constantino and Garcia-Rojas (2023)
Sigma-Aldrich (St. Louis, USA)	Betanin	Sodium carboxymethyl cellulose (CMC) and Ultrasound treated amaranth protein isolate (API-U)	Complex coacervation	Felatin films (Edible)	The EE of microcapsules ranged from 61 to 87 % provided resistance against thermal degradation (50 °C) and culminated roughly 2.92-fold increase in half life. Following the gastrointestinal digestion, edible gelatin films containing betanin microcapsules showed increased antioxidant activity, reduced light transmission, and 84 % bioaccessibility.	Constantino and Garcia-Rojas (2022)
Kinnow	Peel extract	Maltodextrin and whey protein concentrate (WPC)	Spray drying	Breadsticks	WPC exhibited better encapsulation efficacy (69.07–80.36 %), powder yield (77.76–82.87 %) phenolic content (18.04–13.37 mg GAE/ g), and antioxidant activity (63.80–74.20 %) when compared to maltodextrin. Higher encapsulating agent concentrations increased polyphenol retention, and the microencapsulated powder had a major impact on the viscoelastic characteristics and proximate composition of the breadsticks.	Rafiq et al. (2023)
Carrot	Carotenoid extract	Gum Arabic (GA) and whey protein isolate (WPI)	Complex coacervation	Tapioca pancakes	Over 90 % of the original carotenoid content was obtained through complex coacervation, and the highest carotenoid concentration (64.0 mg/100g) was obtained at a WPI:GA ratio of 3:1. The powder's carotenoid concentration decreased to 49.2 mg/100 g after 30 days, suggesting it can be stored at 10 °C for 79.0 % of its life.	Parente et al. (2021)
Beleric fruit powder (*Terminalia bellirica*)	Chebulagic acid (CA)	Maltodextrin and Gum arabic	Spray drying	Orange juice	The microcapsules (highest EE 89.24 %) had a storage stability of 640 days, compared to the free extract, which had only 130 days. The storage capacity of orange juice increased to 200 days (50.13 %) by adding microcapsules.	Guggilla et al. (2023)
Orange peel,	Polyphenol extract (OPP)	Maltodextrin and Gum acacia	Emulsification	Buttermilk	Approximately 95.20 % EE was obtained with 3:10 core to wall ration.The increase of OPP in the buttermilk resulted in higher	Hasan et al. (2023)

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Table 1 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
					levels of TSS, titratable acidity, TPC, TFC, DPPH level.	
Grape and flaxseed	Flaxseed oil (FO) and grape pomace (GP)	Maltodextrin and Gum tragacanth	Spray drying	Stirred yogurt	The GP and FO microencapsulation achieved a yield of 76.54 %. Yogurts that were stirred and contained the microencapsulated form of GP and FO showed the highest amounts of phenolics and antioxidant capacity in comparison to yogurt that contained free bioactive components.	Saberi et al. (2023)
Curcumin and Origanum	Essential oils	Sodium alginate and Tween 80	Emulsification	Chilled chicken breast	The combination of Origanum and Cucumin essential oils used in antimicrobial photodynamic therapy decreased the number of pathogenic microbes. Furthermore, without causing alterations in color or shear force, the chicken breasts' qualitative attributes indicated lower cooking loss, improved antioxidant activity, and reduced lipid oxidation.	Moraes et al. (2023)
Caulerpa sp. macroalgae	Chlorophyll	Gelatin and Gum arabic	Freeze drying	Jelly drink	The increase in Caulerpa sp. microcapsule concentration was accompanied by increases in parameters such as dissolved solids, syneresis, total sugar, dietary fiber, total phenol, and antioxidants; however, the greatest results were observed in terms of sensory acceptance at 2000 ppm concentration.	Dewi and Purnamayati (2023)
Huamei Biotechnology Co. Ltd, China	Rose essential oil	Sodium alginate and perils protein isolate	Complex Coacervation	Ground Beef	The microcapsules had an encapsulating efficiency, payload, and yield of 89.80 %, 53.17 %, and 88.26 %, respectively. Furthermore, the microencapsulated REO showed a superior sustained-release profile and thermal stability compared to free ones. By introducing REO microcapsules, ground beef's shelf life at 4 °C was extended by 6 days.	Srisuk et al. (2021)
Niger seed	Essential oil	Maltodextrin and sodium casienate	Spray drying	Ice-cream	The ice cream sample with 1 % encapsulated powder exhibited superior viscosity, overrun, and sensory character. The ice cream sample containing 2 % Niger seed oil exhibited the highest amounts of TPC (24.23 mg GAE/g) and DPPH inhibition (88.73 %).	Patel et al. (2022)
Sigma Aldrich Chemical	Cod liver oil (CLO)	Lupine protein isolate and sodium alginate	Emulsification	Meatball	CLO microspheres were spherical, homogenous, and more resistant to heat treatments with encapsulation efficacy of 95.62 % and an accumulative release rate of 87.10 %. During storage meatballs containing microcapsules had a substantially reduced thiobarbituric acid-reactive chemicals, conjugated dienes value, peroxide value, carbonyl content and displayed improved sensory profile.	Elsebaie et al. (2022)
Lime peel	Essential oil	Gum Arabic, whey protein isolate, gelatin and carboxymethyl cellulose	Emulsification	Nut	The emulsion was found to have high antibacterial inhibition zones (up to 28.37 mm), anti-mycotoxigenic fungus (up to 37.61 mm), stability (99.61 %), and zeta potential (−21.16 mV).	Hassanein et al. (2023)

