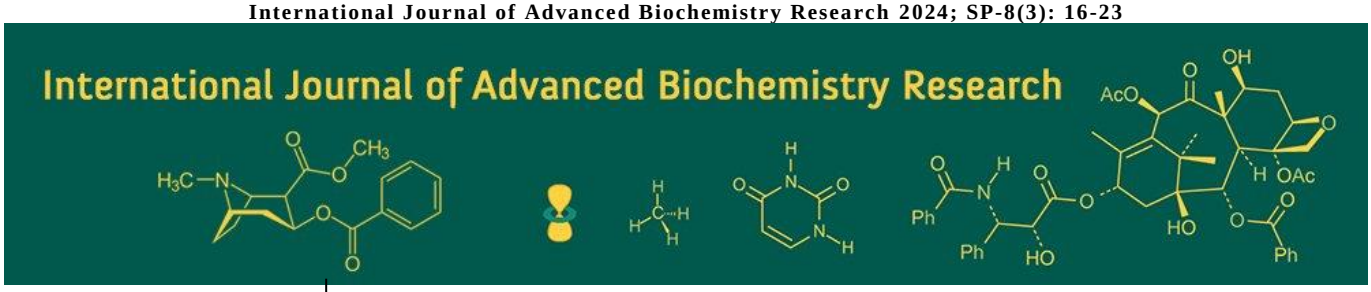

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Encapsulation techniques for enhancing the stability and bioavailability of food: A review

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Abstract
The food industry uses encapsulation for a variety of purposes, such as concealing an unwanted colour, flavour, or taste, preserving bio actives, adding more functional and nutritional elements, and releasing the encapsulated components at a specified location at a predetermined time and pace. Although the pharmaceutical sector has highly developed knowledge of microencapsulation, more comprehension is needed to fully benefit the food industry through the encapsulation technique. The selection of wall material and method of encapsulation is critical for the production of effective encapsulated products, which is mainly influenced by the product's intended use as well as the processing conditions. The several encapsulation techniques and their use in the encapsulation of bioactive food ingredients were emphasised in this review. This review focuses on the major methods of encapsulation, the variety of wall materials suitable for encapsulation and the performance of food encapsulation.

Keywords: Encapsulation, food ingredients, wall material, encapsulation techniques, bioactive.

Introduction
Physiologically active compounds with additional health advantages beyond their nutritional value are known as bioactive dietary components. Some examples of bioactive compounds are proteins, lipids, minerals, vitamins, antioxidants, probiotic bacteria, and phytochemicals (Augustin and Sanguansri, 2007) [3]. Because of their great sensitivity, the food industry finds it challenging to incorporate these bioactives into food without changing their nutritional value. According to Schrooyen, Meer, and Kruif (2001) [47] and Pegg and Shahidi (2007) [41], food ingredients that are sensitive can be effectively protected using encapsulation technology, which also produces innovative food compositions that have higher quality standards. The technique of coating or trapping one material or mixture of ingredients inside another material or system is known as encapsulation. The term core or active material refers to the substance that will be encapsulated. It is sometimes also referred to as a payload, internal phase, or fill. Whereas, the substance that encloses the active component is referred to as the matrix, wall or coating material, capsule, membrane, or carrier material (Barros *et al*., 2018) [4]. Microencapsulation technology has gained a lot of attention in the food industry due to its ability to protect unstable bioactive components, add new functionalities to food products, and deliver the encapsulated substances at a desired location and rate. The microencapsulation process has various applications (Desai and Park, 2005) [12], such as controlling the release of the core material over time, modifying the properties of the original material for better handling, preserving the quality of the core material and reducing its evaporation, masking the unpleasant taste or flavour of the core ingredient, and separating the components of the mixture that would otherwise react. Extending the product's shelf life and raising the engineered product's general acceptability are the ultimate goals of the encapsulation technique (Dziubla *et al*., 2008) [15]. Typically, bioactive and sensitive food ingredients, such as vitamins, enzymes, highly unsaturated edible oils (like fish oils), or various tastes to increase their shelf life and cover up undesirable flavours, are encapsulated in food-grade proteins and polysaccharides (Weinbreck *et al*., 2004) [60]. The functional as well as the structural attributes of shell matrices, along with their core compatibility, determine the effectiveness and acceptability of encapsulated products developed in the food industry.

