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BIOACTIVE ENCAPSULATION OF NATURAL COMPOUNDS: ADVANCES IN THE STABILIZATION OF BIOCOMPOUNDS AND PIGMENTS FROM *Opuntia spp*

Romina L. Abarca Oyarce
Departamento de Ciencias Animales, Facultad de Agronomía y Sistemas Naturales, Pontificia Universidad Católica de Chile, Santiago, Chile

Oliver Taype-Landeo
Universidad Nacional de Huancavelica, Perú

Abstract: The "ayrampo" prickly pear (Opuntia spp.) is a plant characteristic of arid and warm zones, recognized by its distinctive coloration that varies from fuchsia to deep purple. This plant contains high-value biocompounds, such as antioxidants, total polyphenols, betalains and vitamin C. Traditionally, it has been used in preparations such as mazamorras and chicha, in addition to being used as a natural remedy to reduce fever. However, the "ayrampo" prickly pear is at risk of extinction, which increases the relevance of research into its bioactive compounds and their preservation. The main objective of this study is to identify the most efficient techniques to stabilize the bioactive compounds of "ayrampo" prickly pear cactus through microencapsulation processes. The methodology used was based on an exhaustive review of various microencapsulation techniques (physical, chemical and physicochemical), classifying them according to their morphology into three main types: mononuclear, polynuclear and matrix type. The most prominent methods include spray drying, freeze drying and spray drying, using coatings such as maltodextrin, which is widely used in the stabilization of natural biocompounds. Among the most relevant bioactive compounds are flavonoids, a group of polyphenols present in foods of plant origin, as well as in honey and pollen. These compounds are recognized for their potent antioxidant, antibacterial, anti--inflammatory, antiviral and anticarcinogenic properties, making them valuable nutraceuticals for human health. In conclusion, microencapsulation techniques offer an effective way to protect, mask and improve the organoleptic characteristics of bioactive compounds, facilitating their use in the food and pharmaceutical industry. In addition to preserving the functionality of these ingredients, these technologies contribute to increasing their stability and efficacy, which translates into important health benefits.

Keywords: Tuna (Opuntia), Bioactive Compounds, Microencapsulation

INTRODUCTION

The prickly pear "ayrampo" is a cactus that presents bioactive compounds such as anthocyanins, polyphenols, a very important group that presents natural antioxidants, as well as vitamin C, with a characteristic and astringent flavor, capable of trapping free radicals that are the cause of chronic diseases (Jorge and Troncoso 2016). Biocompounds are extracted from vegetables (Guía, et al., 2022). Bioactive compounds are being valued and present stability and bioavailability, for their advantageous characteristics in their processing applied to nanotechnology (Bazana, et al., 2019). Antioxidants are compounds that trap free radicals and prevent cancer diseases; these antioxidants present in vegetables are not enough as a protector and advisable to formulate new functional products incorporating natural antioxidants as biocompounds (Ribeiro et al., 2019). The anthocyanin biocompounds, present in vegetables, are in flavonoids group, for their antioxidant properties present various benefits to human health, as a protector and release of their compounds (Gadioli, et al., 2020; Bazana, et al., 2019).

Bioactive compounds present in food, with respect to responsible consumption, present improvements in consumer health (Bazana, et al., 2019).

Consumers are currently more concerned about their health (Ribeiro, et al., 2020).

Increased interest in natural foods that are beneficial to health and less harmful to the human body (Ribeiro, et al., 2020).

Fruits and vegetables and dehydrated fruits, with healthy components are present daily and in referred amounts, without energetic effect (Ribeiro, et al., 2020).

The encapsulation presented an efficacy higher than 98% of betaxanthin and betacyanin compounds studied for both systems. This efficiency presented dynamic interactions between the polymer and betalains (Vergara et al., 2014). The encapsulation of the betalain compound has a favorable efficiency in opuntia ficus extracts, presenting superior at 60°C storage temperature. Hydrolysis influenced betalain degradability, and prickly pear microparticles present a potential of natural red color, for health foods (Vergara et al., 2014). Encapsulation by freeze-drying and spray drying to address the effect of operational parameters on physicochemical properties and preservation of polyphenol content in fruit encapsulates. Using a speci fi c fruit or vegetable pulp or extract, most of these studies have examined the search for a suitable wall (Ramirez et al., 2015).

Microencapsulation is a technological challenge and present a great interest in the development in the food industry and a promise in future research with new methodical potentialities in encapsulation that could raise these bioactive ingredients to the gastrointestinal tract and in a successful way (Champagne & Fustier 2007). Microencapsulation is an alternative to stabilize the properties and extracts of anthocyanins that are affected by pH, solvent, temperature and other environmental conditions and allow their addition to foods (Gadioli, et al., 2020).

Encapsulations by freeze-drying show inferiority to those encapsulated by spray-drying in the storage of polyphenol stability. It was also studied that the water activity of the encapsulates remains constant with the spray drying technique, during the shelf life analysis of 200 days (Ramirez et al., 2015).

Microencapsulation and nanoencapsulation can protect bioactive compounds from these factors allowing their controlled release, thus favoring their application. Various techniques and materials are used to construct these systems, which must be properly selected as they directly influence their functionality and structural characteristics. Recently, micro- and nanostructures have also been explored as BC carriers with the aim of combating microbial attacks on crops and extending the shelf life of food products.