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Table 1 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
					In filmed peanuts and almonds, the fungal growth decreased from 78.02 % to 84.5 %, as well as a reduction in oxidation.	
Oleafit srl, Teramo, Italy	Extract of olive leaf	Pectin and sodium alginate	Emulsification	Biscuit	Comparing biscuits made with both free and encapsulated forms of olive leaf extract at a concentration of 500 µg GAE/g of dough, it was found that they had higher levels of oxidative stability and radical scavenging activity, and those enriched with encapsulated polyphenols were even more stable. The texture of the biscuits hardened due to the water absorption phenomenon being affected by the alginate and pectin of microsphere.	Paciulli et al. (2023)
Pequi (Caryocar coriaceum Wittm.) fruit pulp	Essential oil	Cashew gum, Chitosan and Gelatin	Emulsification	Fermented milk	The syneresis levels dropped (<50 %) due to an increase in water retention caused by the biopolymers of microcapsules. The microcapsules containing cashew gum and chitosan, and the microcapsules containing cashew gum and gelatin, the beta-carotene retention values were 13.26, 28.03, and 20.16. Improved oil stability and a progressive release over a 120-minute period were made possible by microencapsulation, which also improved bioaccessibility.	Silva et al. (2023a)
Huaxin plant essential oil company (Yunnan, China)	Perilla essential oil (PEO)	Gelatin (GE) and Sodium sulfate solution	Simple coacervation	Peaches	PEO microcapsules exhibited exceptional thermal stability and encapsulation efficiency (91.5 %) at a core-shell ratio of 1.4:1. The microcapsules DPPH/FRAP was higher than free PEO. While the untreated fruit was beginning to decompose after three days, the PEOM-treated fruit showed no signs of rotting or water evaporation.	Tai et al. (2023)
purple tea (Camellia sinensis var. assamica cv. Zijuan)	Polyphenol extract	Sodium alginate	Extrusion	Milky tea	While the addition of microbeads (EE 84 %) containing OPM did not affect the TPC, antioxidant capacity, or color of milk teas, the free extract increased the darkness/greenness of TPC by 2.15-fold (268 vs. 125 mg GAE/L), a 4.1-fold increase in CUPRAC (1261 vs. 501 mg AAE/L), and a 12.2-fold increase in hydroxyl radical scavenging activity (308 vs. 25 mg AAE/L).	Farrell (2023)
Apis mellifera bees	Red propolis and red propolis extract	Arabic gum solution	Spray drying	Non-lactic beverage	Lactic acid bacteria containing no extract, free extract, and microencapsulated extract had respective values of 8.51, 8.47, and 8.55 log CFU/mL. The free propolis extract-produced beverages exhibited greater levels of antioxidant activity, phenolic concentration, and volatile esters, whereas the sample containing propolis microcapsule had higher alcohol content, higher lactic and acetic acid concentrations (1.25 g/L and 0.11 g/L, respectively), and a higher overall sensory score.	Ferreira et al. (2023)

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Table 1 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
Red grape pomace	Lipophilic and polyphenolic extract	β-lactoglobulin and lactose	complex coacervation and freeze drying	Conjugated Food powders	The conjugated powder had a higher capacity for emulsification, allowing for greater retention of fatty acids (264.13 mg/g dry weight (DW)). Non-heated samples had higher levels of tocopherols (1.66 μg/g DW), phytosterols (77.01 μg/g DW) with improved polyphenol and flavonoid retention index for both powders.	Mihalcea et al. (2023)
Roselle (hibiscus sabdariffa) flower	Roselle extract	Modified WPC and Maltodextrin	Spray drying	Gummy candy	Enzymatic hydrolyzed WPC exhibited highest TPC (13.3 mg GAE/mL), anthocyanin (9.1 C3G/L) and improved antioxidant activity (DPPH-79.5 %, $ABTS^{+}$=85 %). Gummy candy developed using 6 % of microparticles illustrated higher TPC and antioxidant activity as well as highest sensory scores.	Younesi et al. (2023)
Saffron flowers	Floral waste extracts	Sodium alginate	Extrusion	Yogurt	The beads carrying saffron floral by-products (1.243 mg GAE/g) had EE of 55.66 %, and in saffron stigma encapsulates (1.065 mg GAE/g), it was 67.55 %. During 21-day chilled storage, the yogurt matrix's antioxidant qualities of the saffron flowers were preserved due to the alginate microencapsulation had no effect on the microbiological profile or physical-chemical characteristics.	Cerdá-Bernad et al. (2023)
Xi An Shouherb Biotech Co., Ltd. (Xi'an, China)	Momordica grosvenorii saponin (MGS)	Sodium alginate and Chitosan	Extrusion	Momordica grosvenorii beverage	The drink had 5.0 % soluble solids, 19.22 mg/mL of total sugar, 0.28 mg/mL of titratable acidity, 3.91 pH, and 19 mg/mL of MGS. It also demonstrated good stability and the antioxidant capacity of the MGS was 77.14 % lower than in its original form. However, the encapsulated MGS retained around 70 % of its antioxidant resistance in an acidic environment.	Liu et al. (2022)
L. *paracasei BGP-1* (Sacco Brasil Campinas, Brazil) and Guaraná (Paullinia cupana) fruit (Rural Economic Recuperation, Taperoá, Brazil)	Guaraná seed extract and *Lacticaseibacillus paracasei BGP-1*	Gelatin and Gum arabic	Spray drying	Yogurt drink	The viability of L. *paracasei BGP-1* during storage was improved by co-encapsulating the probiotic with GSE, which protected the phenolic compounds (88 %). Microencapsulation maked the bitter flavor of GSE and yogurt with microcapsules was more widely accepted overall than yogurt containing free GSE. Moreover, L. paracasei levels of roughly 7 log cfu g − 1 were maintained in yogurt formulations kept at 7 °C for up to 28 days via encapsulation of GSE.	Silva et al. (2022)
ViBERi New Zealand Ltd.	Blackcurrant concentrate (BC)	Whey protein isolate (WPI)	Spray-drying and freeze-drying	Cookies	The total phenolic content (TPC) of Spray-dried BC (SWB) cookies was lower compared to Freeze-dried BC (FWB) cookies, but greater than the TPC of the control cookies. Before digestion, cookies enhanced with FWB demonstrated greater potential to scavenge DPPH radicals and exhibit reducing power compared to cookies enriched	Wu et al. (2021a)