Some of the factors to be taken into account during wall selection are functional attributes like solubility, interfacial properties, gelling capacity, and economic considerations like cost and availability. Similarly, the most crucial component to take into account is the wall's capability to give the final product the appropriate functional attributes (Timilsena *et al*., 2020) [52]. The food industry uses a variety of proteins and polysaccharides extensively. Among them is gelatin, an animal protein that is often obtained from fish or mammals. It has been employed as a wall material in numerous encapsulated foods in the majority of both commercial and academic applications (Karim and Bhat, 2008) [29].

Figure 1 illustrates the two primary types of encapsulates: Matrix type and reservoir type (Zuidam and Shimoni, 2010) [65]. An inactive barrier surrounds the reservoir-type active agents, which form a core. It is sometimes referred to as mono-core, single-core, or the core-shell type. Within an inert polymer, the matrix-type active component dissolves or is dispersed.

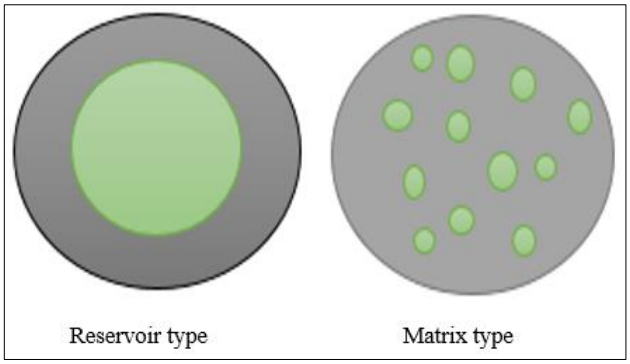

Fig 1: Types of encapsulates

Depending on the size of the encapsulated substance, encapsulation can be classified into three types: Microencapsulation, macroencapsulation, and nano-capsulation. Microencapsulation refers to the process of forming capsules with diameters ranging from 0.2 to 5000 micro meters (µm). Macrocapsulation refers to the process of forming capsules with diameters larger than 5000 µm. Nano-capsulation refers to the process of forming capsules with diameters smaller than 0.2 µm (Jeyakumari *et al*., 2016; Choudhury *et al*., 2021) [27, 10]

Encapsulation Techniques

Microcapsules can be prepared in a number of ways, such as fluidized bed coating, extrusion, co-crystallization, interfacial polymerization, organic phase separation, molecular inclusion, coacervation, liposome-entrapment, freeze drying, spray drying, and spray chilling (Uhlemann *et al*., 2002) [56]. There are two types of microencapsulation processes: Chemical and physical. Physical techniques include coextrusion, rotary disc atomization, fluid bed coating, and spray drying, spray chilling, and pan coating. Phase separation, interfacial polymerization, and simple and sophisticated coacervation are all parts of the chemical process (Gibbs *et al*., 1999; Zuidam and Heinrich, 2010) [21, 64].

Spray Drying

Since the late 1950s, the food industry has been producing vast quantities of material using a well-established technology called spray drying. Spray drying has a comparative advantage over other encapsulation techniques, making it an effective and frequently employed technique for encapsulation in the food and pharmaceutical industries. In addition to being highly automated and economical, it generates high-quality products. The ability of spray drying to handle a variety of materials and generate a fairly dried item with predetermined qualities is one of its most notable advantages (Haque *et al*., 2015) [23]. Using this technique, the encapsulating material and active component are thoroughly mixed to create an emulsion, solution, or suspension. Typically, the combination of hydrophilic shell and lipophilic core components results in an emulsion. The shell material is typically composed of a polysaccharide, a protein, a combination of both or a lipid. Typically, the necessary amounts of both the shell and core ingredients are mixed to create a coarse emulsion. Single- or two-stage homogenization, which produces a fine emulsion, usually comes next. In a drying chamber, this tiny emulsion is atomized at a predetermined flow rate. Water is removed from the emulsion using thermal energy, producing a coated, dry active component that is more resilient to environmental stressors such as light, oxygen, and moisture (Petrović *et al*., 2007) [42]. This technique is relatively easy to use, quick, and scalable, and the necessary equipment is widely accessible. Compared to alternative techniques like freeze drying, the spray-drying method is 30-50 times less expensive. It is possible to utilise hydrophilic and hydrophobic polymers. The product sticks on the wall of the drying chamber, resulting in the loss of a significant portion. The encapsulation processing using spray drying techniques with different wall materials needs to be optimised.

