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REVIEW

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Revolutionizing fruit juice: exploring encapsulation techniques for bioactive compounds and their impact on nutrition, flavour and shelf life

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Abstract

Bioactive compounds in food and beverages, including fruit juices, are susceptible to degradation or oxidation during processing and storage. This vulnerability can lead to a reduction in nutritional value and overall quality of the products. The objective of this research is to explore the potential of encapsulation techniques in preserving and enhancing the nutritional value of fruit juices. The encapsulation of natural compounds, enzymes, and probiotics is seen as a promising approach to fortifying fruit juices, improving their preservation and processing of these encapsulated natural compounds as additives in food packaging. The study involves a comprehensive review of various encapsulation techniques and materials used for encapsulating bioactive compounds. It also investigates the current applications of encapsulated natural products in the preservation of food and beverages. The encapsulation of bioactive compounds has shown the potential in improving the nutritional value and functional properties of fruit juice products and foods. It has also been found to enhance the preservation and processing of these products, contributing to their overall quality and safety. Encapsulation techniques offer a promising avenue for revolutionizing the fruit juice industry by enhancing the nutritional value and shelf life of products. They also present an opportunity for the development of more functional food products. Despite the promising results, more research is needed to fully understand the mechanisms of encapsulation, determine the optimal conditions for encapsulating different ingredients, and assess the effects of encapsulation on the quality and safety of fruit juices. Future studies should focus on these areas to further advance the application of encapsulation techniques in the food and beverage industry.

Keywords Encapsulation, Bioactive compounds, Fruit juices, Food packaging, Nutraceuticals

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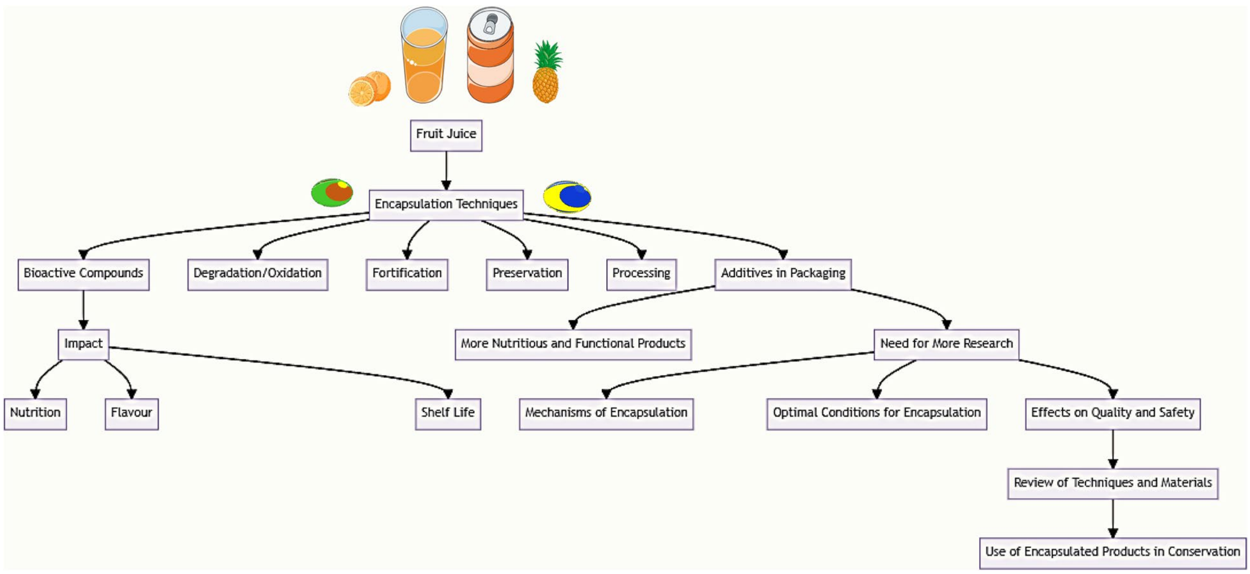
Graphical Abstract



Introduction

Active molecule encapsulation techniques are valuable tools that allow preserving and optimizing the efficacy of bioactive compounds, improving the quality of food, beverages, medicines, and other supplies that contain them, both for human and veterinary use (Ronald B. Pegg 2007). Bioactive encapsulation consists of incorporating one or several active molecules, regardless of their physical state, into a matrix or component that, depending on its nature and affinity with the molecule, will provide beneficial properties for the product and therefore for the consumer (Shahidi & Han 1993). Some effects of encapsulation make it possible to mask unpleasant organoleptic properties, improve the mechanical properties of the compounds, control their release, increase solubility and therefore improve bioaccessibility and bioavailability, increase the chemical, environmental, enzymatic and microbiological stability of the encapsulated active molecule arranged in the final product (Ronald B. Pegg 2007). Consequently, in commercial products, encapsulation makes it possible to enrich foods and beverages with highly active molecules whose use in commercial products is mainly limited by their sensory characteristics, low stability, bioaccessibility, and bioavailability(Onyeaka et al. 2022). Among the active molecules used in food, beverages, medicines, or cosmetics, those of natural origin are increasingly valued by consumers, who seek healthy lifestyles and consume foods enriched with antioxidants, vitamins, healthy fats, and probiotics (Sun-Waterhouse 2011). On the other hand, the exploitation or use of agro-industrial by-products for the extraction of active compounds is in vogue, and with it, promotes a circular economy (Baroi et al. 2022; Oleszek et al. 2023). However, the complexity of the chemical composition of naturally-derived products can affect their effectiveness and sensory characteristics. Essential oils, for example, known for their antioxidant and antimicrobial properties, are highly susceptible to environmental factors such as light, humidity, temperature, or the presence of oxygen (Turek & Stintzing 2013). This is where encapsulation will allow the functional properties of these compounds to be maintained (Dima & Dima 2015). Fruit juices are a source of essential nutrients such as vitamins, minerals, and antioxidants, but they are also perishable and can undergo various changes during storage and processing. The encapsulation of natural active compounds, enzymes, and probiotics can fortify juices with these beneficial components and thus preserve them for a longer time (Ephrem et al. 2018a). In the context of fruit juices, encapsulation has been proposed to enrich their content of health-promoting compounds, such as antioxidants, enzymes, and probiotics, while preserving their nutritional value and sensory characteristics (Ronald B. Pegg 2007). Bioactive compounds (e.g. essential oils, polyphenols (Yang et al. 2023), vitamins (Jiang et al. 2023a; Tchuenbou-Magaia et al. 2022), omega-3-fatty acids (Blanco-Llamero et al. 2022), peptides, etc.) are prone to degradation or oxidation during food processing and storage. Moreover, in general, these bioactive compounds have also poor stability and bioavailability which limits their application as nutraceuticals and food ingredients. Hence, in the last couple of years, the focus of the food industry has been to use several techniques to protect them. In this regard, encapsulation has shown to be a promising alternative (Shahidi & Han 1993). Encapsulation is a process that involves the protection of active compounds by enclosing them within a matrix. This protective layer shields the compounds from degradation and oxidation, thereby enhancing their stability. Additionally, encapsulation improves the pharmacokinetics of bioactive compounds, including their bioaccessibility and bioavailability (Ronald B. Pegg 2007). These encapsulated bioactive compounds can be utilized as food ingredients in the development of functional foods and nutraceuticals, offering potential health benefits. About the materials that are used to encapsulate bioactive compounds (i.e. encapsulating agents), it can be found polysaccharides such as chitosan (Ding et al. 2023; Hashim et al. 2022), maltodextrin and gum Arabic (Lima et al. 2022; Nguyen et al. 2022; Todorovic et al. 2022; Vimercati et al. 2022), cellulose and derivatives (Stoica et al. 2022; Tchabo et al. 2022; Yang et al. 2023); proteins such as Zein (Tchuenbou-Magaia et al. 2022; Yang et al. 2023), whey protein isolate and soy protein isolate (Ding et al. 2023; Safarpour et al. 2022; Sharma & Kumar 2022; Stoica et al. 2022); and lipids such as phospholipids (Hamadou et al. 2020; Hashim et al. 2022; Sharma & Kumar 2022). Regarding the encapsulation techniques, the most widely used are spray-drying and freeze-drying (Lima et al. 2022; Nguyen et al. 2022; Sharma & Kumar 2022; Stefanescu et al. 2022; Tchabo et al. 2022; Tchuenbou-Magaia et al. 2022; Vimercati et al. 2022). In this respect, spray drying is used for the encapsulation of heat-sensitive food ingredients, such as polyphenols since the drying process is very rapid and for a short period. On the other hand, the principle behind freeze-drying is the sublimation of water under low pressure, therefore, it is suitable for heat-labile substances. Other methods that have been used include liposomes (Hashim et al. 2022), nanoliposomes (Hamadou et al. 2020), electrospraying and electrospinning (Pires et al. 2022), foam-mat drying (Santos et al. 2022; Vimercati et al. 2022), microcapsules based on an aqueous two-phase system (ATPS) (Jiang et al. 2023b). The aim of this work briefly reviews the encapsulation techniques and materials used to encapsulate bioactive compounds and up-to-date the use of encapsulated natural products in the conservation of food and beverages.