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Table 1 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
					with SWB. Following intestinal digestion, cookies enhanced with FWB exhibited a decrease in reducing power, but shown higher potential for scavenging DPPH radicals compared to cookies enriched with SWB.	
ViBERi New Zealand Ltd.	Blackcurrant concentrate (BC)	Sodium caseinate	Spray-drying and freeze-drying	Cookies	The inclusion of BC microcapsules altered the functional properties of the cookies, resulting in enhanced TPC and antioxidant activity, as well as a predicted decrease in starch digestion (in vitro glycaemic response). Additionally, the physical attributes of the cookies, including texture and colour parameters, were also affected.	Wu et al. (2021b)
Snake Melon (SM) (Cucumis melo subsp. melo Var. flexuosus)	Snake Melon powder	Pea protein (PP) powder (Nutralys® S85F) and pea fibre (PF) (Pea Fiber I 50 M)	Freeze-drying	Functional snake melon (SM) powder	In comparison to free SM (snake melon), pea-protein SM particle and pea-fiber SM particle encapsulated SM particle had lower moisture content and water activity, were more free-flowing, and were less hygroscopic. PFSM had the highest value of phenols and antioxidant capacity (307 ± 4.0 mg GAE/100g and 204 ± 4.0 mg Trolox/100*g* , respectively).	Igual et al. (2023)
Carrot (local market) L. plantarum (Semnan cheese)	Carrot pomace extract and *Lactobacillus plantarum*	Alyssum homolocarpum seed gum (AHSG) and Sodium alginate	Extrusion	Symbiotic yogurt	The TPC (16.13–48.30 μg GAE/ml) and DPPH radical scavenging activity (7.4–14.64 %), respectively, were displayed in the functional yogurts. The probiotic survival rate of the functional yogurts varied from 6.37 to 8.13 log CFU/g on the 28th day. Probiotic bacteria in yogurt performed substantially better during storage when AHSG and SA-generated beads and carrot pomace extract were employed compared to free pomace.	Sharifi et al. (2023)
BRS Violet Grape Pomace	Phenolic compounds and anthocyanins	Maltodextrin and Xanthan gum	Lyophilization	Gelatin	Compared to samples kept at 4 °C, those kept at 25 °C lost more anthocyanins and phenolic compounds. Encapsulation improved results for the TPC (3.06 to 1.74-fold) and total anthocyanins (1.69 to 1.54-fold). The application of microcapsules in gelatin showed that the encapsulating matrix maintained its color for a duration of thirty days.	Romanini et al. (2023)
Limosilactobacillus reuteri LR 92 (DSM 26,866 Sacco, Sousas, São Paulo, Brazil) and lemongrass (Cymbopogon citratus)	Lemongrass essential oil and *Limosilactobacillus reuteri LR 92*	Acacia gum, sodium alginate and Tween 80	Extrusion	Candy	Due to encapsulation L. *reuteri* was able to survive in both the simulated gastrointestinal conditions (7.10 log CFU/g) and the 28-day storage period (7.50 log CFU/g). Candy's Aw and chemical makeup did not alter with slight reduction in cohesiveness, but color characteristics, a* and b*, increased during the storage period, intensifying its orange hue.	Nascimento et al. (2023)
Sea Buckthorn	Carotenoids	Whey protein isolate, and Carboxymethyl	Complex coacervation	Mayonnaise	The total carotenoid content of the mayonnaise ranged from 0.26 mg/100 g dw to 1.85 mg/100 g	Roman et al. (2022)

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Table 1 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material Or Binding Material	Encapsulation Technique	Developed Functional Food or Beverage	Result/Effect	Reference
		cellulose, Alginate, Agar, and Chitosan	and freeze-drying		dw. Regarding the antioxidant activity, it increased to 293.38 µmol Trolox/g dw from 9.99 µmol Trolox/g dw. After two hours of intestinal digestion, P2 showed a release of 47.14 %, while P1 showed a maximum release of 82.47 %.	
Guaraná Peels	Carotenoid extract	Gum arabic	Spray drying	Oatmeal Paste	When lutein stability was compared to samples with free GPE, the samples enhanced with encapsulated GPE showed a considerable increase (51–89 %). Oatmeal paste's viscosity was decreased by adding microparticles (carotenoid concentration 40–96 µg/g); however, samples containing free GPE experienced the reverse effect. Because of the microparticles, there was a decrease in accessible water, which had an impact on the starch gelatinization of oat flakes. After 90 days, the free GPE had a 45 % carotenoid loss, while the microparticles showed roughly a 30 % loss.	Pinho et al. (2023)
Cornelian Cherry (Cornus mas L.) Fruits and Lactic Acid Bacteria (Chr. Hansen, Hoersholm, Denmark)	Anthocyanin extract and *Lacticaseibacillus casei (*L. *casei) 431®*	whey protein isolates, casein and inulin	Complex coacervation and freeze-drying	Antioxidant and Anti-Proliferative Derivative Powders	Both powders demonstrated a high degree of anthocyanin retention, with EE of 90 % for lactic acid bacteria and 78–79 % for anthocyanins. The powders had roughly 10 log CFU/g DM and anthocyanin content of about 32.00 mg C3R/g DM. For the WPI-I variant, no cytotoxicity has been discovered at doses between 1 and 25 µg/mL; nevertheless, at low concentrations of 1–4 µg/mL, a cell proliferation effect was noted.	Enache et al. (2022)

probiotics with different wall materials, encapsulation techniques, and their effect on developed foods and beverages.

In a study, the gastric resistance and stability of *Lactobacillus plantarum* 550 were enhanced by encapsulating it with soy protein isolate (SPI) and peach gum polysaccharide (PG) using spray drying. Among the different ratios tested, samples with an SPI:PG ratio of 3:1 exhibited the highest viability of 7.88 ± 0.12 log CFU/g during storage (Yao et al., 2023). In another study, *Lactiplantibacillus plantarum* MTCC 25,432, a strain known for its riboflavin production, was encapsulated via spray drying with inulin and maltodextrin. The encapsulated strain demonstrated enhanced survival rates in acidic conditions (pH 2.0 and 3.0) and high concentrations of bile salts (1.0 % and 2.0 %) ((Kumar et al., 2023b). The viability of *Limosilactobacillus fermentum* NCU001464 microcapsules, produced by spray-drying gelatin and xylooligosaccharides by the Maillard reaction, remained at 9.00–6.80 log CFU/g while stored at 4 °C and 25 °C for 10 weeks (Li et al., 2023). Akbari et al. (2023) found that encapsulating *Limosilactobacillus reuteri* TMW 1.656 with cruciferin and alginate capsules extended the shelf life of probiotics to 8 weeks at 4 °C. In contrast, non-encapsulated probiotics lost their viability after just 2 weeks. Moreover, the microcapsules exhibited a significantly greater survivability in stomach circumstances, with an increase of 3 log cycles. Additionally, the microcapsules showed higher resistance to heat at 65 and 75 °C, with increases of 4 and 2 log cycles, respectively, compared to probiotics that were not encapsulated. In the study of Khan et al. (2024), the viability of Bifidobacterium infantis ATCC 15,697 cells decreased and became non-viable after 28 days of storage. However, the microencapsulated cells maintained a high viability with >106–7 log CFU/g viable cells.