Freeze drying

Although spray drying is more appealing due to its shorter processing times and lower energy usage, freeze drying is acknowledged as the optimum technology for producing high-quality dried food items (Schwegman, 2009) [48]. The advantages of using freeze drying for the micro-encapsulation approach over other drying methods have been demonstrated by earlier research (Choi *et al*., 2007; Chen *et al*., 2013) [9, 8]. Freeze drying is particularly appealing to dry heat-sensitive as well as bioactive components since it prevents oxidation and chemical alteration of the goods by operating under a vacuum condition and at temperatures below room temperature. The process for producing a freeze-dried product involves combining the core material with the coating solution, freezing the resulting emulsion for 24 hours at -20°C, and then freeze-drying it for around 48 hours at -90°C to -40°C under pressure of 0.120 milibar. Once the product has dried completely, it is removed and quickly pulverised with a mortar and pestle. (Chen *et al*., 2013) [8]. Products that have been freeze-dried have good oxidation resistance. Additionally, the microcapsule shape is preserved by freeze-drying. Compared to spray-dried products, the yield from freeze-drying is higher. Freeze drying results in an open porous structure, a lengthy processing time, and high energy consumption. Freeze-drying can cost approximately 30-50 times as much as spray-drying.

Extrusion

A practical technique for creating extremely densely packed items is extrusion-based encapsulation. As the cylinder head

spins, the bioactive cores and coating agent can be injected separately through a hole that is centred on the outside of the cylinder head. Coating material passes through one tube and core material passes through the central portion of the tube. The shell matrix and core are co-extruded through the concentric orifices while the head rotates since the device is attached to a revolving shaft. During this process, centrifugal force drives the rod outward, breaking it into tiny fragments. Because of the surface activity of the core, the covering material moves quickly along its surface, completely surrounding the core material (Chen *et al*., 2013) [8]. Gelatin, sodium alginate, carrageenan, starches, cellulose derivatives, gum acacia, lipids and fatty acids, waxes, and polyethylene glycol are among the wall materials utilised in the extrusion process of encapsulation (Schlameus, 1995; Saleeb and Arora, 1995) [46]. Lo1 995). Duct shelf life (extruded flavour oils, for example, 5 years). Eyears). Produces large particles. The selection of coating materials for extrusion is extremely small.

Fluidized bed coating

According to Anal and Singh (2007) [1], the procedure involves preparing the coating solution, fluidizing the core particles, and then coating the core particles with the coating solutions. Major ingredients used in fluidized bed coating as walls are lipids, waxes, and water-insoluble and soluble polymers. At a particular temperature, the coating solution is sprayed over the particles or granules. Since applying a high temperature is not necessary, this procedure effectively conserves both time and energy. To improve stability, this technique is frequently applied to the mostly enclosed products as a secondary coating. For example, fish oil encapsulated in caseinate was coated with a secondary coating made of corn starch (Skelbaek and Andersen, 1994) [51]. Solid particles are coated uniformly with coating material using fluidized bed coating. One important consideration is air temperature and stream control. Droplets must be much smaller than the core in order to obtain a uniform coating.