Micro- and nano-encapsulation can facilitate their application by protecting the bioactive compounds from these factors and allowing their controlled release. Different techniques and materials are used to create these systems, which must be chosen precisely because they directly affect their performance and structural properties. Recently, it has been investigated as a BC carrier to combat microbial attacks on crops and extend the shelf life of food products (Guía, et al., 2022).

However, understanding the safety and toxicity of these nanomaterials requires more research, and global regulations should be drafted to promote the safe commercialization of new nanotechnology products that are (Bazana, et al., 2019).

Nanotechnology is increasingly used in food science, and one of the lines of research is the nanoencapsulation of bioactive compounds. While these compounds promote improvements in human health, they are often inadequately absorbed (Bazana, et al., 2019).

Thus, nanostructured systems improve several characteristics, such as protection against degradation, solubility, stability and bioavailability, among others (Bazana, et al., 2019).

However, the development of nanostructures faces many challenges, from choosing the best method to obtain them to identifying the ideal type of nanomaterial for a bioactive compound of interest (Bazana, et al., 2019).

Vitamin E presents different natural isoforms, being tocopherols and tocotrienols the most common ones. The correct amounts of this compound in the human organism can be maintained through a balanced daily diet, which should include the intake of food products such as green leafy vegetables, fruits, seeds, eggs, olives, nuts, cereals, among others (Ribeiro, et al., 2021(b)).

Bioactive compounds, considered essential for human health, are mostly hydrophobic and poorly soluble. Examples include phenolic compounds, carotenoids, essential oils, essential fatty acids and insoluble vitamins. The main challenges for the application of these compounds in the pharmaceutical and food industry include low bioavailability and stability (Bazana, et al., 2019).

Bioactive compounds (BC) extracted from plants have been the subject of study since ancient times due to their outstanding characteristics, such as antioxidant, anticancer, anti-inflammatory, and antimicrobial properties. This has led to the development of various extraction techniques, which are classified as conventional (e.g., Soxhlet extraction, maceration, and hydrodistillation) and non-conventional (e.g., ultrasound-assisted extraction, ohmic extraction, supercritical fluid extraction), both seeking high yields and recovery effectiveness. However, these compounds have a major disadvantage, as they are highly susceptible to degradation when exposed to heat, light and moisture, among other factors. Micro- and nanoencapsulation can protect bioactive compounds from these factors allowing their controlled release, thus favoring their application. Various techniques and materials are used to construct these systems, which must be properly selected as they directly influence their functionality and structural characteristics. Recently, micro- and nanostructures have also been explored as BC carriers with the aim of combating microbial attacks on crops and extending the shelf life of food products (Guía, et al., 2022).

THEORETICAL FRAMEWORK

BIOACTIVE COMPOUNDS

Nature has given us many blessings, being one of them the various bioactive compounds (phenolic compounds, essential oils, carotenoids, insoluble vitamins and essential fatty acids), present in vegetables, that their interest in extracting plant extracts, essential for health, is due to their own characteristics such as anticancer, antioxidant, antimicrobial and anti-inflammatory properties (Guía, et al., 2022; Bazana, et al., 2019). With main applications in the food and pharmaceutical industry contain low stability and bioavailability (Bazana, et al., 2019). There are agro-food products, more used worldwide based on fruits and vegetables, with potential bioactive components such as polyphenols, antioxidants and vitamins (Alu'datt, et al., 2022).

Bioactive compounds, extracted from fruits and vegetables are important sources and guarantee an encapsulation on the stability of antioxidants, polyphenols, which are obtained from vegetable source and act as a supplement in addition in food and mainly in benefit on human health (Ramirez, *et al.*, 2019 and Ochoa, L. *et al.*, 2015).

When subjected to heat by thermal processing of food, many of the molecules are susceptible and sensitive to degradation and oxidation (Alu'datt, et al., 2022).

At the same time, many bioactive compounds, such as zeaxanthin, are lipophilic and have low water solubility, which limits their application in food (De Campo, et al., 2018).

Fat-soluble substances present several natural isoforms that present vitamin E activity, being tocotrienols (α, β, γ and δ), tocopherols (α, β, γ and δ) and the two most common groups (Ribeiro, et al., 2021). Vitamin E was discovered in 1922, being lately the most investigated for its antioxidant, neuroprotective, therapeutic and anti-inflammatory proper-

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ties. A fat-soluble substance because it presents several isoforms, with respect to color it is associated with the safety, flavor and nutritional value of foods (Ghosh, et al., 2022; Ribeiro, et al., 2021 (b)). Similarly, research suggests that concentrated vitamin E above the daily recommended dose has beneficial effects on nutritional health and prevention of immunoregulatory, inflammatory, and fertility problems (Ribeiro, et al., 2021 (a)). Vitamins in the transformation stage generate losses, so they have to be protected by microencapsulation (Praveen and He 2020). Vitamin E is extremely sensitive to light, oxygen and alkalinity conditions, limiting its application (Ribeiro, et al., 2021 (b)). Therefore, several bioactive components, such as lipophilic, zeaxanthin, have low solubility in water, limiting their use in food. Likewise, the stability of the compounds is affected by exposure to oxygen, light and temperature (De Campo, et al., 2018).

Antioxidants are softer, available and natural substances, such as polyphenol, which are present in some common foods. The contribution of its antioxidant compound is not enough, forcing the production of functional products, added with natural antioxidant compounds (Ribeiro, et al., 2020). Figure 1 shows the traditional classification of bioactive compounds, phenolic and non-phenolic (Koop, et al., 2022).