Encapsulation techniques and mechanisms of shelf-life extension through encapsulation techniques

Due to the diverse nature of the compounds that can be incorporated into food or beverages, multiple techniques can be used for correct encapsulation, which is generally classified as mechanical, physicochemical, or chemical (Fig. 1) (Lengyel et al. 2019). The choice of one technique or another will depend on the nature of the materials to be encapsulated, the properties of the matrix components, solvents used, the need for scaling, economy and/or versatility of the technology. The particle size of the product obtained can fluctuate in the order of mmicrometresor nanometers, with a spherical or non-spherical morphology, with a smooth, rough, or porous surface, being generally classified as microspheres and microcapsules. Microspheres are matrix systems with a homogeneous distribution of the active ingredient, while microcapsules are heterogeneous systems made up of a

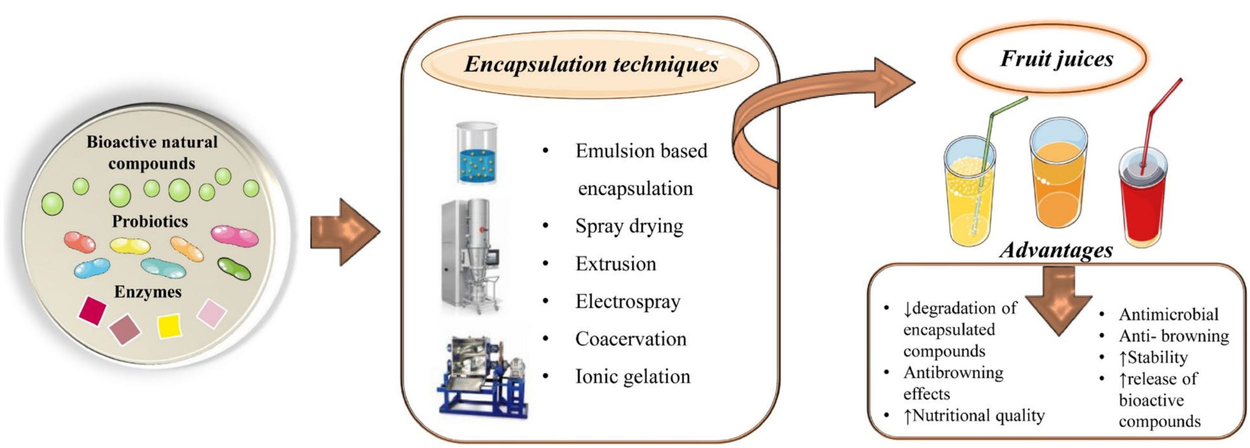


Fig. 1 Illustrative scheme regarding the encapsulation of natural active compounds, enzymes, and probiotics as potential bioactive components for fruit juices and the advantages of their incorporation in fruit juices. Symbols:↑ increase, ↓decrease

crown that surrounds one or several reservoirs that contain the component of interest (Lengyel et al. 2019). There are various methods for the encapsulation of molecules of natural origin, some require equipment, usually called mechanical methods, and others can be carried out on a laboratory scale. Understanding the mechanisms behind the efficacy of encapsulation in extending the shelf-life of fruit juices is vital for its industrial application. Encapsulation techniques employ various mechanisms to protect the bioactive compounds, thereby enhancing the longevity of the juice without compromising on nutritional quality (Ephrem et al. 2018b). Encapsulation acts as follows: physical barrier between bioactive compounds and oxidative elements; the encapsulating material isolates the compound from oxygen, thus preventing degradation due to oxidation (Zabot et al. 2022a); controlled release ensuring that the bioactive components remain active for longer periods, which contributes to the product's longevity (Yun et al. 2021); providing a moisture barrier that protects hygroscopic bioactive ingredients, which are prone to spoilage in the presence of water (Nair et al. 2023).; protective effect from light and UV radiation because some bioactive compounds are sensitive to light, which can degrade their nutritional value and encapsulation serves as a barrier against photo-degradation (Messinese et al. 2023); microbial spoilage is another factor that affects shelf-life and encapsulation can also incorporate natural antimicrobials (Gómez-Llorente et al. 2023). The most commonly used methods are presented below.

Spray drying

Spray drying is one of the most widely used processes for the encapsulation of bioactive ingredients, for use in the food industry (Assadpour & Jafari 2019). It is characterized by being a fast, low-cost, scalable process, where dry particles are obtained in a continuous operational stage by atomizing a liquid (solution, suspension, emulsion, etc.). The product is sprayed using an atomizer and simultaneously comes into contact with a current of hot air that dries the pulverized material, and The particles fall by gravity and dry in the path of the drying chamber, where they later reach the cyclone and are collected in the form of powder. Process parameters such as inlet temperature, feed rate, drying airflow, and humidity are critical to the morphological characteristics, quality, and stability of the final product. In addition, it is important to control variables such as material viscosity, and total solids concentration, among others (Ziaee et al. 2019). Recently, bioactive products can be nano-encapsulated using nano-spray drying, which, unlike conventional equipment, produces nanodroplets of the preparation with an ultrasonic atomizer and uses a high-voltage electric field that efficiently separates and collects the nanoparticles obtained (Arpagaus et al. 2018).

Extrusion

Storing bioactive compounds in powdered form is a viable approach to enhance their stability and facilitate their use in food and beverage applications as flavourings or fragrances. Among the methods available, both spray drying and extrusion offer advantages in terms of stability and handling, without the need for organic solvents. Extrusion, similar to spray drying, is a single-stage process that can effectively convert bioactive compounds into particulate form, making them more suitable for long-term storage and utilization in various food and beverage products. However, unlike the latter, it has low power consumption. In the process, carbohydrates at a temperature above the glass transition temperature are normally used as matrix components, extruded through a mould or mesh, and the extrudate is sheared by a knife to reduce its size to a few millimetres. The bioactive compounds are enveloped by the matrix component, while the surface residue is washed away (Uhlemann & Reiß 2010; Yuliani et al. 2004).

Electrospray

A relatively recent technology to encapsulate bioactive compounds is the electrospray (Tapia-Hernandez et al. 2015), which consists of passing through a spray nozzle a solution with the matrix component and the molecule of interest. The solution is subjected to a high-voltage electric field that generates the Taylor cone and with it the fractionation of this solution into fine droplets that will constitute the particles. If the compound to be encapsulated is oily, there is the alternative of using coaxial electrospray, which will allow an internal fluid to be coated with an external one that will have the matrix component (Castro Coelho et al. 2021; Gómez-Mascaraque et al. 2016). Despite being a scalable method that does not require the use of temperature, the standardization of process parameters is still complex given recent technology, on the other hand, the collection of the encapsulated material is difficult, as is the hardening of the wall of the particles, as well as their aggregation.

Coacervation

Coacervation consists of the separation of colloidal systems into two liquid phases, on the one hand, is the coacervate highly concentrated in polymer, and the other phase is made up of solvent (Eghbal & Choudhary 2018). To encapsulate a compound, it must be dispersed in a material that will form the nucleus of the particle (for example, an oil). This phase will be surrounded by the continuous phase containing the polymer. Then coacervation is induced, and the coacervates are located at the interface, in this phase, it is possible to incorporate another agent that hardens or solidifies the shell, forming a micro/nanocapsule. Coacervation can be simple or complex, the first occurs if the polymeric material is only one and will precipitate in the presence of a non-solvent, incorporation of salts, or due to changes in temperature or pH. On the other hand, coacervation will be complex when two or more oppositely charged macromolecules or polymers interact, causing phase separation (Napiórkowska & Kurek 2022). Among the parameters that can be controlled and that will affect the encapsulation efficiency and release characteristics are the concentration of the components, the ionic strength, the pH, and the affinity between the active molecule and the agent that will form the nucleus (Timilsena et al. 2019). The resulting particles are spherical and insoluble in water. The particle size is defined by the speed of agitation during the process. Among the most used materials are proteins (whey proteins, soy proteins, gelatin) and polysaccharides (acacia gum, xanthan gum).

Emulsion-based encapsulation

When bioactive compounds are oily or lipophilic in nature, encapsulation from the formation of an oil-in-water (O/W) emulsion is a quick and practical alternative. The simplest way consists of dispersing or dissolving the active principle in a solution of volatile, water-immiscible organic solvent, which will also dissolve the hydrophobic polymeric material, usually, a polyester derived from lactic and/or glycolic acid. This phase will be dispersed in an aqueous phase containing a surfactant in such a concentration as to stabilize the dispersed phase globules. The mixing of the immiscible phases with each other must be carried out under stirring, which, depending on its magnitude, will define the size of the particles obtained. The particles will be formed by evaporation of the solvent, a method called emulsion-evaporation of solvent, using a rotary evaporator or, at room temperature under constant agitation. The main disadvantage of this method is its high cost and the fact that most of the surfactants used are not food-grade (Singh 2016). It is also possible to make multiple emulsions, for example, water-in-oil-in-water (W/O/W), to encapsulate hydrophilic bioactive compounds or to increase the stability of the encapsulated compounds (Heidari et al. 2022). In this case, a variant concerning the emulsion stabilizing agent is the development of Pickering emulsions, which are stabilized by adsorbed particles at the liquid–liquid interface. The main advantage is the greater stabilization of the emulsion and with it less possibility of coalescence (Klojdová & Stathopoulos 2022; Yang et al. 2017). In addition, natural materials such as cellulose derivatives or chitosan can be used, which are widely accepted in the food industry. The encapsulation of probiotics in Pickering emulsions has shown promising effects to increase their environmental stability and loss of viability during handling (Haji et al. 2022). In recent years, studies of the encapsulation of bioactive compounds in solid lipid nanoparticles produced from an O/W emulsion using lipids that are solid at room temperature have been documented (Mukurumbira et al. 2022). The emulsion must be stabilized with a mixture of surfactants and the globule size is reduced by applying high energy using ultrasonication, high-pressure homogenization, or high shear homogenization. The main advantage is the high efficiency of encapsulation of lipophilic compounds and the controlled release that they can generate. A variant of these systems is nanostructured lipid carriers, which are made up of mixtures of solid lipids and liquid lipids to increase the stability of the nanoparticles and thereby preserve encapsulation efficiency in the long term. Several phenolic compounds, due to their lipophilic nature, have been encapsulated using these lipid matrices, from an emulsion (Borges et al. 2020). Emulsions can not only be used as delivery systems but can also be used as excipient systems. Bioactive components can be left in their natural environment (such as fruits or vegetables), but consumed with specially designed "excipient foods". An "excipient emulsion" can be defined as an emulsion that increases the bioavailability of bioactive agents in foods that are co-ingested, by altering their bioaccessibility, absorption, or transformation within the gastrointestinal tract, without necessarily having any intrinsic bioactivity. O/W emulsions are particularly effective vehicles for developing "excipient foods" due to the great flexibility in the design of their compositions and structures (McClements & Xiao 2014; McClements et al. 2015 2016).