8. Impact of microencapsulation on sensory attributes of foods and beverages

Active ingredients, e.g., polyphenols, essential oils, proteins, organic acids, antioxidants, prebiotics, probiotics, etc., can affect the food's organoleptic properties, which can be undesirable to consumers. Bioactive compounds such as proplis and astaxanthin have strong flavors and aromas; microencapsulation can conceal their odor and taste, thus making it easier to integrate them into various food products (Su et al., 2023). Probiotics can ferment food's sugar into organic acids or peptides, which can cause bitterness (Siddiqui et al., 2023). Encapsulation can be used as a tool to mask the odd flavors and smells of functional ingredients, which will improve the sensory attributes of foods and beverages. For example, rose petal jam containing microencapsulated L. plantarum had better texture and sensory attributes compared to one's free probiotics (Shoaei et al., 2022). The greatest scores of overall acceptability were achieved by microencapsulating green coffee extracts by spray drying and freeze-drying methods, employing polydextrose (PD) and inulin (IN) as encapsulating agents (Carmo et al., 2022). In the study conducted by Pamunuwa et al. (2021), the sensory panel expressed a high preference for the ready-to-serve

Table 2
Microencapsulation of Probiotics with different wall materials, encapsulation techniques, and their effect on developed foods and beverages.

Source of Functional Ingredient	Core Material	Wall Material	Encapsulation Technique	Developed Functional Food/Beverage	Result/Effect	Reference
Thailand Institute of Scientific and Technological Research	*B. breve TISTR 2130* and L. *delbrueckii* subsp. *bulgaricus TISTR 2290*	Sodium alginate	Extrusion	Green Soybean Yogurt (GSY)	The viability of encapsulate probiotics in GSY was greater than 6 log CFU/mL after 10 days of storage at 4 °C, but began to decline in the subsequent days. The highest level of syneresis (91.0 % ± 1.41 %) was seen at the beginning of storage, whereas the lowest level (91.0 % ± 1.41 %) was recorded on day 20.	Naklong et al. (2023)
National Institute of Food Science & Technology (NIFSAT), University of Agriculture Faisalabad, Pakistan.	L. *acidophilus ATTCC 8826*	Sodium alginate and whey protein isolate	Electrospinning	Dried apple snack	Antacids were used to enable probiotics to pass through highly acidic gastric fluids safely and improve the survival rate of probiotics. In dried apple snacks, sodium alginate and $CaCO_3$ microcapsules exhibited the lowest drop in viability (0.92 log CFU/g) and had the highest acceptability among other formulations.	Afzaal et al. (2023)
American Type Culture Collection [ATCC] 53,103; Manassas, VA, USA	*Lactobacillus rhamnosus GG* and *cocoa butter*	Sodium alginate, whey protein, pullulan and Tween 80	Extrusion	strawberry nectar	The number of living cells of L. *rhamnosus* GG fell by 57.9 % and 78.63 % after 4 weeks of storage at both 4 and 25 °C, respectively. Significantly, there was an apparent drop in both pH and anthocyanin values in strawberry nectar. Nevertheless, the addition of red probiotic beads had a positive effect on the sensory characteristics.	Morsy et al. (2022)
Thailand Institute of Scientific and Technological Research (TISTR), Thailand	*Lactobacillus acidophilus TISTR 2365*	Sodium alginate, egg and fruiting body of bamboo mushroom (Dictyophora indusiata)	Extrusion	Sweet fermented rice or Khoa-Mak	Every formulation exhibited viability of >8 log CFU/g and high encapsulation efficiencies of 95.72–98.86 %. The addition of bamboo mushrooms, particularly 3 % egg stage in beads, improved the viability of L. *acidophilus* in Khoa-Mak saps during storage. The inclusion of bamboo mushrooms (egg and fruit body) greatly increased the product's TPC and DPPH activity without affecting their sensory qualities.	Srisuk et al. (2021)
Dept. of Bioengineering and Alcoholic Drink Technology, Institute of Food Science and Technology, Hungarian University of Agriculture and Life Sciences.	*Lactobacillus plantarum 299v*	Whey Proteins	Lyophilization	Probiotic Apple Juices	The cell count in the fruit juice decreased after 4 weeks and reaching a final value of 5.04 Log CFU/g after 2 months of storage, starting with an initial value of 9 Log CFU/g. The core-to-wall ratios, storage duration, temperature, and fermentation or fortification techniques all had an impact on the pH variations of probiotic apple juices.	Sun et al. (2022)
Department of Pharmacy and Biotechnology, University of Bologna, Italy	L. *crispatus BC4* and L. *gasseri BC9*	Commercial soy beverage	Spray drying	Fermented soy beverages	Encapsulated bacterium samples, namely E-BC4+BC9, exhibited higher levels of lactic acid (1.43 %), a greater water holding capacity (62.29 %), and shown remarkable antagonistic activity against enteropathogens. In addition,	D'Alessandro et al. (2023)

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Table 2 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material	Encapsulation Technique	Developed Functional Food/ Beverage	Result/Effect	Reference
					the strains were protected from simulated gastrointestinal conditions (>1 log) using encapsulation; however, the desirability of the final products was reduced.	
L. casei 431 (Chr. Hansen, Horsholm, Denmark), Palm tocotrienol-rich fraction (TRF) and flaxseed oil (SOP Green Energy, Sarawak, Malaysia)	L. *casei 431, Palm tocotrienol-rich fraction (TRF)* and *flaxseed oil*	Sodium alginate and Sodium carboxymethyl cellulose	Extrusion and Emulsion technique	Functional orange juice	The viability of L. casei in the juice decreased from 7.88 to 5.47 log CFU/mL after 30 days. However, there was only a 1 log reduction observed for both individually encapsulated and co-encapsulated L. casei in juice. The orange juice containing single-encapsulated and co-encapsulated beads exhibited greater resistance to oxidation in flaxseed oil, regardless of the presence of tocotrienol, compared to the free L. casei and free flaxseed oil.	Sultana et al. (2023)
Sigma-Aldrich, Cairo University, Egypt	*Lactiplantibacillus plantarum, Ligilactobacillus salivarius* and *chromium oxide nanoparticles (Cr2O3-NPs)*	Sodium alginate and Arabic gum	Extrusion	Yogurt	The pH of yogurts containing hydro-beads containing Cr2O3-NPs was lower than that of controls. Green-generated Cr2O3-NPs levels had no effect on the encapsulation yield or overall acceptance of any yogurt. Additionally, the acidity, protein content, fat value and dry matter increased over the 21 days cold storage.	El-Sayed et al. (2023)
BioGaia AB, Stockholm, Sweden	*Limosilactobacillus reuteri DSM 17,938*	Sodium alginate	Extrusion	Probiotic tomato juice	After 28 days' storage at 4 °C, the viable cell count was 5.70 and 5.94 Log CFU/ml for free untreated and sonicated samples, where the values were above 6.0 Log CFU/ml for microencapsulated samples. Most importantly, sonicated cell did not change the juice's pH at refrigerated condition.	Giordano et al. (2022)
Chr. Hansen, Horsholm, Denmark	L. *casei 431*	Sodium alginate and Quince seed gum	Freeze drying	Synbiotic drink powder	The powder's functional characteristics were measured and found to have a TPC (total phenolic content) ranging from 19.78 to 21.35 mg GAE/g, an ORAC (oxygen radical absorbance capacity) ranging from 193.45 to 194.19 µmol TE/g, and a DPPH (2,2-diphenyl-1-picrylhydrazyl) activity ranging from 67.34 to 71.14 %. After undergoing freeze-drying, the survival rate of free probiotics was 42.16 %, whereas the survival rates of probiotics encapsulated in Alg and Alg-Qsg microcapsules were 86.40 % and 87.56 %, respectively, in the functional drink powders.	Jouki et al. (2021)
Persian Type culture collection (Tehran, Iran)	L. *plantarum (ATCC 8014, PTCC: 1058)*	Sodium alginate and Arabic gum	Extrusion	Rose petal jam	The amount of bacteria in the jam samples was more than the allowed limit (10^6 CFU/g). Probiotic and non-probiotic jam's physicochemical characteristics did not differ substantially; however, probiotic jams with microencapsulation received	Shoaei et al. (2022)