STABILITY IN BIOCOMPOSITES

The stabilization of biocompounds such as betalains and polyphenols could be implemented with the use of microencapsulation technologies, using atomicity drying as a source (Desai and Park, 2005). Anthocyanins are affected by the type of solvent, temperature, pH, for this reason there is the possibility of microencapsulation and stability of these properties (Gadioli, et al., 2020). In this context, the use of natural pigments such as anthocyanins, betalains (Figure 2) and curcumin is increasing worldwide due to their stability, health benefits and color change (Abedi, et al., 2023). However, vitamins are very sensitive to unfavorable environments such as light, high temperatures, alkaline conditions and oxygen, their use of Vitamin E may be limited by its low water solubility (Ribeiro, et al., 2021 (a); Ribeiro, et al., 2021 (b)). A variety of food encapsulation materials including proteins, polysaccharides, other biopolymers and lipids, also known as walls, coatings, liners or carriers (Alu'datt, et al., 2022).

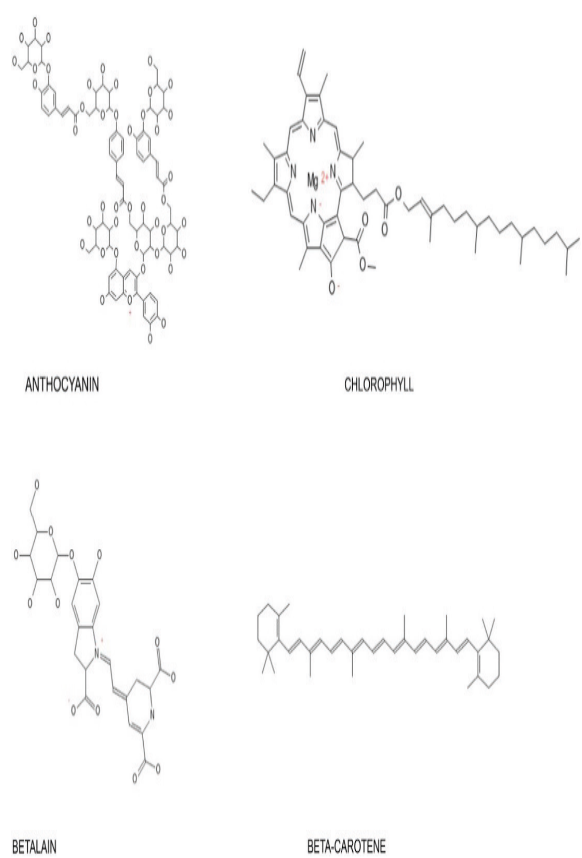

Figure 2. Examples of pigment molecules

Source: Ghosh, et al., (2022).

Thus, encapsulation adequately protects vitamin E being an option for its inclusion in functional products in the food, pharmaceutical and cosmetic industries in the future (Ribeiro, et al., 2021 (b)). It is advisable to optimize the parameters to efficiently encapsulate the

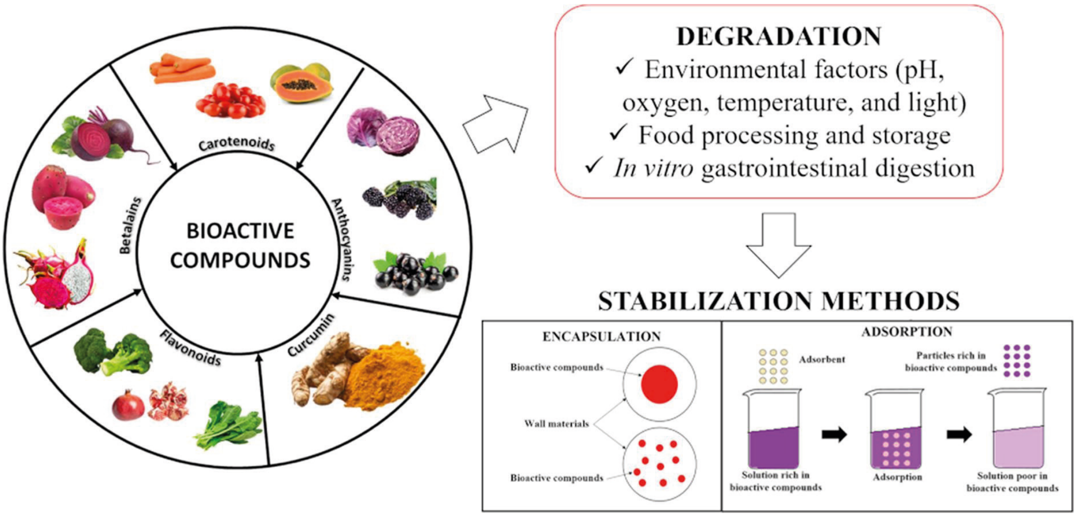

Figure 1. Traditional classification of bioactive compounds.

Source: Koop, et al., (2022).

stability of microparticles and to have an adequate purpose of the encapsulating agent with the desired characteristics of the final product (Estevinho et al., 2016; Carvalho et al., 2016). The stability of bioactive compounds is affected by light, oxygen and temperature; factors that contribute in their oxidation and isomerization. Therefore, new strategies are needed to improve their stability and solubility efficiency (De Campo, et al., 2018). Likewise, betalain stability is affected by temperature, pigment concentration, pH, co-presence of compounds, water activity, oxygen, light, chelating agents, storage, handling and enzymes (Ghosh, et al., 2022).