Emulsion-based freeze drying

Emulsion-based freeze drying is an innovative encapsulation technique that has garnered significant interest in the field of food science and technology (Liu et al. 2022). This method combines the principles of emulsification and lyophilization (freeze drying) to create stable micro- and nano-encapsulated particles (Prosapio & Lopez-Quiroga 2020). Prior to freeze drying, bioactive compounds are incorporated into an emulsion, typically a water-in-oil (W/O) or oil-in-water (O/W) system. The use of surfactants or emulsifiers, such as lecithin or polysorbate, ensures the stability of the emulsion, this encapsulated emulsion then undergoes freeze drying (Rezvankhah et al. 2020). Emulsifying creates a physical barrier around the bioactive compounds, offering protection against environmental factors like oxidation (Martínez-Ballesta et al. 2018). The freeze-drying process effectively reduces water activity, which is crucial for the longevity of the product as it inhibits microbial growth (Alp & Bulantekin 2021) and also the emulsion maintains the structure and stability of sensitive compounds during the freeze-drying process (Oyinloye & Yoon 2020).

Ionic gelation

Ionic gelation is a process where a solution of polymer or hydrocolloid is gradually added drop by drop to an ionic solution with an opposite charge, while constant stirring is maintained. The active compound that needs to be encapsulated is dissolved within the polymer solution. When the droplets of the polymer solution come into contact with the ionic solution, they rapidly form spherical structures known as gel beads or capsules. These gel beads possess mechanical strength and integrity and effectively encapsulate the active compound, which is dispersed throughout the polymer matrix. Alginate, low methoxylation pectin, chitin, and chitosan are commonly used as coating agents, and sodium tripolyphosphate and Ca^{2+} ions are the most widely used crosslinking agents. Oppositely charged polymer solutions (e.g. chitosan and alginate) have also been used. It is a simple and easy procedure, it does not require specialized equipment, high temperature, or organic solvent and can be considered low cost (Bennacef et al. 2021; Kurozawa & Hubinger 2017). This is why it has been widely used for the encapsulation of probiotics (Altamirano-Ríos et al. 2022).

Materials used to encapsulate bioactive compounds

The encapsulation material can be diverse, highlighting natural, semi-synthetic or synthetic polymers, and lipid or protein matrices. However, matrices of natural origin are usually selected when developing products for human or veterinary use (Saberi-Riseh et al. 2021). Other excipients that will help to cross-link or harden the main matrix component, such as salts ($CaCl_2$) or charged molecules, can also be incorporated. Sometimes, combinations of oppositely charged polymers are used (for example, alginate and chitosan), favouring their cross-linking and thus slowing down the release of the encapsulated molecule (Sæther et al. 2008). The encapsulation materials must not be toxic, in addition, they must preserve their stability and functionality. It is important to consider, depending on the desired effect, the properties of the encapsulation material, both mechanical, degradability, permeability, susceptibility to pH changes, presence of salts, temperature, and humidity. Which must be previously analyzed, since the behaviour of the encapsulated material in the final product will depend on it. Below are some of the most used materials as matrix components in the encapsulation of bioactive compounds.

Polysaccharide-based matrices

Commonly used carbohydrate-based materials are gums, maltodextrin, cyclodextrin, and modified starches. In general, they stand out for improving the physicochemical properties of bioactive compounds as a dry product, increasing their stability against enzymatic processes, or environmental conditions (Buljeta et al. 2022). Cyclodextrins are macromolecules formed by a different number of D(+) glucopyranose residues linked by α(1–4) bonds, they are characterized by being safe for their application in food and beverages. They have an internal cavity of a hydrophobic nature that allows them to trap lipophilic compounds. The external surface is hydrophilic, which increases the solubility of the compounds that are encapsulated in its cavity. The most commonly used are β-cyclodextrin and hydroxy propyl β-cyclodextrin due to their greater solubility in water (Escobar-Avello et al. 2021).

Gum arabic is obtained from the acacia plant, it is composed of galactose, rhamnose, arabinose, 4-O-methyl glucuronic acid, and glucuronic acid, it is characterized by its high solubility in water, good emulsifying properties and its ability to retain volatile compounds (Pakzad et al. 2013). It is usually combined with another matrix component to reduce its cost. Combined with maltodextrin, it has been shown to preserve the antioxidant properties of anthocyanins from *Hibiscus sabdariffa* L. (Nguyen et al. 2022). In a study by Rezende et al. (2018), a matrix of gum arabic and maltodextrin was also used by encapsulation by spray drying and freeze drying to give greater commercial value to acerola (*Malpighia emarginata* DC.) pulp and residue extracts. The particulate material obtained presented good physical properties and preserved the antioxidant effect, thus being a promising extract to be used in functional foods.

Chitosan is a linear polysaccharide obtained from chitin deacetylation, it has a positive charge due to its amino groups, making it an attractive polymer for developing nanoparticulate and microparticulate systems, hydrogels, biofilms, and other active agent delivery systems (Carlan et al. 2017; Do et al. 2022; Granata et al. 2021). In addition to the positive charge that differentiates it from other polysaccharides, antioxidant, and antimicrobial properties have been attributed to it (Akbari-Alavijeh et al. 2020). Although it is insoluble at neutral pH, its solubility increases at pH below 6 (Hamed et al. 2016). Most of the studies have focused on nanoencapsulation using modified chitosan in combination with other polymers or matrix components, with varied objectives, for example, controlled release of clove essential oil enhancing its antifungal activity in vitro (Hasheminejad et al. 2019), preservation of the antioxidant properties of resveratrol

(Chanphai & Tajmir-Riahi 2017), black tea (Zhang & Zhao 2015) and propolis (Zhang et al. 2018).

Alginate, sodium or calcium salt, is a linear polysaccharide from brown algae, composed of two uronic acids encompassing (1–4)-linked-β-D-mannuronate and α-L-guluronate. It is characterized by being soluble in water with viscous, film-forming, and stabilizing properties, and can be used alone or associated with other polysaccharides such as chitosan to promote cross-linking and thereby favour the controlled release of the bioactive component studied. In a study conducted by Sorasitthiyanukarn et al. (2019), curcumin was nano encapsulated in a mixture of alginate and chitosan by emulsification and ionic gelation methods, protecting this bioactive compound from enzymatic degradation, UV radiation, and heat treatment. It also improved in vitro bioaccessibility and cellular uptake through the colon cancer cell line Caco-2. Another work, carried out by Flamminii et al. (2021) had the objective of providing added value to olive by-products, specifically to a phenolic extract of the leaves through microencapsulation in an alginate matrix and other materials such as pectin, casein, and whey protein. The encapsulation efficiency was higher with the matrix composed of alginate and pectin, a matrix that also contributed to improving the physicochemical properties of the final product.

Pectin corresponds to the main component of the skin and pulp of fruits; it is a high molecular weight heteropolysaccharide composed of poly α-1–4 galacturonic acid residues with degrees of methylation of carboxylic acid residues. It is also composed of sugars, such as arabinose, galactose, and rhamnose (Zabot et al. 2022b). It is a safe ingredient for consumption that has several benefits such as improving the flavour and texture of food, being a stabilizer, and having a binding capacity. There are different types of pectin, depending on the degree of esterification, giving various properties to this polysaccharide. On the other hand, there are mono, di, and trivalent salts that will affect their solubility in water. Its decomposition rate will depend on the temperature and pH variation, for example, at alkaline pH it can degrade at room temperature (Noreen et al. 2017). As befits an indigestible polysaccharide, it can protect the encapsulated compound from stomach enzymes and pH present in the upper digestive tract until it reaches the large intestine (Khotimchenko 2020). It is for this reason that bioactive compounds sensitive to stomach conditions such as probiotic bacteria are being encapsulated in this model to improve their survival (Tarifa et al. 2021).

Maltodextrin is a product obtained from the partial hydrolysis of starch, considered as a D-glucose polymer linked by α-(1,4) and α-(1,6) bonds. Contains 2–3% glucose and 5–7% maltose (Xiao et al. 2022). The degree of starch degradation is indicated by the dextrose equivalent (DE) value, which indicates the percentage of reducing sugars, being inversely proportional to the molecular weight. Maltodextrin is a matrix component highly used in the encapsulation of bioactive compounds by different technologies, due to its versatility, low cost, high-water solubility, low apparent density, thermal stability both in hot and cold conditions and reported protection of active components, oxidation, which is very useful for its incorporation into food matrices (Caliskan & Dirim 2016; Fioramonti et al. 2017). In addition, the high percentage of hydroxyl groups in its structure provides sites for its chemical modification, forming even more versatile derivatives. In order to increase the bioavailability of green tea polyphenols and preserve their antioxidant power, Parvez et al. (2022) encapsulated this extract in maltodextrin as a matrix component, using ultrasonic homogenization and subsequent lyophilization. Encapsulation considerably enhanced its antioxidant properties under simulated gastrointestinal conditions. In another study, Thyme (*Thymus vulgaris* L.) essential oil was encapsulated using a mixture of maltodextrin and casein by spray drying, to evaluate its potential in the preservation of meat foods, such as hamburgers. The study showed that the encapsulated product had high thermal resistance, preserving its antioxidant and antimicrobial properties (Radünz et al. 2020). Maltodextrin conjugates with hydrolyzed whey protein were used to encapsulate *BidifobacBifidobacteriumobacillus* by spray drying. The encapsulation of these probiotics provided a high survival rate during storage at different temperatures, with appropriate solubility and wetting to be incorporated into a food matrix (Minj & Anand 2022). In another study, co-encapsulation by spray drying of paprika and cinnamon oleoresins using maltodextrin as a matrix component in a 3:1 ratio with whey protein isolate was beneficial in preserving the stability of the mixture after storage and could be useful as a colorant and antioxidant in food matrices such as mayonnaise or vegetable oils (Ferraz et al. 2022).