Coacervation

A homogeneous polymer solution can separate into two phases: The coacervate, which is high in polymers, and the equilibrium phase, which is low in polymers. This process is called coacervation. (Jyothi *et al*., 2010) [28]. This was the first encapsulation method for industrial microencapsulated product manufacture that was documented. The two primary types of coacervation are simple and complex coacervations. With the exception of how phase separation is accomplished, the process of microcapsule creation is the same for both procedures. In complex coacervation, two polymers with opposite charges interact with each other. In simple coacervation, phase separation is achieved by adding a dissolution agent. Basic processes in complex coacervation include: 1) preparing two polymer solutions; 2) mixing lipophilic core and polymer solutions to generate an emulsion; and 3) mixing additional polymer solutions. 4) Changing the temperature or pH to induce the two immiscible phases to separate; 5) coating the core with coacervates; and 6) heating or cross-linking the coating to make it more stiff. With this technique, particles between 1 and 100µm in size can be produced. Furthermore, it provides an exceptionally high payload (up to 60% for multi-core encapsulation and as much as 90% for single-core). Typically, the shell components in complex coacervation are selected to be proteins and carbohydrates (gum). It enables encapsulation to be water-soluble because it lacks an aqueous continuous phase. According to Zhang *et al*. (2009) [63] and Timilsena *et al*. (2019) [53], a significant drawback of the sophisticated coacervation-based micro-encapsulation technique is the stability of coacervates within a very limited pH and ionic strength spectrum. This restricts the variety of polymers that can be utilised in intricate coacervation processes as shell material. The exact solute concentration used to create complicated coacervates in solution is another drawback.

Spray chilling or Spray cooling

The process of hardening an atomized liquid spray into particles is called spray chilling. By atomizing a combination of the wall and core into the cooled or chilled air, these approaches solidify the wall surrounding the core (Oxley, 2012) [40]. Mass transfer is not required for spray-chilling, unlike spray-drying (the evaporation of water). Consequently, the process is more energy-efficient. The wall material utilised is usually a variety of plant oils or their derivatives, such as fat and stearin, which have melting temperatures between 45°C and 72°C (Favaro-Trindade *et al*., 2015) [19]. Vegetable oil that has been hydrogenated or fractionated and has a melting point between 32°C and 42°C is commonly used as the coating material in spray-chilling. It is a more energy-efficient and less costly process. The major disadvantage is that spray-chilling and spray-cooling create lipid coatings on microcapsules that make them insoluble in water. According to Desai and Park (2005) [12], this encapsulating procedure is improper.

Liposome Entrapment

In the nutraceutical and medicine delivery industries, liposome entrapment has gained a lot of popularity recently. A phospholipid-based membrane encloses the whole aqueous phase of liposomes (Anandharamakrishnan and Ishwarya, 2015) [2]. According to Shade (2016) [49], they have been used to administer hormones, vitamins, enzymes, vaccinations, and other delicate neutraceuticals. Usually, one or more lipid layers envelop the unstable core of liposome-based encapsulated products. The end product is excellent in quality and quite stable. Large unilamellar vesicles are thought to be the most suitable liposomes among the other varieties utilised to encapsulate food ingredients because of their improved storage durability, ease of manufacture, and high encapsulation efficiency. Not to mention, in applications with significant water activity, the liposome-based microencapsulation technique gives water-soluble materials more stability. A method for maintaining vitamin C in the liposomes' aqueous inner core has been devised (Kirby *et al*., 1991) [36]. Encapsulating vitamin C significantly extended its shelf life (up to two months). The encapsulated substance can be delivered using liposomes at a precise and determined temperature. One benefit of liposome entrapment is the targeted distribution of its material at a chosen location under predetermined circumstances (Kheadr *et al*., 2000) [32]. The primary problem with this approach is related to the micro-encapsulation process's commercial scale, as it has a low yield (Desai and Park, 2005) [12].

Inclusion Complexation

There is just one molecular encapsulating technique, and that is inclusion complexation. Cyclodextrins, mainly B-cyclodextrin, which has seven glucose units connected 1-4, are used to achieve this. Its outside surface is hydrophilic and its centre is hollow and hydrophobic. Water molecules retained in the centre of the cyclodextrin will be replaced by less polar molecules when in solution. According to Reich (1995), this compound will become less soluble and will precipitate out of solution. The most successful technique for preserving aromas among all currently used microencapsulation techniques is the molecular incorporation of flavour volatiles into β-cyclodextrin molecules. This method of encapsulating flavours can offer enhanced resistance against volatilization during extrusion (Timilsena *et al*., 2020) [52]. In the food business, cyclodextrin is rarely used due to its high cost (Yuliani *et al*., 2004) [62]. According to Jeyakumari *et al*. (2016) [27], just a small amount of flavour (9%-14%) can be added.