(*continued on next page*)

Table 2 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material	Encapsulation Technique	Developed Functional Food/ Beverage	Result/Effect	Reference
					better scores for acceptability and flavor.	
Christian Hans, Denmark	L. *acidophilus La5* and *Selenium*	Basil Seed Mucilage and Sodium Caseinate	Extrusion	Yogurt	The encapsulation efficiency of both selenium and L. acidophilus LA5 was 58.27 % when using basil seed mucilage and 41.73 % when using sodium caseinate. The yogurt samples that contained both free and encapsulated selenium had the lowest and greatest viscosities, respectively.	Shahmoradi et al. (2023)
Sigma Aldrich USA	*Lactobacillus reuteri CECT-925*	Sodium alginate	Extrusion	Guava juice	After storage, the viability of encapsulated probiotics in the control sample decreased from 7.68 to 1.96 log CFU/ml, whereas in the T1, T2, and T3 samples, they were 7.39, 7.7, and 7.87, respectively, and decreased to 5.97, 6.87, and 6.02 log CFU/ml. The outcomes showed that *Lactobacillus reuteri* viability in guava juice was maintained at >90 % when microencapsulated using sodium alginate and sesame oil.	Javed et al. (2023)
Persian Type culture collection (Tehran, Iran)	L. *acidophilus ATCC 4356*	Sodium alginate and galbanum gum	Extrusion	Probiotic tahini halva	Under heat stress, MLA (Microencapsulated LAB) and FLA (Free LAB) had survival rates of 50.13 % and 34.6 %, respectively. The cell viability loss for MLA and FLA, respectively, during preservation in Tahini halva was 3.25 log CFU g − 1 and 6.94 log CFU g − 1. After six hours of exposure to simulated gastrointestinal conditions, the amount of microcapsulated and free bacteria decreased by approximately 3.58 and 4.77 log CFU/g, respectively.	Sekhavatizadeh et al. (2023)
Probiotics (Centro Sperimentale del Latte, Italy) Mango	L. *acidophilus, Bifidobacterium lactis* and *Mango peel powder*	Sodium alginate	Extrusion	Ice cream	Mango peel powder improved the ice cream's viscosity and the viability of *Bifidobacterium lactis* and L. *acidophilus*, but it decreased its overrun and general acceptability. After 180 days of storage, this formulation demonstrated a probiotic population of $>10^6$ CFU/g, 72.97 % overrun, 292 mPA apparent viscosity, and good overall acceptance.	Hayayumi-Valdivia et al. (2021)
Food Science and Human Nutrition Dept. (NUTBRO group), Faculty of Veterinary Sciences, University of Murcia, Spain	*Lactobacillus rhamnosus*	Sodium alginate, skim milk, denaturated whey protein	Extrusion	Ice milk fortified with sweet cherry	L. rhamnosus exhibited the highest survival rate (94.94 %) when encapsulated in alginate-denatured whey protein and 90.04 % with alginate-skim milk. The addition of Sweet cherry powder (SCP) lowered the pH and melting rate of ice milk while increasing overflow. The TPC and AOA of ice milks increased with the addition of SCP, and these values reduced after storage.	Aly (2021)
Persian Type culture collection (Tehran, Iran)	*Lactobacillus reuteri (ATCC 23,272)*	Sodium alginate, Ferula assa-foetida and Zedo	Extrusion	Milk desert	Heat exposure at 72 °C for 5 mins resulted in 7.6 log reduction in free L. *reuteri*	Karimi et al. (2021)

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Table 2 (*continued*)

Source of Functional Ingredient	Core Material	Wall Material	Encapsulation Technique	Developed Functional Food/ Beverage	Result/Effect	Reference
		(Amygdalus scoparia) gum			viability, whereas only 2 log reduction observed with microencapsulated sample. In gastrointestinal condition, the survivability of free and microencapsulated bacteria were 18.8 % and 44.8 % respectively.	
Chr. Hansen, Horsholm, Denmark	*Lactobacillus delbrueckii* subsp. *Bulgaricus, Streptococcus Thermophiles*	Sodium alginate	Extrusion	Oat Yogurt	The microbial viability of the synbiotic microcapsules in all four varieties of yoghurts exceeded 10 log CFU/g. In addition, fermentation reduced the scent of oats, and the resulting products exhibited comparable qualities to conventional yoghurt. In addition, the amino acid analysis revealed the presence of 12 amino acids, with 4 being essential and 8 being non-essential.	Luca and Oroian (2022)
Probiotic (Dairy department, National Research Centre, Egypt)	*Bifidobacterium bifidum NRRL B-41,410, Bifidobacterium lactis BB12, Lactobacillus rhamno-sus NRRL B-442, Lactobacillus paracasei NRRL B-4564, Lactobacillus salivarius NBIMCC 1589* and *Lactobacil-lus acidophilus CH-2*	Sodium alginate and Sterilized guar gum	Extrusion	Probiotic Yogurt	The number of live cells in all formulations exceeded 7 log CFU/mL after 30 days of storage. The Green-Se-NRs concentration exhibited stronger antibacterial effects on Gram-negative organisms compared to Gram-positive strains. The least inhibition was observed against *S. aureus* (12 mm), while the largest inhibition was shown against *Y. enterocilitica, S. typhimurium, A. niger, E. coli*, and L. *monocytogenes*.	El-Sayed et al. (2022)
Dioscorea villosa L. leaves	*Kocuria flava Y4*	Sodium alginate, Psyllium and Persian gums	Extrusion	Orange juice	Highest EE (99.01 %) and probiotic cell viability (8.12 ± 0.077 CFU/mL) obtained following 5 weeks of storage at 4 °C. Anthocyanin concentrations increased in the probiotic juice containing K. *flava Y4* during the fortification period. The flavonoid concentration in orange juice containing probiotic K. flava Y4 encapsulated in a psyllium matrix is higher compared to other encapsulants such as PG and psyllium + PG, as well as the control.	Barik et al. (2023)