In the food industry, different flavors are used to satisfy consumers. Due to the industrial process, it is very sensitive and loses its characteristic flavor during processing and storage (Estevinho & Rocha, 2017).

Fragrances and flavors are highly volatile, react with other compounds and are sensitive to heat and moisture. In other cases, the flavor is only present during consumption or is expected to remain in the food for a long time. For these reasons, nanocapsules and microcapsules are very important to preserve flavor under optimal conditions (Estevinho & Rocha, 2017).

Vitamin E presents several important isoforms, of which alpha-tocopherol is the most abundant and active vitamin E found in nature. Therefore, in the present investigation, α-tocopherol was selected from different encapsulation materials by adsorption drying most suitable method in morphology techniques, size and properties of encapsulating particles, performance and release state (Ribeiro, et al., 2021).

Chlorophyll is unstable and its stability is strongly affected by pH, temperature, humidity and light. Chlorophyll is more thermolabile than carotenoids. Normal microwave heating destroys 42% to 100% of kiwifruit chlorophyll. Discoloration is usually due to loss of chlorophyll during processing and storage (Ghosh, et al., 2022).

The stability of the antioxidant compounds was successful, by the application of encapsulation, with favorable results (Ribeiro, et al., 2020).

The use of anthocyanins in foods and medicines is limited because it is established by degradation and unstable. Temperature, pH, oxygen, light, metal ions and enzymes affect the stability of anthocyanins (Ghosh, et al., 2022).

The present review inspects the effectiveness of encapsulation on bioactive compounds and how encapsulation technology can be used in the food industry to optimize and protect their biofunctional and bioactive property of natural foods (Alu'datt, et al., 2022).

PHENOLIC COMPOUNDS

Polyphenols, flavonoids and their glycosides are good sources of vitamin C, fatty acids, carotenoids and other antioxidants, making their nanoformulations effective in deterring various disease-causing microbes (Godswill, et al., 2022).

There are different chemical structures of phenolic compounds and intuit as flavonoids, stilbenes, phenolic acids and lignans. In addition, many of them are stronger antioxidants than antioxidant vitamins and their main functions is to be antibacterial, anti-inflammatory and antiviral, (Fang and Bhandari 2010).

In addition, the bioactive compounds in these fruits prevent oxidation by replacing synthetic antioxidants (De Campo, et al., 2018).

Polyphenols

Currently, it presents greater interest to study the encapsulation of polyphenols, which are present in yeast cells, β-cyclodextrins, alginate-gelatin mixtures, chitosan, proteins, maltodextrin, mesquite gum, gum arabic, and others, are used as wall or coating materials (Ribeiro et al., 2019). Natural polyphenols are valuable compounds that exhibit scavenging properties of oxygen radical trapping species (Corciova *et al.,* 2015).

It is associated with antioxidants due to the presence of polyphenols and carotenoids (De Campo, et al., 2018). Goji berries are used to acquire phenolic compounds that are used in the production of cosmetics, medicines and certain foods (De Campo, et al., 2018).

The dominant compound in the polyphenol subgroup of hydroxy- and methoxy-benzoic acids is gallic acid (3,4,5trihydroxybenzoic acid), which is normally found in plant tissues in ester form and is widely distributed in fruits and plants (Dewick, P., Haslam, E. 1969).

Betalaìnas

Betalains are natural pigments found in many green caryophyllous plants, with a progressive demand. Betalains present bioactives such as antioxidant, antitumor and anti-inflammatory; betalain is unstable mainly at temperature, environment and intrinsic (Carreon, et al., 2022). Betalains are water-soluble nitrogenous pigments, divided into betacyanins (red-violet) and betaxanthins (yellow-orange) with beneficial effects, containing antioxidant, antimicrobial and pH-regulating properties (Abedi, et al., 2023). Stabilization techniques, such as encapsulation, reduce the degradation of betalain (Carreon, et al., 2022). Currently, betalain is widely used as a food colorant due to its excellent color and homogeneity at pH 3 and 7 (Abedi, et al., 2023).

Betalains are used in food products and have many potential applications (Figure 3) (Carreón, et al., 2022).

Antioxidant capacity

Nowadays, more and more diseases such as cancer, Alzheimer's and Parkinson's are caused by free radicals that damage the immune system due to unbalanced antioxidant protection (Ribeiro, et al., 2020). By Ramirez, et al., (2019) mentions that, antioxidants are transcendental when obtaining a juice from citrus fruit sources, due to the healthy profile that the acquired beverage. Currently, various sources of antioxidants are found, therefore, they are available in agricultural residues such as in citrus peels, pomegranates, bananas and grapefruits. In this context, antioxidants