Wall material used for encapsulation

The choice of wall material is crucial. According to Venugopalan *et al*. (2021) [57], the wall material of an encapsulated material is crucial for its flowability, packing, encapsulation effectiveness, and chemical stability.

Table 1: Wall material used for encapsulating bioactive compounds

Protein	Carbohydrate	Lipid
a. Whey protein b. Soy protein c. Gelatin d. Egg white powder e. Albumin f. Zein g. caesin	a. Gum Arabic b. Maltodextrin c. Carragenan d. Starch and cellulose including their derivatives e. Chitosan f. Alginate g. Dextran h. Flax and chia seed gum	a. Vegetable oil b. Camauba wax c. Bee wax d. Palm stearin e. Hydrogenated fat

Choosing the right wall material for a specific application depends on specific factors. When spray drying or electro spraying, for example, the wall materials should dissolve in water and generate a low-viscosity solution that may be pumped if needed. In addition, the wall materials should cause a powder to form that possesses the necessary properties of stickiness, dispersibility, solubility, and flowability, in addition to the capacity to prevent unwanted chemical reactions and gas diffusion. Table 1 provides a summary of some of the wall materials that are most frequently used in the food encapsulation industry.

Protein

Proteins are excellent encapsulating materials with extensive uses in the food industry due to their superior physicochemical and functional features, such as their ability to form gels, films, and emulsify substances (Li *et al*., 1998; Bylaite *et al*., 2001) [38, 6]. The fact that some people are allergic to proteins is one of the main drawbacks of using them as encapsulants. Many people have reported that soy proteins, wheat proteins (including gluten), and peanut proteins are extremely allergenic. This restricts their use and ensures that the maker declares their presence in the meals that are intended for them on the label. Furthermore, proteins are susceptible to structural alterations, and several factors, such as pH, ionic strength, and solution temperature, significantly impact their efficacy as wall materials (McClements, 2004; Damodaran, 2005) [39, 11]. But mixing these proteins with other substances-more specifically, biopolymers based on carbohydrates-like lactose, maltodextrin, and solid corn syrup has been shown to be a useful way to reduce the impact of the environment on their ability to serve as encapsulants (Sheu and Rosenberg, 1998; Keogh *et al*., 2001) [50, 31].

Carbohydrate

Carbohydrates are used as wall materials to encapsulate a variety of food materials, containing vitamins, proteins and bioactive peptides, enzymes, taste, and oxygen-sensitive and PUFA-rich oil, due to their widespread availability, bland flavour, and excellent core protection ability (King *et al*., 1976; Drusch *et al*., 2006; Jafari *et al*., 2008) [35, 14, 24]. According to research, modified starches give exciting emulsion stability (Trubiano and Lacourse, 1998) [55] and exhibit superior protection compared to native and waxy starch (Jeon *et al*., 2003) [26]. It has been demonstrated that gum acacia (Arabic) is the best wall material for encasing volatile compounds, including flavours, during the spray-drying process (Bertolini *et al*., 2001; Gascon *et al*., 2001; Fang *et al*., 2005) [5, 20, 17]. Chia and flax seed gums have been used to make complex coacervates with chia and flax seed proteins, respectively, in order to encapsulate PUFA-rich oils (Kaushik *et al*., 2016; Timilsena *et al*., 2016) [30, 54]. Gums and starches without protein are also appropriate for making hypoallergenic goods aimed at individuals with protein allergies.

Lipid

Water does not dissolve lipids since they are hydrophobic substances. As a result, they are frequently employed to encapsulate hydrophilic materials. The capacity of various lipids, such as phospholipids, waxes, fatty acids, and glycerides, to encapsulate dietary actives has been investigated (Wandrey *et al*., 2010) [59]. Lipid-based encapsulation technology is a very new and developing industry, but it's gaining a lot of traction as a way to provide bioactive ingredients for food, medicine, and nutraceuticals. According to Fathi *et al*. (2012) [18], there are four typical forms of lipid delivery systems: Solid lipid nanoparticles, nano-emulsions, nanoliposomes, and nanostructured lipid carriers.