(RTS) pineapple beverages that were encapsulated with folic acid. Carotenoid, chlorophyll, and anthocyanin are the predominant pigments present in fruits and vegetables, contributing to their distinct colours. Microencapsulation enhances the durability of natural pigments by shielding them from various stressors encountered during manufacturing and storage (Agarry et al., 2022). The addition of spray-dried Guaraná peel extract, which is abundant in carotenoids, to oatmeal paste resulted in improved thermal stability and increased levels of beta-carotene throughout storage (Pinho et al., 2023). The pigments curcumin and anthocyanin were encapsulated by the processes of spray drying and freeze drying, resulting in enhanced thermal stability and prolonged shelf life (Buljeta et al., 2022). Yu et al. (2023) found that using thyme essential oil microcapsules (TEOMs) created by the emulsion method and subsequent freeze drying improved the sensory characteristics of mutton patties. Shamshad et al. (2023) conducted a study that demonstrated that incorporating black carrot anthocyanin into ice cream using microencapsulation improved the stability of the anthocyanin and positively affected the sensory attributes of the ice cream. Furthermore, the diameter of microcapsules plays a vital role in the sensory acceptability of food products. Microcapsules with a higher diameter than 1000 μm have a negative impact on the sensory attributes, and <1 μm diameter microcapsules are unstable (Shoaei et al., 2022). Microcapsules of Lactobacillus plantarum developed using sodium alginate and arabic gum had diameters ranging from 14.80 ± 1.23 to 35.02 ± 2.18 μm, which had no negative effect on the sensory attributes of food (Shoaei et al., 2022). According to Xia et al. (2020), for suitable microencapsulation of probiotic without affecting the sensory properties of food, microcapsules should have a diameter ranged from 40 to 100 μm. The large microcapsules exhibit poor dispersibility, unpleasant mouthfeel, coarse and gritty texture, the small microcapsules provide better mouthfeel and improved solubility (Jouki et al., 2022; Lim et al., 2024).

9. Effect of microencapsulation on bioaccessibility and bioavailability

Bioaccessibility refers to the proportion of a molecule consumed in a meal that is released from the food structure during digestion, making it available for absorption in the small intestine or transformation by the gut bacteria. Bioactivity refers to the functional properties of the substances that are absorbed or their metabolites within metabolic pathways, which result in physiological impacts on the body (Rodrigues et al., 2022). In contrast, bioavailability refers to the amount of substances that pass through the digestive system, become absorbed, and reach the intended location either in their original state or as metabolites, thus carrying out their biological action (Rodrigues et al., 2022). Microencapsulation enhances the ability of the body to absorb and use active chemicals by safeguarding them with protective coatings and regulating their release at the specific location in the digestive system (Grgić et al., 2020). According to Meira et al. (2023), in vitro analysis of mulberry leaf extract microcapsules, the bioaccessibility and bioavailability of flavonols increased significantly. Similarly, the encapsulation of coffee husk polyphenols positively favored the bioaccessibility of polyphenols (over 70 %) in the intestine and displayed quick gastrointestinal release (Silva et al., 2024). Microparticles of sheep whey hydrolysate obtained through spray-drying showed 65.7 % ABTS radical scavenging activity, 78.4 % iron chelating capacity, and 70.1 % inhibition of angiotensin I-converting enzyme that remained unaffected during simulated gastrointestinal conditions (Corrêa et al., 2023). In comparison to the free anthocyanin extract, the encapsulated one showed 10 % higher bioaccessibility during gastrointestinal digestion when spray dried with taro starch (Rosales et al., 2023). A similar phenomenon was observed with the spray-dried microcapsules of Laurus nobilis L. leaf polyphenolic extracts, where the bioaccessibility increased by nearly 50 % and 10 % for the gastric and intestinal phases, respectively, compared to the non-encapsulated extract (Dobroslavić et al., 2023).

10. Evolution of coating/wall materials in encapsulation

Wall material, or coating material, refers to the substances that safeguard the core materials (bioactive compounds, probiotics, etc.) from different stresses (mechanical stress, pH, acidity, water activity, temperature, etc.) during food processing, subsequent handling, as well as storage (Díaz et al., 2023; Coimbra et al., 2021). The choice of wall material depends on the source, type, encapsulation method, and characteristics of both the core and wall material. When commercial β-glucan powder was microencapsulated using maltodextrin, the spray drying technique was more effective with higher yield, TPC, and TFC values (44.38 ± 0.55 %, 3.40 ± 0.17 mg GAE/g, and 3.07 ± 0.29 mg QE/g), compared to the freeze drying method (22.97 ± 0.33 %, 3.01 ± 0.46 mg GAE/g, and 2.80 ± 0.36 mg QE/g) (Valková et al., 2022). Similarly, higher encapsulation efficiency (64.13 ± 0.59 % to 83.54 ± 0.57 % vs. 61.62 ± 0.24 % to 70.98 ± 0.87 %) and extended β-carotene half-life (336.02 vs. 102.44 h) were observed with the spray drying method in comparison to freeze drying when a composite matrix of pullulan and whey protein isolate was used as wall material (Drosou et al., 2024). In addition, saffron extract was microencapsulated using gelatin via electrospinning and freeze drying, where the electrospinning method had higher encapsulation efficiency, better crocin retention percentage, and longer half-life than the freeze drying method (Golpira et al., 2021). Encapsulation utilizes food-grade materials that are generally recognised as safe (GRAS), such as proteins (soy protein, whey protein, gelatine), carbohydrates (starch, cellulose, maltodextrin), lipids (wax, paraffin, phospholipids), and hydrocolloids (agar, pectin, alginate, chitosan, gum acacia) (Timilsena et al., 2020; Petkova et al., 2022). Considerable progress has been achieved in the field of coating or wall material to enhance the stability and efficacy of encapsulation in nanoparticles and microcapsules. In order to mitigate the premature reaction of baking powder, carnauba wax and beeswax were utilised as wall materials. The study conducted by Khosronia et al. (2023) found that carnauba wax was more effective than beeswax in delaying the chemical reaction.