Protein matrices

Proteins are biomacromolecules made up of amino acids linked together. There are vegetable proteins, such as zein, soy protein, and pea protein; of animal origins, such as gelatin, derived from milk or eggs; of microbial and marine origin (Zhang et al. 2022). Each one presents different properties in terms of solubility, spatial arrangement, or molecular weight. In general, proteins stand out for their impermeability to gases and satisfactory mechanical properties, being one of the main materials for biodegradable food packaging (Chen et al. 2019). Protein matrices can be used to increase the absorption of fat-soluble compounds after their oral administration, since the peptides released after digestion can act as emulsifiers, favouring the formation of micelles (Iddir et al. 2022). This emulsifying property has also been widely reported in matrices based on milk protein (Ubeyitogullari & Rizvi 2020). From this, casein, the main component, and whey protein are obtained. In a study reported by Sassi et al. (2022) nanoencapsulation with a 1:3 mixture of whey protein isolate and maltodextrin preserved the natural antifungal effect of a mixture of citrus extracts and cinnamaldehyde-rich essential oils in grated cheese for more than 7 days. In a study presented by Selim et al. (2021), the oxidative stability of encapsulated fish oil by spray drying was evaluated using 3 different matrices: whey protein, maltodextrin, and gum arabic. The study found that whey protein was the most effective agent to protect against oxidative deterioration, although all the matrices studied extended the shelf life of the oils. Plant-based proteins can also be used to encapsulate bioactive compounds. Chen et al. (2021) encapsulated eugenol in a matrix based on quinoa protein and gum arabic by complex coacervation, preserving the antimicrobial properties of this compound in minced meat stored for 15 days at 4 °C, with a better preservative effect when compared to free eugenol. In addition to the use of vegetable and terrestrial animal proteins, matrices based on aquatic proteins have also been used, which have high nutritional value, and good sensory and functional characteristics (Han et al. 2022). A study presented by Wang et al. (2021b) reported the use of cod protein for curcumin encapsulation, showing a good encapsulation rate and an increase in photostability and thermal stability.

Lipid matrices

The incorporation of bioactive compounds of a lipophilic nature in food matrices constitutes a technological challenge, so lipid matrix components are ideal for this purpose. Such is the case of essential oils or phenolic compounds that have been encapsulated in nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers, or liposomes (Faridi Esfanjani and Jafari 2016; Pavoni et al. 2020). The matrices are composed of solid lipids at room temperature, liquid lipids, semisolids, or mixtures of these. Control of particle or globule size is achieved by using well-controlled emulsifiers and process parameters. In the case of liposomes, phospholipids are used, a system formed by bilayers, in whose hydrophobic portion the compounds of a lipophilic nature are housed. Limonene, a bioactive component of citrus peel, has been encapsulated in various matrices to enhance its antioxidant, anti-inflammatory, and anticancer effect. Souto et al. (2020) developed solid lipid nanoparticles using glyceryl monostearate with -/+limonene to decrease their volatility and offer a controlled release. Dhital et al. (2018) developed D-limonene liposomes as a preservative material for strawberries with promising results using soybean lecithin as a matrix component. In other studies, vitamin D was encapsulated in lipid matrices to increase its stability and bioavailability in order to fortify beverages and promote their consumption. In this regard, nanostructured lipid carriers based on compritol and precirol were used (Mohammadi et al. 2017), nanoliposomes with mixtures of lecithin and cholesterol (Mohammadi et al. 2014) and nanoemulsions with soy lecithin and canola oil as lipid components (Mehmood & Ahmed 2020).

Encapsulation of natural active compounds, enzymes, and probiotics as potential bioactive components for fruit juices

Encapsulation of natural active compounds, enzymes, and probiotics is an emerging field of research that has the potential to improve the nutritional quality, shelf life, and functionality of fruit juices (Ephrem et al. 2018a; Speranza et al. 2017). The coated substance (food or flavour molecules/ingredients) is more stable in an enclosed wall. Encapsulation improves the stability and release of bioactive foods at the active physiological site. Masking food flavours or tastes or converting liquids into solids are popular applications (Pateiro et al. 2021). Enzymes can improve the processing of fruit juices and make them more palatable (Wang et al. 2021a). Encapsulation allows the probiotics to survive in the juice and deliver their health benefits to the consumer (Terpou et al. 2019; Vivek et al. 2023). Studies have shown the potential of encapsulation to improve the antioxidant activity, microbial stability, and sensory attributes of fruit juices (Dadwal & Gupta 2021; Speranza et al. 2017).

Encapsulation of natural active compounds in fruit juices

Fruit juice is a valuable vehicle for the delivery of bioactive ingredients, including carotenoids, phenolic acids, flavonoids, polyunsaturated fatty acids, minerals, and vitamins (Speranza et al. 2017). The use of native and autochthonous fruit varieties as raw materials for functional fruit juice production can also provide economic benefits, as these products can be highly profitable in the marketplace. This trend is supported by data from the European Union, which shows a 5.4% growth in the production of non-concentrated juices and a 4.8% growth in the production of freshly squeezed juices over the last five years (Putnik et al. 2020). Despite these benefits, there are challenges to the production of functional fruit juices. One of the major causes of fruit imports and the reduced per capita availability of fruit in each country is post-harvest losses. This is due to inadequate storage and processing, which increases post-harvest losses due to enzymatic reactions and microbiological growth. To increase the income and economic viability of fruit growers, it is important to address these issues by reducing the excessive moisture content of fruits and implementing appropriate storage and processing methods to reduce postharvest losses (Srivastava et al. 2022). Encapsulation of natural compounds, enzymes, and probiotics in fruit juices can also be an effective approach to improve the nutritional quality, shelf life, and functionality of the juice while maintaining its fresh character and desired flavour profile. Table 1 and Fig. 1 provides a summary of various fruits and vegetables along with the natural compounds and encapsulation process used to study their effects on stability, bioavailability, and preservation of juice quality.

Emulsion-based delivery systems are a method to encapsulate bioactive compounds in fruit juices. A recent study aimed to create a stable emulsion-based delivery system for carotenoids extracted from carrot pomace using flaxseed oil and a natural emulsifier. The optimal emulsion was selected based on particle size, zeta potential, colour values, and viscosity and was found to be stable for up to 15 days with high carotenoid content, antioxidant activities, and microstructure (Tiwari et al. 2021). The results demonstrate the potential to utilize carrot pomace as a source of valuable micronutrients and carotenoids through emulsion-based delivery systems. Conservation was used for the microencapsulation of fish oil for the fortification of pomegranate juice. Efficiency and core oil content were found to be higher in capsules prepared with a ratio of 1.5% encapsulate to 3% fish oil (Habibi et al. 2017). Liposomes are spherical vesicles composed of phospholipids that can encapsulate both hydrophilic and lipophilic compounds (Speranza et al. 2017). They are biocompatible, biodegradable, and non-toxic. Liposomes can protect encapsulated materials from environmental, biological, and chemical factors. They can be prepared by various methods such as mechanical dispersion, solvent dispersion, and detergent removal. However, their use is limited due to chemical and physical instability, low encapsulation yield, and the need for additional compounds to increase their efficiency (Anandharamakrishnan and Padma Ishwarya 2015). Liposomes have been studied for the encapsulation of food additives such as enzymes, vitamins, antioxidants, antimicrobials, and flavours (Ephrem et al. 2018a). As reported by Istenič et al. (2016), they used liposomes and liposome-enhanced alginate or chitosan microparticles and found that more than 30% of non-encapsulated (-)-epigallocatechin gallate was degraded in 14 days, whereas only 6% of the compound encapsulated in liposomes or liposome-enhanced chitosan microparticles was degraded.

The formation of inclusion complexes with cyclodextrins is mainly used in the encapsulation of volatile organic molecules, such as vitamins, to mask odors and tastes and to preserve flavours. Shao et al. (2014) used inclusion complexation with β-cyclodextrin and 2-(hydroxypropyl)-β-cyclodextrin to encapsulate chlorogenic acid in grape juice and found that this method reduced the degradation of anthocyanins due to the pigmentation effect.

The choice of encapsulation method depends on the characteristics of the bioactive compound and the desired end product. It is important to ensure that the method does not adversely affect the organoleptic characteristics and microbiological stability of the juice and is palatable to the end consumer.

Encapsulation of enzymes in fruit juices

Enzymes are biological molecules that catalyze chemical reactions in living organisms. They are widely used in the food industry to improve the yield and organoleptic properties of food products. In the case of fruit juice, enzymes can be used to enhance the flavour and aroma of the juice by hydrolyzing tasteless glycosidic precursors and releasing volatile compounds. Beta-glucosidase and naringinase are two enzymes commonly used in fruit juice processing. Beta-glucosidase is used to hydrolyze *O*-glycosidic linkages between saccharides and aglycons, resulting in the enrichment of juice flavour and aroma. Naringinase, on the other hand, is used to debitter citrus juice by hydrolyzing the bitter compound naringin, which reduces the bitterness of the juice (Ephrem et al. 2018a). Enzymes can also be used to clarify juice by hydrolyzing polysaccharides (pectins, starch, and hemicellulosic components) that cause turbidity (Cerreti et al. 2017; Shahrestani et al. 2016). The fruit processing industry uses various types of enzymes such as pectinases, cellulases, and mixtures of both to fortify fruit juices. Pretreatments such as steaming, cooling, or heating are applied to fruit to increase juice recovery, and a greater degree of tissue breakdown by freezing and thawing of whole fruit coupled with pectinase enzyme treatment of fruit macerate results in higher solids (Joshi et al. 2011; Sharma et al. 2017). Hot water extraction with enzyme addition in apple pomace with a combination of pectinases and cellulases results in higher yields (Sharma et al. 2017). Enzymatic extraction of bael fruit results in a 17.5% increase in juice yield, and enzyme treatment of plum, peach, pear, and apricot also increase juice yield (Joshi et al. 2011; Singh et al. 2012). The increase in juice yield is attributed to the hydrolysis of pectin, which releases the sap within the cells of the pulp; however, the increase varies in different fruits due to the amount of pectin present and