Applications of encapsulation

The bioactive component has low stability, but encapsulation produces a powder that is more resistant to environmental influences. These bioactive substances release more quickly when encapsulated. A viable method for boosting the stability of probiotics, polyphenols, carotenoids, pigments, fatty acids, phytosterols, vitamins,

minerals, and bioactive peptides is encapsulation. The following discusses the various encapsulation techniques utilised for bioactive substances:

A. Encapsulation of fish oil

Fish oil is a significant dietary source of polyunsaturated fatty acids (PUFAs), particularly docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are thought to have particularly strong biological activity and health benefits (Jedrusek-Golinska *et al*., 2020) [25]. It has been proven necessary to regularly consume high enough amounts of PUFAs to lower the prevalence of numerous illnesses and chronic diseases (Venugopalan *et al*., 2021) [57]. Due to their oxidative breakdown susceptibility, these unsaturated fatty acids may generate unwanted odours (also known as "Rancidity"), which could decrease consumer approval (Khoshnoudi-Nia *et al*., 2020) [33]. Furthermore, if ingested often over an extended period of time, certain lipid oxidation reaction products show toxicity and may cause long-term health issues (Grootveld *et al*., 2020) [22]. Modern encapsulation techniques, which transform the omega-3 PUFAs into colloidal forms before incorporating them into food and beverages, may frequently overcome these difficulties. To make handling, storage, and use of these colloid materials easier and to boost their resistance to oxidation, they can be ground into a powder for specific uses.

Table 2: Different techniques and wall/coating materials for encapsulation of omega-3 PUFAs from fish oil

Encapsulation Technique	Wall/coating materials	Reference
Freeze Drying	Gum Arabic, sodium caseinate, egg-white powder, carbohydrate, maltodextrin and lactose	Vijeth *et al*., 2019; Ezhilarasi *et al*., 2013 [58, 16]
Complex coacervation	Gum arabic-gelatin, cross-linked with transglutaminase.	Díaz-Montes *et al*., 2023 [13]
Simple coacervation	Hydroxypropyl methylcellulose	Jeyakumari *et al*., 2016 [27]
Spray drying	Gum Arabic, maltodextrin, gelatin, sodium caseinate, whey protein isolate, whey protein concentrate, soy protein isolate, lactose etc.	Jeyakumari *et al*., 2016 [27]

B. Encapsulation of bioactive peptides and protein hydrolysates

In contrast to other food bioactive components like vitamins or polyphenols, bioactive food protein hydrolysates and peptides have a highly diverse chemical composition. The main reason bioactive peptides are encapsulated is to cover up the bitter taste that occurs when taste receptors are exposed to hydrophobic residues of amino acids that are produced during the breakdown of proteins. Reducing hygroscopicity is another important goal of encapsulation, which helps to maintain the texture as well as storage stability of peptides and protein hydro lysates. Peptide encapsulation and protein hydrolysates are carried out via lipid, polysaccharide, and protein-based carrier systems. While lipid-based carriers aim to enhance the bioavailability as well as biostability of encapsulated peptides, the protein hydrolysates' bitter taste is covered up and their hygroscopicity is decreased by the employment of polysaccharide and protein-based carriers. One of the main challenges is that peptides are easily broken down by the gastrointestinal tract (GIT), potentially resulting in the loss of structural and functional integrity. The term "bioavailability" refers to the amount of the bioactive substance that is absorbed, remains unaltered, and enters the bloodstream. Before bioactive peptides enter the systemic circulation, they are known to be subjected to the activity of at least 40 distinct enzymes when consumed orally. According to Kim and Baianu (1991) [34], A number of experiments have shown that the majority of bioactive peptides produced from dietary proteins that have more than two or three amino acid residues are not able to endure enzymatic digestion in the mouth. In order to convert *in vitro* activities into bioactivities in humans, bioactive peptides must be protected. Encapsulation has therefore emerged as a useful method for fish-derived bioactive peptides.