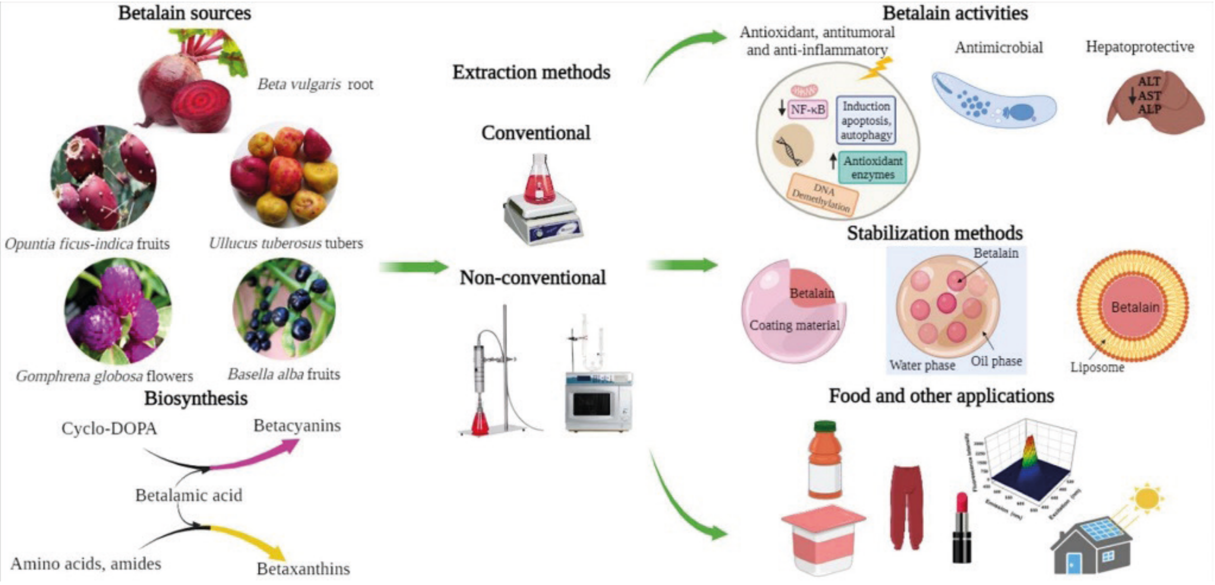

Figure 3. Betalaines in plant sources and their various applications

Source: Carreón, et al., (2022).

seem to be effective and offer good protection against the diseases mentioned above (Ribeiro, et al., 2020).

Antioxidants are soft substances and are naturally present, such as polyphenols, in some everyday foods. They lack antioxidants that are necessary their functionality in protecting antioxidant compounds to prevent degenerative diseases (Ribeiro et al., 2019; Ribeiro, et al., 2020). In the face of oxidative damage to the human organism, due to their high capacity to interact with free radicals, inhibiting oxidative reactions (Casanova, Estevinho, & Santos, 2016).

Flavonoids

Flavonoids are the most important polyphenols and are found in a free and glycosylated phase, the largest group of natural phenols. They are present in plant origin and widely distributed in plants, flowers, fruits, vegetables, honey and pollen. Being the important qualities that flavonoids produce, for the treatment of various ailments such as inflammation or cancer, disease including anticancer, anti-inflammatory, antibacterial, immunostimulant, anti-allergic and antiviral and for cosmetic purposes in anti-aging, or for nutraceutical applications and represent a very valuable component in the diet of humans (Corciova *et al.*, 2015; Dawidowicz et al., 2006).

Flavonoids, as natural antioxidant agents, protect the body from oxidative reactions by trapping radicals (reducing agents) (Routray and Orsat, 2012).

Enhancement of biological properties by encapsulation

Bioactive compounds can exhibit a variety of biological properties, such as antioxidant, antidiabetic, antihypertensive, antimicrobial, antiallergic, anti-inflammatory, immunomodulatory, neuroprotective, and anticancer properties (Alu'datt, et al., 2022). Encapsulation and adsorption increase the thermal and chemical stability of biologically active compounds (Koop, et al., 2022).

Several studies have shown that encapsulation can preserve and enhance these properties by protecting bioactive substances from adverse conditions and facilitating transport to target tissues or cells (Alu'datt, et al., 2022).

Encapsulation of bioactive compounds

The term encapsulation is one of the few technologies, which is experiencing continuous growth for its potentialities, in maintaining process or improving physicochemical properties by encapsulating bioactive compounds in coating materials during food processing, storage or consumption (Figure 4.) (Cerro, et al., 2023; Alu'datt, et al., 2022). Encapsulation protects pigments from degradation and improves their efficiency and performance in the food industry in an invisible way (Ghosh, et al., 2022; Estevinho & Rocha, 2017). The encapsulation process is a technology of encapsulating liquid, solid, or gas compounds in small sealed containers called capsules. Several manufacturers of membrane capsules can make them in nanometer (<1.0 μm) or micrometer (1.0-1000 μm) sizes employing natural materials such as gums, polysaccharides, proteins, and lipids (Guía, et al., 2022; Ribeiro, et al., 2021 (b)). Encapsulation is the process by which a core, which can be solid, liquid or gaseous, is covered with a permanent film of a natural or synthetic polymer (encapsulation). agent or wall material to protect against adverse environmental systems and its controlled release in terms of time, rate, amount and duration of operation (Ribeiro, et al., 2021 (b)). Coating is the process of capsulating an active material with a continuous film of a synthetic or natural polymer. It is mainly used to protect sensitive inputs from adverse environments and to control instant, velocity, size and position. The capsules contain bioactive compounds such as terpenes, polyphenols, and betalains, to preserve and enhance their activity by increasing their solubility and bioavailability (Ribeiro, et al., 2021; Guía, et al., 2022). The resulting particles (capsules, spheres or emulsions), fibers or films can have different morphologies, composition and size (Ribeiro, et al., 2021 (b)).

Several encapsulating techniques for less water-soluble bioactive compounds capsulated influencing polymeric carriers or biodegradable catalysts as a controlled process have been reported and discussed (Dong, et al., 2019; Estevinho & Rocha, 2017).