Table 1 Summary of fruits and vegetables with natural active compounds and encapsulation process for juice stability, bioavailability and quality preservation

Source(s)	Natural active compound(s)	Encapsulation Process(es)	Main Outcome(s)	Reference
Apple	Folic acid	Impregnation/Mesoporous silica particles	Improved stability and controlled release of folic acid after consumption	(Ruiz-Rico et al. 2017)
Apple	Orange oil	Nanoemulsion (Ultrasound emulsification)	Important antimicrobial activity against *S. cerevisiae* in apple juice	(Sugumar et al. 2016)
Apple	*trans*-Cinnamaldehyde	Nanohydrogel (Alginate-chitosan- nanoparticles)	Good radical scavenging activity of *trans*-cinnamaldehyde in apple juice	(Loquercio et al. 2015)
Apple	Steppogenin	Oil-in-water microemulsion	High inhibition of juice browning	(Tao et al. 2017)
Apple	Artocarpanone and ascorbic acid	Oils (ethyl butyrate, ethyl oleate, DL-α-tocopherol, soybean oil, isopropyl myristate, caprylic capric triglyceride)-in-water microemulsion	Strong anti-browning effects in apple juice after 24 h	(Dong et al. 2016)
Apple	Pectinase	PLGA nanocapsules (Entrapment)	Good adaptability to acidic solution and high clarification yield (80%) of apple juice	(Cerreti et al. 2017)
Cantaloupe	Thymol and nisin	Emulsions: O/W emulsion: Homogenization: High-speed homogenization followed by high-pressure homogenization	Enhancement of the antibacterial activity of thymol and nisin in cantaloupe juice	(Sarkar et al. 2017)
Carrot	Isoeugenol	Spray-dried emulsion (High-pressure homogenization followed by spray-drying)	Enhancement of the antibacterial activity of isoeugenol in carrot juice	(Krogsgård Nielsen et al. 2016)
Carrot pomace	Carotenoids	Emulsions: O/W emulsion: Homogenization	High encapsulation efficiency (92.745 ± 0.384%)	(Tiwari et al. 2021)
Carrot, Orange, and Apple	Carvacrol	Emulsions: O/W emulsion: Homogenization	Good antibacterial activity of carvacrol in carrot, orange, and apple juices	(Char et al. 2015)
Grape	Chlorogenic acid	Inclusion complexation/β-(cyclodextrin and 2-hydroxypropyl)-β-cyclodextrin	Reduced degradation of anthocyanins due to the copigmentation effect	(Shao et al. 2014)
Grape	Pimaricin	Nanohydrogel	Good antimicrobial activity against *S. cerevisiae* in grape juice	(Fuciños et al. 2015)
Orange	(−)-Epigallocatechin gallate	Liposomes and liposome-reinforced alginate or chitosan microparticles	Lower degradation of encapsulated (−)-Epigallocatechin gallate compared to non-encapsulated	(Istenič et al. 2016)
Pomegranate	Fish oil	Complex coacervation/Gelatin-gum Arabic coacervates	Pomegranate juice can be fortified with up to 0.07% fish oil with fair acceptability, increase in turbidity and lightness	(Habibi et al. 2017)
Watermelon	*trans*-Cinnamaldehyde	Nanoemulsion (High-energy homogenization)	Significant antibacterial activity against *E. coli*, *S. Typhimurium*, and *S. aureus* in watermelon juice	(Jo et al. 2015)

PLGA Poly(lactide-co-glycolide)

the activity of the enzymes. The fruit juice industry has invested in methods to improve the clarity of juices due to natural turbidity caused by polysaccharides, proteins, tannins, and metals. Pectin, in particular, leads to colloid formation and can make filtration difficult. Enzymatic depectinization using pectinases has proven to be an efficient alternative to reduce turbidity and increase clarity (Sharma et al. 2017). Enzymatic treatment can also affect the physicochemical properties of fruit juice, increasing the total soluble solids and reducing the viscosity of the juice (Sin et al. 2006; Singh et al. 2012). The use of different enzymes in combination can also reduce juice viscosity. In addition, the use of free enzymes has limitations, such as low stability under different temperature and pH conditions and difficulty in recovering the enzymes from solutions (Ephrem et al. 2018a; Sharma et al. 2017). To overcome these limitations, enzymes can be immobilized on a solid support or matrix or encapsulated in nanoparticles. This approach has advantages such as the ability to choose batch or continuous processes, rapid reaction termination, controlled product formation, ease of enzyme removal, and improved thermal stability (Speranza et al. 2017). Table 2 summarizes the results of various studies that have investigated the use of encapsulated enzymes to clarify juice and improve quality attributes.

The use of hydrogels to encapsulate enzymes for fruit juice processing has been proposed as a method to improve thermal stability and increase clarity. Gassara-Chatti et al. (2013) found that encapsulating ligninolytic enzymes in hydrogels resulted in improved thermal stability and increased clarity compared to using free enzymes. Additionally, Mosafa et al. (2013) used magnetite nanoparticles encapsulated in a silica matrix to immobilize papain and found increased enzyme activity, better tolerance to pH and temperature variations, and good reusability. Bhushan et al. (2015) also showed that encapsulated xylanase resulted in a higher clarification rate, lower viscosity, and lower suspended solids in pineapple juice. Furthermore, Deng et al. (2019) immobilized polygalacturonase in calcium alginate microspheres and found that the immobilized enzyme had increased stability and activity, resulting in improved clarification of apple juice. Recently, the use of silica gel to immobilize xylanase improved the clarity of orange juice (Alagöz et al. 2022). Co-immobilization of amylase, pectinase,

Table 2 Summary of encapsulated enzymes for improving juice quality and stability

Source	Enzyme Compound(s)	Encapsulation Method(s)	Main Outcome(s)	Reference
Apple	Pectinases	Immobilized in PVA gel	Reduction in apple juice clarity	(Cerreti et al. 2017)
Apple	Pectinases	Immobilized in calcium alginate microspheres	Increased light transmission in apple juice	(Deng et al. 2019)
Apple, Grape, Pear	Amylase, Pectinase, Cellulase	Co-immobilized on silica gel	Co-immobilized enzymes for juice clarification	(Ozyilmaz & Gunay 2023)
Apples, Pineapples, Oranges	Xylanase	Immobilized on functionalized silica-encapsulated MNPs	Xylanase improved juice clarity	(Shahrestani et al. 2016)
Apple, Grape, Pomegranate, Cranberry, Blueberry, Lemon, Elderberry, Blackberry	Lignin Peroxidase, Laccase, Manganese Peroxidase	Microgel, polymers (Hydrogel/Pectin, Gelatin, Carboxymethylcellulose)	Polyphenol reduction and clarity improvement are higher with encapsulated enzyme	(Gassara-Chatti et al. 2013)
Grapefruit	Pectinase, Naringinase	Co-immobilized on chitosan-coated MNPs	One-step clarification and debittering of grapefruit juice	(Ladole et al. 2021)
Orange	Xylanase	Immobilized covalently/physically on silica gel	Improved orange juice clarity	(Alagöz et al. 2022)
Orange, Pomegranate, Apricot, Peach, Cherry, Apple	Laccase	Covalently immobilized on poly(methacrylate) beads	Laccase treatment improved the sensory profile of orange juice	(Lettera et al. 2016)
Pineapple	Xylanase	Entrapment/Alginate	Improved juice clarification efficiency	(Bhushan et al. 2015)
Pomegranate	Papain	Sol–Gel/Silica-coated Magnetite Nanoparticles	Increased enzyme activity, pH, and temperature tolerance improved stability	(Mosafa et al. 2013)
Pomelo	Naringinase	Adsorbed on resin and deposited onto IDE-patterned PCB	Reduced bitterness with minimal nutrient loss	(Gupta et al. 2023)

Abbreviations: *MPNs* Magnetic nanoparticles, *PVA* Polyvinyl alcohol, *IDE* Interdigitated electrode, *PCB* Printed circuit board and cellulase on silica gel improved the clarification of apple, grape, and pear juices (Ozyilmaz & Gunay 2023). Naringinase adsorbed to resin and deposited on an interdigitated electrode (IDE)-patterned printed circuit board (PCB) reduced bitterness while preserving nutrient content in pomelo juice (Gupta et al. 2023). The use of hydrogels and immobilization techniques in fruit juice processing has shown promise in improving thermal stability, increasing clarity, and enhancing enzyme activity. These results suggest that enzyme encapsulation and immobilization can effectively improve juice quality.

Encapsulation of probiotics in fruit juices

Probiotics are live microorganisms that can provide health benefits when consumed in adequate amounts. They can be beneficial for health in fruit juices because fruits and vegetables are good carriers for probiotics due to their high content of vitamins, mineral salts, fiber, and antioxidants, and the absence of competing starter cultures (De Prisco & Mauriello 2016). Studies have shown that gut microbiota converts phenolic compounds present in juices into bioactive metabolites that can contribute to intestinal homeostasis, stimulate the growth of beneficial bacteria (*Lactobacillus* spp. and *Bifidobacterium* spp.), and inhibit pathogenic bacteria, thus acting as prebiotics (Duque et al. 2016). Probiotics must survive the passage through the stomach and small intestine and be metabolically active in the large intestine in order to have a positive effect on the composition of the gut microbiota (Martín et al. 2015). The critical level of probiotics is 10^6–10^7 colony-forming unit (CFU)/g or mL (Bhat et al. 2015); however, factors such as pH, hydrogen peroxide, oxygen, and storage temperature can negatively affect their viability and impact health. To counteract this, several approaches can be used, such as an appropriate selection of acid and bile-resistant strains, the use of oxygen-impermeable containers, stress adaptation, the incorporation of micronutrients (peptides and amino acids), and microencapsulation (Martín et al. 2015). Probiotics are generally loaded into capsules by Ionic gelation, emulsion, freezing, and spray-drying (Speranza et al. 2017).