C. Encapsulation of probiotic microorganism

Live microorganisms known as probiotics aid their host, which can be either an animal or a human, physiologically. Particularly in dairy products, these bioactive components have led the way in the creation of functional foods (Sanders, 2003) [44]. Probiotics have been microencapsulated using five different techniques: Spray-drying, extrusion, emulsion, spray-chilling (gel-particle technology), and spray-coating (fluid bed coating). Probiotics are most frequently microencapsulated using spray-coating and gel-particle technologies (Champagne and Patrick, 2007) [7]. Probiotics can be sold commercially as meals, pharmaceuticals, or nutritional supplements. According to international criteria, a product must include at least 106-8 live probiotic bacteria cells/g of product when it is marketed in order to be classified as a "probiotic product." Many products fall short of this need when consumed since probiotic cells die while being stored, even in a refrigerator. It has been demonstrated that microencapsulation increases the ability of probiotics to survive in a variety of food products (Sbehat *et al*., 2022) [45]. Encapsulation protects the small intestine from bile salt accumulation and environmental variables that may cause harm.

D. Encapsulation of vitamins and minerals

Microencapsulation is a method of encapsulating vitamins that are water-soluble (ascorbic acid) and fat-soluble (A, D, E, and K), (Wilson and Shah, 2007) [61]. One of the most essential components for human health is iron, and insufficient consumption of this element might result in an iron deficiency. Iron fortification of food is one strategy to avert this issue.

However, interactions between iron and dietary elements, including tannins, phytates, and polyphenols, impact iron's bioavailability. Additionally, iron catalyses the oxidative processes in vitamins, amino acids, and fatty acids, which causes the food to lose its sensory qualities and nutritional value. These reactions can be avoided by using microencapsulation.

Table 3: Application of encapsulation of some other bioactive components

Bioactive components encapsulated	Purpose to encapsulate
Flavoring agents	To convert liquid flavourings into more manageable, stable, and free-flowing powders
Acidulants	Used to aid in the flavour and colour development. Examples are baking soda used in confectionaries.
Colorants	In addition to being easier to work with, encapsulated colours provide better stability against oxidation, and control over stratification from dry blends.
Sweetners	In order to prolong the feeling of sweetness, enhance flowability, and decrease hygroscopicity

Future Perspective

For over sixty years, encapsulation technology has been employed in diverse industries. Since its initial commercial use in 1950, there have been numerous scientific and practical developments related to this approach. With its ability to mask unwanted flavour, colour, and taste, control the release of bioactive ingredients, and extend the shelf-life of active ingredients, it is becoming more and more popular in the pharmaceutical, nutraceutical, and food industries. New bioactive encapsulation techniques are being investigated, and research is progressing to enhance the procedure and product attributes. To meet customer expectations and other technical requirements while lowering manufacturing costs, novel food-grade encapsulants are being investigated. Although the spray drying technique of microencapsulation is currently widely employed in many commercial applications, more sophisticated techniques, such as complex coacervation, have recently attracted more interest. It has been claimed that complex coacervation technology yields a good product and that the resulting product is stable for a long time, even at very high payloads (up to 99%). It also produces goods at the lowest cost per unit. The main drawback of this approach is the scarcity of shell materials. The only protein that has been effectively utilised on a commercial basis to date is gelatine. Further research is required to determine the efficacy of bioactivity in agricultural applications and bioavailability for food applications. However, encapsulation into a polymeric matrix is a useful way to preserve bioactive chemicals and increase their application in agriculture and food.

Conclusion

Encapsulating bioactive food ingredients is a smart way to help create more effective and superior functional food designs. The market for fish nutrients as alternatives to pharmaceuticals and nutraceuticals will grow as a result, and studies on bioactive nutrients will advance. The process of microencapsulation effectively shields the active ingredient in food against oxidation, evaporation, or migration. In order to create better products, the development of superior functional food ingredients with better attributes and functional properties is essential. The selection of coating material and the microencapsulation process method are critical factors in the production of successful encapsulated products. The food industry has not yet adopted microencapsulation technology as a standard tool for creating innovative and healthy food items. This can be accomplished by using a multidisciplinary research strategy and taking into account the demands and limitations of the sector.

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