When compared to traditional complex coacervation, the combination of complex coacervation and self-coated polydopamine (PDA) in bilayer capsules showed improved thermal stability, structural stability, and enhanced bioavailability of essential oils (Tian et al., 2024). The encapsulation process of Cornus officinalis flavonoid involved the combination of gelatine, soy protein isolate (SPI), whey protein isolate (WPI), and maltodextrin (MD) in a protein/MD ratio of 3:7. This resulted in the formation of microcapsules with the highest encapsulation efficiency (96.32–98.24 %) when compared to microcapsules made solely from individual proteins and maltodextrin (Zhao et al., 2022). Choi et al. (2023) found that the use of PLGA (Poly lactic-co-glycolic acid) polymeric micro-particles, generated using a batch microfluidic hybrid method, resulted in an improvement in encapsulation efficacy to approximately 85 %. These micro-particles contained several inner micro-chambers. A study conducted by Zhao et al. (2023) proposed that the synergistic impact of ultrasound and dietary fibre on transglutaminase-induced peanut protein gel improved the effectiveness of encapsulation, chemical stability, and gel production of lutein. Furthermore, the combination of acetylated wheat starch and sodium caseinate (in a 7:3 ratio) showed a higher emulsifying capacity compared to single wall material. This combination achieved a maximum encapsulation efficacy of 84.05 % (Liu et, al., 2023).

The study conducted by Xie et al. in 2023 found that Shikonin nanoparticles, when coated with sophorolipid and saponin, showed improved resistance to light and heat. Additionally, they exhibited higher bioavailability and a longer shelf life, with encapsulation efficiencies of 97.3 % and 97.6 % respectively. Kalajahi et al. (2023) found that the use of maltodextrin and enzymatically modified whey protein in the development of microencapsulated powder from Ginkgo biloba extract resulted in improved values of TPC, ABTS, and DPPH. Additionally, the partial enzymatic hydrolysis of whey proteins enhanced their surface activity and emulsifying properties, resulting in a lighter colour. In recent years, there has been a notable shift in the materials used for walls or coatings. This shift has resulted in improved stability of microcapsules or nanoparticles against heat and light, longer shelf life, and enhanced physicochemical and phytochemical qualities.

11. Challenges associated with microencapsulation

The primary objective of encapsulation is to safeguard the functional ingredient, such as bioactive chemicals, prebiotics, and probiotics, from the external environment or the components of the food matrix. Nevertheless, the execution of microencapsulation is accompanied by a considerable amount of issues. A significant obstacle in microencapsulation is determining the optimal combination of core and wall materials, together with the right encapsulation process. This factor greatly influences the size, shape, viscosity, and stability of microcapsules (Petkova et al., 2022; Raddatz et al., 2021). In order to have a greater encapsulation efficiency, it is crucial to have a synergistic interaction between the properties of the core and wall materials while forming microcapsules or nanoparticles. The precise administration of the active substance, leading to increased absorption and bioavailability (Huang et al., 2023). Moreover, the deterioration of polymers and the immunogenic reaction of the consumer's body to these polymers pose difficulties in microencapsulation (Marikar et al., 2022). In addition, every method of encapsulation has its own disadvantages. However, the most prevalent challenge is the difficulty of scaling up microencapsulation procedures from the laboratory to the industrial level. This process is complex and demanding, necessitating a substantial investment, which ultimately leads to an increase in the price of the final product (Choudhury et al., 2021; Yan et al., 2022). Regulating temperature is a significant obstacle in spray drying due to the harmful effects of elevated temperatures on bioactive compounds and probiotics (Guía et al., 2022). In contrast, freeze drying is significantly costlier than other drying methods since it takes a substantial amount of energy to maintain a vacuum. In addition, the capital, operating, and maintenance expenses associated with freeze drying are 4 - 8 times greater compared to other conventional drying processes, such as hot air drying (Waghmare et al., 2022).

An analogous issue arises in the process of fluidised bed coating, where there is a risk of bioactive chemicals undergoing oxidation as a result of the elevated temperature (Soni et al., 2023). In addition, the elevated viscosity of polymeric solutions poses challenges during the process of simple or co-extrusion microencapsulation (Sultana et al., 2022). Chemicals such as formaldehyde, glutaraldehyde, glyoxal, or epichlorohydrin are employed for chemical crosslinking during complex coacervation. However, this procedure is hindered by its toxicity to the human body, which is a significant drawback (Napiórkowska et al., 2022). Cittadini et al. (2022) found that the end result of complicated coacervation or coacervates demonstrated stability within a specific pH and ionic strength range. However, the disadvantages associated with using emulsion in food items stem from the restricted supply of food-grade lipophilic emulsifiers and the energy needed for shear (Mudrić et al., 2019). Electrospinning, also known as electrospraying, is commonly recommended for the encapsulation of probiotics and bioactive compounds since the process does not involve extreme conditions, e.g., high temperature, low pH, etc.; however, the major challenges with this method are industrial scale-up, process optimization, and time consuming, high voltage power supply, etc. (Vivek et al., 2023; Omer et al., 2021). Additionally, the usage of highly concentrated solutions and volatile solvents makes the process harder to control and overall decreases the accuracy and reproducibility of the process (Vass et al., 2020). A significant drawback of SCF-assisted microencapsulation is the polymer's solubility, which starts to plasticize upon contact with the supercritical fluid. Additionally, the process incurs considerable equipment costs (Park et al., 2021). Furthermore, the challenges commonly associated with ionic gelation and fluidised bed coating include uneven particle sizes and shapes, expensive equipment costs, and difficulties in large-scale production (Vivek et al., 2023; Koop et al., 2022).