Table 3 summarizes the results of different studies on encapsulation methods for probiotic microorganisms and their effects on probiotic survival and stability in different fruit and vegetable juice sources.

Gandomi et al. (2016) used ionic gelation to microencapsulate *Lactobacillus rhamnosus* GG and found a higher survival rate. Chaikham and Apichartsrangkoon (2014) successfully encapsulated *Lactobacillus acidophilus* using the ionic gelation method and added the resulting pearls to pasteurized longan juice. They then used the Simulator of the Human Intestinal Microbial Ecosystem (SHIME®) to assess the effect of this juice-probiotic combination on the gut microbiota. The researchers found that the combination of juice and probiotics increased the concentration of short-chain fatty acids such as acetate, propionate, and butyrate. Freeze drying, also known as lyophilization, is a process that preserves microorganisms by sublimating water from frozen cells under a high vacuum. However, it can also cause damage to the cell membrane and stress the cells due to crystal formation and high osmolarity (Speranza et al. 2017). Various protective agents have been proposed to mitigate these effects, including skim milk powder, whey protein, glucose, maltodextrin, and trehalose (Martín et al. 2015). Bhat et al. (2015) found that the use of a microencapsulation technique improved the survival of *Bifidobacterium longum* (NCIMB 8809) and *Bifidobacterium breve* (NCIMB 8807) during lyophilization. After 39 days at 4 °C, the encapsulated cells remained at 6.5 to 6.6 log CFU/mL, while the free cells were below the detection limit after only 20 days. Spray drying is a common technique used to produce fruit juice powders and has been applied to a variety of fruits such as orange, acai, pomegranate, black mulberry, lime, mango (Vivek et al. 2023), and others. The application of probiotics in spray-dried fruit juice powders is gaining interest to fortify fruit juices with probiotic strains while maintaining their taste and nutritional profile. The viability of probiotic cells is greatly affected by storage conditions, with high temperatures and relative humidity leading to loss of cell viability. Therefore, it is recommended that probiotic bacteria be stored under optimal conditions of low temperature and low relative humidity. Furthermore, due to the high osmotic stress during the rehydration process, it is necessary to achieve the best rehydration conditions for the manufactured probiotic fruit juice powder (Vivek et al. 2023). In recent years, several studies have been conducted to optimize the process variables and drying aids to increase the survival rate of probiotics in the final product. For example, Alves et al. (2016) used a maltodextrin drying aid and gum arabic to encapsulate *Lactobacillus casei* NRRL B-442 s in orange juice, while Barbosa et al. (2015) used maltodextrin to encapsulate *Lactobacillus plantarum* 299v and *Pediococcus acidilactici* HA-6111–2 in orange juice. In the case of orange carrot juice, the addition of *Arctium lappa* L. by spray-drying and freeze-drying with alginate and gum arabic resulted in a significant improvement in probiotic viability (Esmaeili et al. 2022). Similarly, microencapsulation of *B. longum* 51A in acerola juice using cellulose acetate, phthalate, and maltodextrin showed higher protection of *B. longum* 51A viability (Costa et al. 2022). The use of spray drying with maltodextrin in acerola and ciriguela juice containing *L. rhamnosus*, *L. casei*, and *L. plantarum* also resulted in a reduction of 2 decimal log units in the number of viable cells, with all powders having probiotic cell counts

Table 3 Summary of studies on encapsulated probiotic microorganisms for improving juice stability and quality

Source	Probiotic microorganism(s)	Encapsulation Method(s)	Main Outcome(s)	Reference
Acerola	*B. longum* 51A	Spray-drying/Cellulose acetate phthalate and maltodextrin	Higher protection for *B. longum* 51A viability	(Costa et al. 2022)
Acerola and ciriguela	*L. rhamnosus*, *L. casei,* and *L. plantarum*	Spray drying/maltodextrin	Spray drying resulted in a reduction of 2 decimal logarithm units in the number of viable cells	(Souza et al. 2022)
Apple	*L. rhamnosus* GG	Ionic gelation/Chitosan-alginate with/without inulin	4.5-fold higher survival after 90 days with inulin having a positive effect	(Gandomi et al. 2016)
Apple	*L. gasseri*	Emulsification and ionic gelation	The encapsulation method protected *L. gasseri* under simulated gastric and intestinal conditions	(Varela-Pérez et al. 2022)
Grape, Orange, Pineapple	*B. adolescentis* (ATCC 15703)	Water-in-oil emulsion/Pea protein-alginate mixture	Survived in pineapple and grape juice, not in orange juice	(Wang et al. 2015)
Longan	*L. acidophilus* LA5	Ionic gelation/Alginate	↑ lactic acid, acetate, propionate, and butyrate	(Chaikham & Apichartsrangkoon 2014)
Longan, Maoberry, Melon, Mulberry	*L. casei* 01, *L. acidophilus* LA5, B. lactis Bb-12	Ionic gelation/Alginate-Thai herbal extracts	↑stability after refrigerated storage	(Chaikham 2015)
Orange	*L. casei* 431, *L. acidophilus* La-5	Ionic gelation/Alginate	Bacteria at 8 log CFU/mL after 4 weeks	(Tootoonchi et al. 2015)
Orange-carrot	*Arctium lappa* L	Spray-drying and freeze-drying/maltodextrin, and gum arabic	↑probiotic viability	(Esmaeili et al. 2022)
Orange, Pomegranate	*B. longum* (NCIMB 8809), *B. breve* (NCIMB 8807)	Freeze drying/Bacterial poly-γ-glutamic acid	6.5 to 6.5 log CFU/mL after 39 days, lower the death rate of encapsulated probiotics	(Bhat et al. 2015)
Peach	*L. acidophilus* (NRRL-B-4495), *L. reuteri* (NRRL-B-14171)	Ionic gelation/Alginate or alginate-chitosan	Alginate-chitosan provided better protection	(García-Ceja et al. 2015)
Pineapple	*B. longum*	Ionic gelation/oligosaccharides mixture	Better survival and more acceptable to consumers	(Phoem et al. 2015)
Pineapple	*L. acidophilus*, *L. plantarum*	Emulsion/chitosan and tragacanth gum	Encapsulated with chitosan and tragacanth showed the highest overall palatability	(Sabbaghpour et al. 2021)
Sugarcane	*B. animalis* subsp. lactis BLC1	Coacervation	Microcapsules protected BLC1 and maintained high contents of phenolic and proanthocyanidin compounds	(Holkem et al. 2020)

Abbreviation: *CFU* Colony-forming unit greater than 10^6 CFU/g (Souza et al. 2022). Finally, the results of the apple juice and *Lactobacillus gasseri* study show that the ionic gelation and emulsification encapsulation method protects *L. gasseri* under simulated gastric and intestinal conditions (Varela-Pérez et al. 2022). These studies highlight the potential of using spray drying techniques to produce probiotic-enriched fruit juice powders with improved stability and functionality.

Use of encapsulated natural compounds as additives in food packaging

The main tasks of food and beverage packaging technology are (i) ensure the security and harmlessness of the product, (ii) extend its shelf life, (iii) give information about the quality of the food, and (iv) improve flavour and nutrient compounds in the food matrix (Enescu et al. 2019). The technology at nanoscale applied to improve these tasks have been developed in the lasts decades resulting in what is known as active and intelligent packaging. Active packaging is those who maintains and control the safety and quality aspects of the food; and intelligent packaging is those that provides information about the history and quality of the food through an indicator incorporated into the packaging (Ahmed et al. 2022). Active packaging has been classified into two types of systems: packaging with (i) non-migratory or (ii) migratory active compounds (Qian et al. 2021). Non-migratory active compounds are mainly oxygen scavengers, moisture absorbers and ethylene absorbers. Migratory active compounds are mainly carbon dioxide emitters, antimicrobial compounds and antioxidant agents (Yildirim et al. 2018). Those active compounds could have releasing, absorbing, blocking or buffering properties (Ahmed et al. 2022).

Encapsulation of natural antimicrobials agents in food packaging

One of the main focuses of food technology is to reduce food spoilage and avoid microbial pathogens along the food chain minimizing economical losses and controlling food safety hazards (Brandelli & Taylor 2015). Several metal oxides and oxidizing ions have been traditionally used as antimicrobial agents in food packaging encapsulated into nanoparticles or forming nanocomposites with polymeric materials. Besides their well-known antimicrobial activity, these metal oxides have been encapsulated in nanoparticles which provide improvements in barrier, optical, thermal and mechanical properties in the polymers used as packaging material (Nikolic et al. 2021). Zinc oxide (ZnO) nanoparticles in plastic films for packaging have shown activity over a broad spectrum of foodborne bacteria: *Escherichia coli*, *Staphylococcus aureus*, *Salmonella enterica*, *Micrococcus luteus*, *Enterococcus faecalis*, etc. (Al-Naamani et al. 2016; Mirhosseini & Firouzabadi 2013; Quek et al. 2018). Titanium oxide (TiO_2) nanoparticles are lower cost materials and have a bacterial and fungicidal effect: *E. coli*, *S. aureus*, *Pseudomonas aeruginosa*, *Penicillium expansum*, etc. (Maneerat & Hayata 2006; Xing et al. 2012). Other metal used in nanocomposites and nanoparticles in active packaging such as Cu_2O, CuO, Ag, Fe_3O_4 and MgO have also shown a broad spectrum against bacteria, fungi and viruses involved in food contamination (Eghbalian et al. 2021; Nouri et al. 2018; Peter et al. 2021; Yan et al. 2021; Zarandona et al. 2023). An increasing interest of consumers in less processed, ready-to-eat and more natural food, coupled with the fact that health organizations cannot rule out the complete concern for metal oxides safety used in active packaging has led to researchers to focus on replacing these metal oxides for natural additives with antimicrobial properties in active packaging that possess fewer toxic effects. The main sources from where natural antimicrobials come from are vegetal, animal and microorganism's sources (Fig. 2). Natural extracts with antimicrobial activity have been used as part of packaging to maintain organoleptic properties (colour, taste, odour) and the quality of the food. One of the most studied natural extracts use as antimicrobial on food tinhnology are essential oils. They have been widely investigated as natural non-toxic alternatives in active packaging. But despite their proven safety and antimicrobial efficacy of essential oils, they address problems with the impact on the organoleptic quality of the food and their low thermal stability can be overcome with encapsulation techniques. The most used essential oils with antimicrobial effects are mainly monoterpenoids (thymol, carvacrol or linalool), monoterpenes (limonene, pinene or cymene) and phenylpropanoids (eugenol, vanillin or cinnamaldehyde) (Pandey et al. 2016). Natural antimicrobial agents are extracted from herbs and spices, such as mustard, vanilla, cinnamon or basil. Beside their inhibitory effect on microorganisms, they have been widely used in food as flavouring and preservative agents (Pilevar et al. 2020). Antimicrobials isolated from animal sources include lysozyme, spheniscin, chitosan and diverse free fatty acid, all of them coming from sources like eggs, milk and seafood (Lopes et al. 2019). Bacteriocins peptide-types from microorganisms are also used in food packaging such as nisin, pediocin, lysostaphin or plantarisin S (Verma et al. 2022). The encapsulation technology is wide and is mainly focused on pprotectingthe active compounds during storage life and acontrollingrol their release into the food matrix. Table 4 shows some examples of natural extracts and compounds used in active food packaging as antimicrobials.