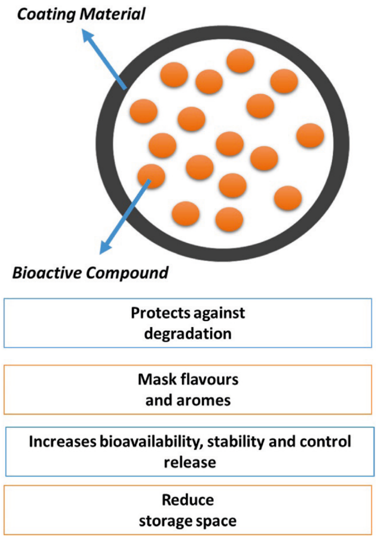

Figure 4. Structure of the frequent active compound encapsulation scheme and its benefits.

Source: Cerro, et al., (2023).

Encapsulation techniques

The traditional encapsulation technique, which requires very high temperatures, does not guarantee the stability of heat-sensitive materials such as antioxidants. Therefore, other methods, such as high pressure, can allow the formation of particles and guarantee the quality of active compounds (Cruz, et al., 2020). The encapsulation technique most commonly used in the preservation and administration of vitamin E over the years (Ribeiro, et al., 2021 (b)). There are various techniques of encapsulating food bioactive compounds, textile and pharmaceutical industry, adequately and availability of equipment (Ribeiro, & Velosob, 2021; Ghosh, et al., 2022) that, facilitates the solubility of hydrophobic compounds in hydrophilic media and allows the presence of lipophilic bioactive compounds in functional foods, which are difficult to overcome for food application. Encapsulation prevents the loss of volatile compounds and hides unfavorable odors and flavors (Cruz, et al., 2020).

Methods to extend shelf life have been investigated, especially sputtering, drying, double coating, gelation by ion spraying, nanoliposomes, hydrogels, cocrystallization, and unexplored methods such as complex coacervation, and electrospraying (Carreón, et al., 2022). Encapsulation is the process of surrounding the core (bioactive compound) with a wall of multilayer material. The resulting particles have a micro or nanometer size (Guía, et al., 2022). Regarding the core material, many studies focused on encapsulating natural colorants, due to the high commercialization of food additives (Ribeiro, & Velosob, 2021). Encapsulation helps to create good sensory qualities such as aroma, texture, color and flavor, as they play an important role in the design and development of new foods and beverages (Alu'datt, et al., 2022). Micro- and nanoscale pigment encapsulation provides a broad and powerful platform for the development of new steps in the production of novel and healthy foods (Ghosh, et al., 2022). The importance of encapsulation with vitamin E and discuss aspects such as composition, sources and therapeutic properties of the vitamin. Finally, for each application and route of administration of vitamin E, different combination procedures were compared and contrasted to evaluate the method of food administration (Ribeiro, et al., 2021 (b)).

Yacon leaves, root and flower petals were encapsulated for their phytochemical, antioxidant, antimicrobial, antibacterial and anti-inflammatory properties in the food and health industry (Cruz, et al., 2020). Microencapsulation and nanoencapsulation is an effective platform to provide controlled and targeted release by protecting pigments from harmful environmental conditions and with this we can obtain a number of desired effects such as protection to adverse conditions, among others (**Figure 5.**) (Ghosh, et al., 2022).

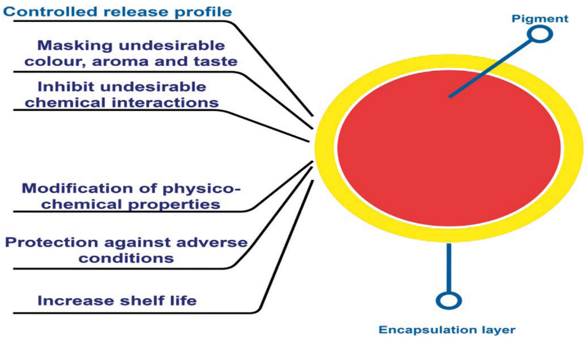

Figure 5. Pigment encapsulation according to purpose.

Source: Ghosh, et al., (2022).

Encapsulation (nanocapsules and microcapsules) is the most demanding technology with new methods, biotechnological materials and natural colorants. In recent years, it has been widely used in the food industry because it can increase the stability of the coating by reducing exposure to air and other nutrients, which is one of the most important factors in product development (Ribeiro, & Velosob, 2021; Estevinho & Rocha, 2017). Microencapsulation and nanoencapsulation are seditious methods for the inspected and targeted release of pigments that enhance system design for anti-inflammatory activity and future experimental applications in food films and coatings (Ghosh, et al., 2022; Leite, et al., 2023).

MICROENCAPSULATION

Microencapsulation offers important advantages to the pharmaceutical industry in the controlled release for oral formulation of health-promoting bioactive compounds and therapeutic enzymes (Bodade, & Bodade, 2020). The microencapsulation technique is shown to be effective in protecting pigments from unfavorable environmental conditions and allows for controlled and targeted release (Ghosh, et al., 2022). Microencapsulation is a technique that, is being widely applied in optimizing bioactive compounds and conducive to combine ingredients of synergistic active compounds, for the production of functional foods, being a technique (Champagne & Fustier 2007) that allows transforming food juice into solid powder (Sobel et al., 2014). An encapsulation of the size of 1μ is obtained, by a layer of polymers. The encapsulating agent is comprised of an internal phase (core material, filler, active agent) and wall material or external phase (carrier material, coating, matrix) (Zuidam & Shimoni, 2010).