12. Feasible solutions for challenges associated with microencapsulation

In recent times, synthetic zwitterionic polymers, such as polyoxazolines, have been employed to address the problems associated with the charges of core materials. These polymers are electrically neutral but possess both cationic and anionic properties. Additionally, they do not provoke an immune response (Sanchez et, al., 2020; Hoang et, al., 2020). Furthermore, the utilisation of diverse wall materials and an increased core to wall ratio can improve the effectiveness of encapsulation and the availability of bioactive chemicals (Garzón et al., 2023). In order to minimise heat losses during the process of spray drying, one can employ a nano spray dryer. This type of dryer is particularly suitable for heat-sensitive products as it utilises laminar air flow instead of the turbulent flow found in traditional dryers. As a result, the residence time of the product in the heating chamber is reduced, leading to decreased heat loss (Piñón et al., 2020). Spray-freeze drying is an innovative technology that can be implemented in the food sector to minimise the degradation of functional ingredients. In addition, the technique of spray drying can be utilised in conjunction with freeze drying or vacuum drying to enhance the survival rate of probiotic cells (Ermis et al., 2022).

Hot-melt extrusion can decrease the viscosity of polymeric solutions by utilising heat to lower the viscosity of the solution. This process also enhances the solubility of wall materials containing active ingredients (Sultana et al., 2022). Instead of using synthetic chemicals that can be harmful, natural crosslinking agents like citric acid, vanillin, tannic acid, genipin, and epigallocatechin gallate can be employed in the complex coacervation method. Similarly, natural emulsifiers such as gypenosides, soy proteins, and pea proteins can be utilised to address this issue (Francisco et al., 2020; Teixe et, al.,2023; Sapula et al., 2023). Furthermore, the issue of the compatibility of bioactive substances with solvents in the rapid expansion supercritical solution (RESS) encapsulation method can be resolved by employing the supercritical anti-solvent (SAS) process encapsulation. This method involves the use of supercritical CO_2 as an anti-solvent, which not only enhances the solubility of the active ingredients but also addresses the problem of miscibility (Klet,tenhammer et, al., 2020; Soh et, al., 2019). In summary, there is a growing need for more study in the food processing business on natural coating materials, functional ingredients, and the widespread implementation of encapsulating techniques.

13. Emerging market of functional food

In recent times, there has been a significant increase in consumer interest towards functional foods and beverages that contain bioactive chemicals or probiotics. This interest has been particularly evident in the aftermath of the COVID-19 epidemic. The primary cause of this occurrence is the presence of supplementary nutrients that serve specialised tasks beyond simply providing energy. The demand for functional beverages is expanding and projected to continue growing, which accounts for the growing consumer interest in products that offer extra health advantages in addition to providing nutrients (Gupta et al., 2023). The global market size of functional foods was approximately 129.39 billion USD in 2015 and increased to around 353 billion USD in 2019 (Nath et al., 2023). According to Grand View Research (2000), the value was USD 280.7 billion in 2021 and is projected to increase to USD 586.1 billion in 2030, with a compound annual growth rate of 8.5 %. Probiotic-containing functional foods make up around 60 % of all functional foods, and this sector is steadily growing (Ballini et al., 2023). Nevertheless, the main obstacles impeding the expansion of this burgeoning business are the restrictions particular to each country and the requirement for substantiating health claims (Bansal et al., 2023). Companies such as Royal DSM, Anabio Technologies, PepsiCo, Washington H. Soul Pattinson, Commonwealth Scientific and Industrial Research Organisation, Advanced BioNutrition, etc. have obtained several patents for the microencapsulation of proteins. Meanwhile, Progel, Chr. Hansen, PepsiCo, and Colarome are well-known for their various uses in the field of microencapsulation (GlobalData, 2023). As consumers become more proactive about their health, it is expected that the food processing sectors will continue to innovate in order to suit the health demands and preferences of customers by introducing a wider range of food products.

14. Future perspective

Active ingredients, such as bioactive compounds, prebiotics, and probiotics, have a significant impact on extending the shelf life and improving the nutritional content of food. Additionally, these ingredients can contribute to overall health improvement. Microencapsulation enhances the stability of the food matrix, protects the functional ingredients from the severe conditions of the stomach, and enables controlled release at the desired location. In recent years, there has been a substantial amount of study conducted on microencapsulation. However, there is still considerable room for additional investigation and discovery in this field. Priority should be given to supporting research on co-encapsulation, which has the potential to provide not just nutrients but also serve various purposes such as illness prevention and improvement of gut health. The expanding need for functional food and beverages, along with the rising health consciousness among individuals, highlights the necessity for these innovations. It is essential for the scientific community to conduct further study on microencapsulation in order to solve its limitations and fully explore its potential in the development of functional foods and beverages.

15. Conclusion

Food processing businesses are incorporating functional meals and drinks into the market in response to consumers' emphasis on the health advantages they offer. Currently, microencapsulation is extensively used as an innovative approach in creating advantageous foods by including functional substances in the form of capsules or microparticles. The article showcased recent advancements in functional foods and beverages, specifically focusing on the incorporation of bioactive chemicals and probiotics as microcapsules or nanocapsules in the final products. Furthermore, the article also elucidated the indispensability of microencapsulation, the methodologies employed in encapsulation, the impact of encapsulation on the active constituents and resultant food products, the progression of wall materials over time, the burgeoning market of functional foods, and other related aspects. Efficiently delivering bioactive ingredients to the desired location in the gastrointestinal tract is a major challenge. Microencapsulation can be a valuable technique to enhance the stability, bioavailability, and durability of these functional ingredients. Additionally, it can greatly improve their organoleptic and sensory properties. Utilising innovative wall materials derived from natural substances or waste food byproducts can boost the performance of microcapsules. The use of functional foods that include active chemicals in microencapsulated form has shown several benefits, such as reducing the risk of disease, improving gastrointestinal health, and enhancing the body's immune system. Numerous studies have provided evidence of microencapsulation utilising various wall materials. To facilitate the use of microencapsulation in the food business, additional study is necessary.

List of abbreviations

TPC: total phenolic content; TFC: total flavonoid content; EE: encapsulation efficiency; LAB: lactic acid bacteria; CFU: colony forming unit; DPPH: 2,2-diphenyl-1-picrylhydrazyl.

Ethics declarations

No human or animal participants were involved in this study.

CRediT authorship contribution statement

Dwip Das Emon: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **MD. Sakibul Islam:** Writing – original draft. **Md. Anisur Rahman Mazumder:** Writing – review & editing. **Mohammad Gulzarul Aziz:** Writing – review & editing, Supervision. **Md. Saydar Rahman:** Writing – review & editing, Writing – original draft.

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.

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Data availability

Data will be made available on request.

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