Encapsulation of natural antioxidant agents in food packaging

Active packaging can contain antioxidant agents that migrate to the food or absorb and neutralize radicals that

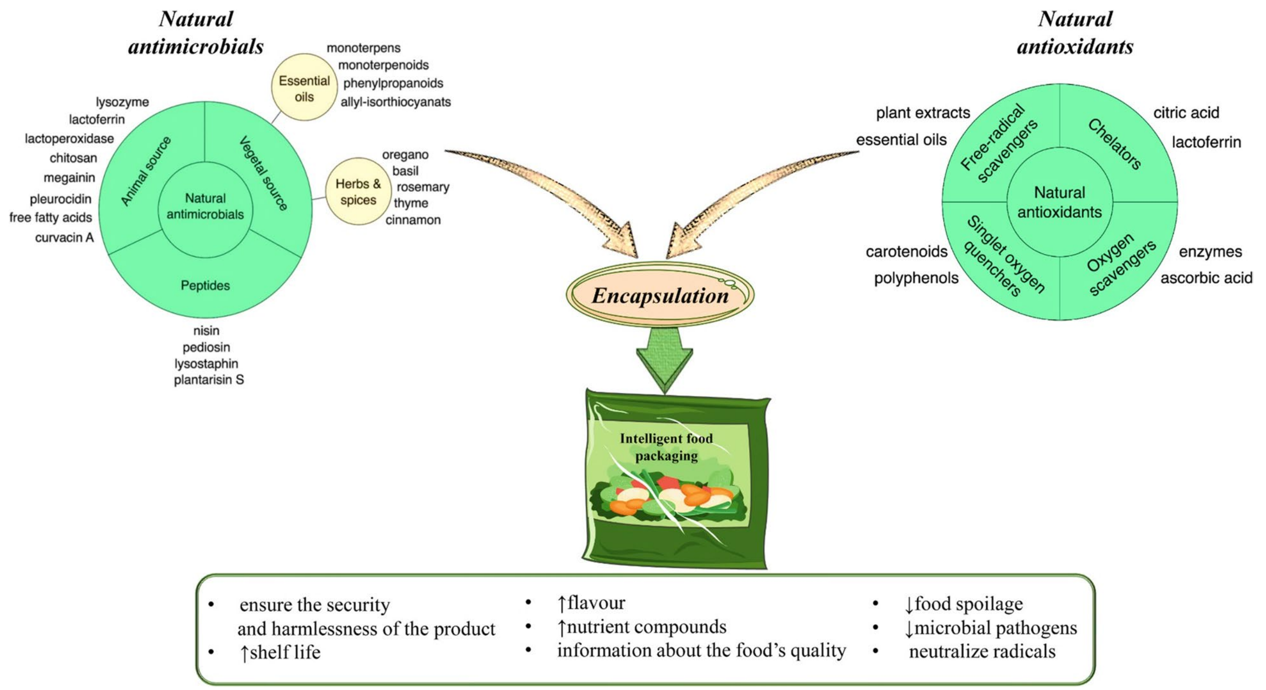


Fig. 2 Schematic representation regarding the role of natural compounds encapsulated as part of active food packaging

Table 4 Encapsulated antimicrobial natural extracts used in active food packaging

Natural extract	Vehicle	Purpose	Reference
Basil oil	Silica nanoparticles in chitosan films	Inhibition of Gram-positive and Gram negative bacteria and pathogenic yeast	(Sultan et al. 2023)
Red onion skin extract	Electrospinning encapsulation with ultrafine fibers of yellow and white sweet potato starch	Controlled release of phenol compounds with inhibition of *Escherichia coli* and *Staphylococcus aureus*	(Cruz et al. 2023)
Clove oil extract	Encapsulated into halloysite nanotubes and chitosan	In vitro inhibition of *Bacillus mojavensis* and *Escherichia coli*	(Saadat et al. 2022)
Thyme essential oil	Encapsulated into liposomes chitosan-based emulsions	Growing of mesophilic, phsychrotrophic bacteria, yeast and mould on Karish cheese	(Al-Moghazy et al. 2021)
Prunus domestica L	Encapsulated into κ-carrageenan-poly(vinyl alcohol)	Spoilage of minced beef meat	(Goudarzi et al. 2023)
Mentha longifolia L. essential oil extract	Encapsulated into carboxymethyl cellulose-gelatin nanofibers	Inhibition of microbial population in peeled giant freshwater prawn	(Shahbazi et al. 2021)
Cinnamaldehyde, limonene and eugenol	Encapsulated with β-cyclodextrins in the core of nanofibers via coaxial electrospinning	Improve functional properties of fish gelatin mat and prove antifungal activity	(Mahmood et al. 2023)
Carvacrol and thymol	Bionanocomposites based on thermoplastic starch and layered silicate	Active packaging of strawberries as protection against *Botrytis cinerea*	(Campos-Requena et al. 2017)
Ginger essential oil	Encapsulated in ultrafine fibers based on soy protein isolate, polyethylene oxide and zein	Reduce microbial contamination as food packaging	(Silva et al. 2018)

can oxidize components in the food, thus the shelf life of the product can be prolonged by minimizing oxidation process (M. Rangaraj et al. 2021). Synthetic antioxidant are widely used in food packaging, such as hydroquinone derivatives (tert-butylhydroquinone TBHQ), metal oxides, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), sulphites, among others (Berdahl et al. 2010). Despite the efficacy of these antioxidant agents, they have potential toxic effects on the organism, so natural alternatives in food are looked for constantly. Natural compounds present in plant extracts and essential oils have been serious candidates for their replacement in food-active packaging. Natural antioxidants used in active packaging can be classified by molecular structure or mechanism of reaction. Figure 2 shows a classification of natural antioxidants by reaction mechanism. These natural compounds have been micro- and nano encapsulated in order to model the release from the packaging into the food matrix, or can be fixed into the polymer matrices where they can act as oxygen scavengers (López-de-Dicastillo et al. 2012). Figure 2 and Table 5 show some examples of natural compounds encapsulated as part of active food packaging.

Encapsulation of natural functional ingredients in food packaging

Enrichment and fortification of food is a solution when nutrients are lost during the manufacturing of food or when the food matrix is not stable in time. The most common bioactive compounds incorporated in food as nutraceuticals are: polyphenols, carotenoids, phytosterols and probiotics (Ferreira & Santos 2023). An efficient encapsulation of these nutraceuticals or additives can assure the stability, protection and correct delivery of food (Ruiz Canizales et al. 2018). Several efforts have been made to achieve suitable encapsulation technologies to incorporate natural compounds in food to enrich their nutritional quality, they include spray and freeze drying (Fang & Bhandari 2012), fluid bed coating (Meiners 2012), extrusion (Hossain & Jayadeep 2022), emulsions (Zhang et al. 2023), liposomes (Bonechi et al. 2019), niosomes (Elmi et al. 2021), among others.

Probiotics have proved to be useful in facilitating the bioavailability of some nutrients and keeping thhealthth of the gastrointestinal tract (Wan et al. 2016). Encapsulation techniques have been applied to improve the administration of probiotics as functional ingredients along with natural extracts. *L. acidophilus* were co-encapsulated with *Ganoderma lingzhi* extract (Reishi medicinal mushroom) into alginate, chitosan, maltose hydroxyethyl-cellulose, hydroxypropyl methylcellulose and calcium lactate beads (Mirmazloum et al. 2021). Co-microencapsulation of *L. plantarum* along with docosahexaenoic acid (DHA) fatty acid-rich oil into algine-pectine-gelatin biocomposites showed that they increased the protective effect on the probiotic cells under in vitro gastrointestinal conditions (Vaziri et al. 2018). The stability of probiotics in simulated gastrointestinal conditihashave been also evaluated by delivering *Lactobacillus bulgaricus* and *Lactobacillus paracasei* from microcapsules based on calcium alginate coated with whey protein isolated wall system (Han et al. 2020). Composite microspheres produced by co-gelation of alginate and arabinoxylan for probiotic *L. plantarum* encapsulation have been developed for improving the survival rate of probiotics, storage stability and bile salt resistance (Wu & Zhang 2018). Several nutraceuticals have been obtained from waste along processes in the food industry. Valorisation of agroindustrial by-products has become a growing concern for economic and environmental reasons (O'Connor et al. 2021). Many of these agricultural product waste or non-edible parts of fruits could potentially