These biocompounds have been widely used in the pharmaceutical industry as vaccines and more frequently used in the incorporation of new food products in the food industry for their functionality (Olive Li, Dueik Gonzalez, & Diosady, 2014). The use of coatings provides protection by masking these sensitive compounds, resulting in their long-term stability and disintegration of the drug (Bodade, & Bodade, 2020).

Types of Microencapsulation

Microencapsules are classified in three conventions according to their morphology as: mononuclear, polynuclear and matrix type, so there are several types of microcapsules (Ghosh, 2006), as shown in Figure N° 6.

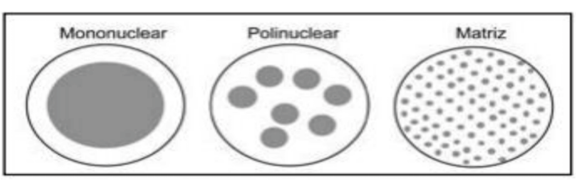

Figure 6: Types of microcapsules (Ghosh, 2006).

Microencapsulation techniques and methods

Microencapsulation is a scientific method of food to increase safety and control the release of colors, flavors, fats, nutrients, enzymes, microorganisms and cosmetics (Ribeiro, & Velosob, 2021).

This method reduces the effect of high temperatures on the dye, reduces water activity (reduces bacterial load and storage and transport costs) and allows the use of compounds present in food, being possible incongruent by pH or dissolution situations (Ribeiro, & Velosob, 2021).

The techniques in microencapsulation are four main ones such as: spray coating, atomization, and extrusion one of the physical processes, while emulsion is based on chemicals. The last one is based on techniques to encapsulate vitamins (Oxley 2014). Currently, there are many techniques in coating in encapsulation of various biocomponents such as hydrophilic and hydrophobic and emulsion, spray coating (Champagne & Fustier 2007).

The most widely used microencapsulation is the spray drying technique, due to its low cost, flexibility and high encapsulation efficiency and accepted by several authors (Ribeiro et al., 2019) and the spray drying technique most used in natural dyes (Ribeiro, & Velosob, 2021).

Microencapsulation has been extensively studied to increase the stability and utilization of natural colorants in foods (Ribeiro, & Velosob, 2021).

Microencapsulation is the process of encapsulating a material with an insulator to form a non-porous film that protects bioactive food compounds. This process is widely used in food research to preserve and conserve colors, flavors, antioxidants, enzymes, nutrients, preservatives and microorganisms. The purpose of the coating is to protect surfaces from light, heat, oxidation and moisture (Ribeiro, & Velosob, 2021).

Spray drying is a widely used technique due to its low cost, ease of use, continuous operation, and availability. On the other hand, the drying time of this process is short and can be used several times to protect thermosensitive materials (Ribeiro, et al., 2021). It involves mostly production processes in the form of liquid, powder and gas, then surrounding the encapsulating droplets in liquid or gas phase, with the exception of the use of yeast as natural encapsulants (Zuidam & Shimoni, 2010).

Microencapsulation today

Currently the most widely used microencapsulation technology aimed at preserving and protecting sensitive food ingredients such as protein and peptides is the microencapsulation of environmental elements by spray drying, which has increased the stability of biocompounds. Maltodextrin and WPC is a mixture being the best wall with a protective capacity, for microencapsulation of hydrolyzed proteins and their protection against UV radiation (Sadeghi, A. *et al.*,2020; Praveen and He 2020).

Future research is likely to use coencapsulation methodologies or techniques, through the addition of bioactive compounds, for the production of functional foods developed for the food industry (Champagne & Fustier 2007).

In recent years, several methods and techniques have been developed for the encapsulation of various bioactive products in the food, pharmaceutical and cosmetic industries. These two parameters must be carefully selected as they affect the final characteristics of the material and the encapsulation process (Ribeiro, et al., 2021).

Microencapsulation of bioactive compounds

Encapsulation favors bioactive compounds of plant origin, mainly probiotics, vitamins, minerals, fatty acids, lutein, phytosterols, lycopene and antioxidants, combining many bioactive ingredients to obtain highly synergistic compounds (Champagne & Fustier 2007).

Several reports have confirmed that this process is technically and economically advantageous for various bioactive products and plant extracts for therapeutic applications. Among therapeutic proteins, enzymes are unique for some diseases due to their high activity and selectivity (Bodade, & Bodade, 2020). It is advisable to deploy new options in inquiring a carbohydrate-based coating or substantial ingredients to have a stable, assimilable and undoubted vitamin for consumption (Praveen and He 2020). Microencapsulation provides important advantages in the pharmaceutical industry over oral formulations with controlled release of bioactive health compounds and therapeutic enzymes (Bodade, & Bodade, 2020).

NANOENCAPSULATION

Recently, nanoencapsulation has played an important role in determining the development of bioactive and therapeutic drug supplements in the food industry (Ghosh, et al., 2022).