Table 5 Encapsulated antioxidant natural extracts used in active food packaging

Natural extract	Vehicle	Purpose	Reference
Thymol	Encapsulated in potato starch/mesoporous-silica	Sustained release of thymol	(Cui et al. 2023)
Red propolis extract	Microencapsulated by pray-drying/spray-chilling	Controlled release of flavonoids and formononetin	(Gomes Sá et al. 2023)
Açai fruits (*Euterpe oleracea* Mart.)	Encapsulated pulp with three-wall maltodextrin, Arabic gum and citrus pectin particles	Encapsulation efficiency of polyphenols and anthocyanins	(Murillo-Franco et al. 2023)
Pomegranate peels phenolic extract	Encapsulation into a matrix of sucrose	Antioxidant active packaging	(Chezanoglou et al. 2023)
Olive leaf extract (*Olea europea* L.)	Encapsulation into gelatin/tragacanth gum as wall materials	Reduce oxidative degradation of sheep meat hamburger	(Oliveira et al. 2022)
Eggplant peel extract	Encapsulated into maltodextrin/gum Arabic particles	Gummy candy for colour and overall acceptability	(Sarabandi et al. 2019)
Cordia myxa L. fruit extract	Micro and nanoencapsulated into alginate beads	Antioxidant capacity of phenolic compounds in food	(El-Massry et al. 2021)
Natural extracts: anthocyanins, tannin, anatto, curcuma, oliva oil	Encapsulated into silica network by acid or base-catalyzed sol–gel methods	Controlled release and antimicrobial effect over *Staphylococcus aureus*, *Escherichia coli*, *Bacillus cereus*, *Candida* sp. and *Aspergillus niger*	(Steiner et al. 2017)
Pimpinella anisum L. and *Coriandrum sativum* L	Co-encapsulated into chitosan nanoemulsions	Inhibition of fungal proliferation in stored rice	(Das et al. 2022)

provide valuable natural compounds that can be useful as prebiotics, antioxidants, water-holding and gel-forming products (Jouki et al. 2021). Encapsulation of these extracts by diverse technologies had helped in achieving potential bioactive formulations with functional properties. Brazilian guaraná peel extract has been studied for its carotenoid content to fortify food matrices such as peanut butter by the co-encapsulation of this functheseal ingredients (Silva et al. 2022b). Polyphenols from grace pomace have been extracted as a by-product from wine production and encapsulated into mesoporous silica-type matrices for use as nutraceuticals (Brezoiu et al. 2019). Melanoidins extracted from a food by-product have been micro- and nanonano encapsulatedo hydroxypropyl methylcellulose nanostructures and projected in a wide range of applications including food area (Silva et al. 2022c).

Encapsulation to protect different bioactive to be used as nutraceuticals and food ingredients

The pharmacokinetics of encapsulated bioactive compounds are improved as shown by in vitro digestion studies when compared with the unencapsulated compounds. In general, it improved the protection and release profile as shown by liposomes of phenolics compounds extracted from date palm seeds (*Phoenix dactylifera* L.) (Hashim et al. 2022); phenolic extract from cashew apple by-products which were freeze-dried using maltodextrin as encapsulating agent (Lima et al. 2022); polyphenol extracted from the waste biomass of *Camellia sinensis* (L.) Kuntze where it was found that the maximum release (>50%) of catechins was in the gastric phase followed by intestine and oral phases (Sharma & Kumar 2022); phenolic compounds of three *Vaccinium spp.* leaf extracts showed that the bioaccessibility of the microencapsulated extracts were higher than the non-encapsulated extract (Stefanescu et al. 2022); red onion (*Allium cepa* L.) skin anthocyanins encapsulated by gelation and free-drying using Arabic gum, carboxymethyl cellulose and soy protein isolate demonstrated that an increased polysaccharides concentration offered a controlled release of the anthocyanins in the intestinal medium, therefore, protecting the anthocyanins by the selected matrices against in vitro gastric digestion (Stoica et al. 2022). In addition, when mulberry (*Morus alba* L.) leaf extract was submitted to spray-drying and freeze-drying using sodium carboxymethyl cellulose and maltodextrin as encapsulating agent, the results showed that the product obtained using maltodextrin and spray-drying led to higher bioaccessibility and bioavailability, while carboxymethyl cellulose and freeze-drying resulted in a better efficiency. Also, from the results, it can be concluded that maltodextrin and carboxymethyl cellulose had a major effect on the digestibility and antioxidative activity, while the drying techniques (spray-drying and freeze-drying) influence the bioaccessibility and bioavailability of the bioactive compounds (e.g. phenolics compounds) (Tchabo et al. 2022). Despite all the efforts to protect the bioactive compounds, the final objective is to test if the encapsulated product could be used in food systems. Thus, sage (*Salvia officinalis* L.) leaf extract (SLE) was nano encapsulated using whey protein isolate and qodumeh shahri seed gum, then used to protect sunflower oil against oxidative degradation. The results showed that the nanoparticles had an encapsulation efficiency higher than 60% as well as gradual release during storage. Overall, encapsulated SLE proved to be a natural antioxidant to extend the shelf life and oxidative stability of sunflower oil (Safarpour et al. 2022). In a different study, chicken patties were added with pumpkin flower (*Cucurbita maxima* Duchesne) powder obtained by three different drying methods (foam-mat drying, freeze drying, and oven drying). Out of the three methods, the foam-mat drying method was selected to be incorporated in the chicken patties, since patties with this powder presented the better antioxidant scores (2,2-diphenyl-1-picrylhydrazyl DPPH, 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid ABTS, and ferric reducing antioxidant power FRAP) even after 7 days of storage. Also, the sensorial attributes of the chicken patties were improved as noted by consumers acceptance (Santos et al. 2022). Another example can be seen when phenolic-rich extract from grape pomace (*Vitis labrusca* L.) was microencapsulated and evaluated for lipid and protein oxidation in raw and precooked beef burgers. In general, the freeze-dried and microencapsulated grape extracts had better results than the synthetic antioxidant (sodium erythorbate) used as control, increasing the oxidative stability of beef burgers, with no significant colour changes during the storage (Silva et al. 2022a). Also, crackers have been used as a model to determine the suitability of incorporating red onion (*Allium cepa* L.) skin anthocyanins which were encapsulated by gelation and freeze-drying. After adding the powder to the crackers, an improvement of the functional characteristics such as antioxidant activity was seen. These results were supported by sensory tests which revealed that the new crackers with added powder (3%) had the highest score for general acceptability (Stoica et al. 2022).

Advantages of the encapsulation of bioactives for food and beverages

The use of certain bioactive compounds as ingredients for the preservation and enrichment of food or beverages is limited by a series of drawbacks. However, these drawbacks can be largely overcome by encapsulating them, making it possible to take advantage of all the functional properties of bioactive compounds.

Table 6 summarizes the main advantages of the encapsulation of bioactive compounds to enable their use as ingredients in foods and beverages.

Table 6 Main advantages of the encapsulation of bioactive compounds to enable their use as ingredients in food and beverages

Advantages	Reference
Control of the release of bioactive compounds	(Morales-Medina et al. 2022)
Increased dispersibility in the water of insoluble bioactive compounds	(Hu et al. 2015)
Increased bioaccessibility and bioavailability	(McClements et al. 2016)
Masking of undesirable organoleptic characteristics	(Yang et al. 2012)
Increased environmental, enzymatic and microbiological stability	(Barajas-Álvarez et al. 2022)
Preservation of food and beverages by obtaining active packaging with preservative properties	(Becerril et al. 2020; Ribeiro-Santos et al. 2017; Sharma et al. 2022)
Prevents undesirable interactions with the food matrix or other bioactive compound	(Nedovic et al. 2011; Tan et al. 2021)
Increase stability and prevent evaporation of aromatic compounds (e.g. essential oil) to preserve or improve the organoleptic profile of the product	(Kader and Abu Hashish 2020, Das et al. 2021, Jeyakumari 2016)
Protect the consumer from the irritant effect of some bioactive compounds	(Wu et al. 2022)
Improve handling of compounds bioactive by returning to the solid-state liquid components or oils	(Jeyakumari 2016)

Conclusion

Fruit juice is a valuable vehicle for delivering bioactive ingredients that can improve the nutritional quality and shelf life of the product while maintaining its fresh character and desired flavour profile. Encapsulation methods such as emulsion-based delivery systems, coacervation, liposomes, and inclusion complexation are popular options, each with its advantages and limitations. The choice of encapsulation method depends on the characteristics of the bioactive compound and the desired end product. It is important to ensure that the method does not adversely affect the organoleptic characteristics and microbiological stability of the juice and is palatable to the end consumer. In addition, enzymes and probiotics are widely used in the fruit juice industry to improve juice yield, flavour, and aroma, as well as to provide health benefits. However, further research is needed to optimize process variables and drying aids to increase the survival rate of probiotics in the final product, highlighting the potential of using spray drying techniques to produce probiotic-enriched fruit juice powders with improved stability and functionality. In summary, encapsulation techniques have proven to be a useful tool to improve the stability of bioactive compounds. Every one of them has advantages and disadvantages that must be considered when selecting the best for a given purpose. In addition, the selection of the most suitable encapsulating agent will also affect the physicochemical properties of the final product. Hence, further research is needed and especially, the incorporation of the encapsulated bioactive compound into real food matrixes.

Abbreviations

ABTS	2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid
ATPS	Two-phase system
BHA	Butylated hydroxyanisole
BHT	Butylated hydroxytoluene
CFU	Colony-forming unit
DE	Dextrose equivalent
DHA	Docosahexanoic acid
DPPH	2,2-Diphenyl-1-picrylhydrazyl
FRAP	Ferric reducing antioxidant power
IDE	Interdigitated electrode
MNP	Magnetic nanoparticle
O/W	Oil-in-water
PCB	Printed circuit board
PLGA	Poly(lactide-co-glycolide)
PVA	Polyvinyl alcohol
SHIME®	Simulator of the Human Intestinal Microbial Ecosystem
SLE	Sage leaf extract
TBHQ	Tert-butylhydroquinone
W/O/W	Water-in-oil-in-water

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