In recent years, there has been a growing interest in the nanoencapsulation of bioactive compounds for the nutraceutical industry and food products using the Supercritical Fluid Emulsion process for the production of useful functional foods and nutraceuticals (Cerro, et al., 2023). The development of nanocapsule delivery of bioactive compounds has attracted great interest due to their unique characteristics such as high encapsulation efficiency and loading efficiency, enhanced bioavailability, improved stability, sustained release profile and tasteless mask (Kailash, et al., 2023). Nanoencapsulation is defined as the technology of encapsulating gaseous, liquid or solid nanoparticles, also called nuclei or actives, in nanocapsules within another material called matrix or shell (Kailash, et al., 2023). Nanoencapsulation tends to protect bioactive compounds from nutrients, nutraceuticals, including emulsification, coacervation and supercritical fluids and other bioactive ingredients (Godswill, et al., 2022). Nanoencapsulation involves a technology in the processing of nanometer level particles, solubilizing lipid nuclei and entrapping in biodegradable particle. This method allows soluble food bioactive compounds to dissolve and protects from thermal oxidation and chemical degradation (De Campo, et al., 2018).

Nanoencapsulation involves the encapsulations of substances in nanocarriers through adsorptions, incorporations, chemical interactions or dispersions (Bazana, et al., 2019).

Nanocapsules of bioactive compounds play an important role in the fight against unwanted diseases as they are concentrated in food and the body. Nanoencapsulated food delivery systems use a variety of natural and synthetic ingredients designed for better bioavailability and preservation of active ingredients (Godswill, et al., 2022), being key future benefits/prospects for nanoencapsulation of bioactive compounds (Bazana et al., 2019), as well as recent advances in extraction routes, quality control measures and encapsulation techniques for saffron bioactive compounds (Garavand et al., 2019).

For nanoencapsulation purposes, the use of mucilages and gums for wall materials has been investigated to demonstrate their effective to protect the encapsulated compounds (De Campo, et al., 2018).

Nanoencapsulation techniques

There are several techniques for nanoencapsulation of food ingredients, such as emulsions, coacervation, inclusion, and nanoprecipitation of complexation. These techniques reduce the effect of high dye temperature, reduce water activity (reduces microbial growth and storage and transport) and improve the use of biocompounds in foods, being incompatible in solubility or pH conditions (Ghosh, et al., 2022; Ribeiro, & Velosob, 2021).

Nanoencapsulation today

Nanoencapsulation is revolutionizing the entire food, pharmaceutical, nutraceutical and agricultural industries, enabling the safety of nanomaterials in the agroindustrial industry and being able to protect various compounds, as seen in Figure 7. (Godswill, et al., 2022).

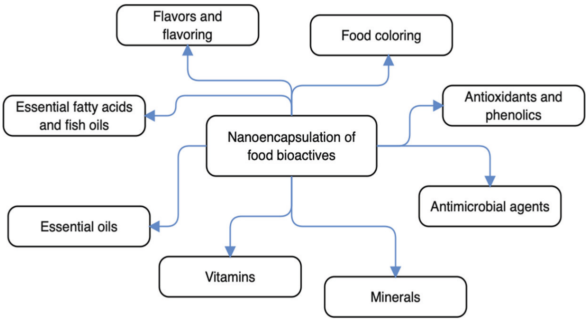

Figure 7. Different compounds that are currently being nanoencapsulated.

Source: Godswill, et al., (2022).

Nanoencapsulation technology has a high level of sustained release and biocompatibility with tissues and cells, which can alter the bioavailability of drugs and improve the pharmacokinetic profile of various agents. In addition, antimicrobial chemical encapsulation reduces toxicity, overcomes resistance and reduces distribution costs (Kailash, et al., 2023).

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Vitamins in nanocapsules are important micronutrients in the body because they are molecular organic and water-soluble vitamins. Nanocapsules in carbohydrates is employed as a food ingredient (Godswill, et al., 2022). Currently, the introduction of nanomaterials in industrial products, including food, is becoming increasingly important as a way to offer new additional functionalities and novel benefits to consumers (Bazana, et al., 2019). In recent decades, the food and agricultural industries have used nanotechnology in a variety of ways, including the use of nanostructures in solid emulsions to improve the texture, taste and stability of food products (Godswill, et al., 2022).

Nanocarriers

Nanocarriers tend to transform the release of antimicrobials keep them out of the adverse environment, improve stability and reduce the side effects and impact of antimicrobials (Kailash, et al., 2023).

Nanocarriers in general and inorganic nanocarriers such as metal nanostructure as quantum dots and organic nanocarriers such as, polymeric nanoparticles and liposomes, carbon-based nanoemulsions and nanocarriers, dendrimers, hydrogels, etc. are considerably used in nutraceuticals and food (Godswill, et al., 2022). Nanocapsule technology has characteristics of stable growth, small particle size and good interaction with tissue cells, which has changed the biotransformation of drugs and improved the pharmacological properties of various active substances, reducing toxicity (Kailash, et al., 2023).

Supercritical fluid

The use of supercritical fluids in encapsulation processes has a number of advantages, such as: high purity of the final product; controlled crystalline polymorphism; Capable of performing unique and environmentally friendly work (Cruz, et al., 2020).

Recently, supercritical fluid technology has emerged as an innovative eco-friendly method to encapsulate bioactive compounds using supercritical carbon dioxide ($scCO_2$). CO2 is a food grade solvent generally recognized as Safe (GRAS), inert, flammable and non-toxic (Tirado, et al., 2021). Currently, the use of pressurized fluids to obtain particles formed in a polymer matrix is the subject of research in various industrial and scientific fields. The pressurized, supercritical fluid has a high degree of dispersion in micro and nanoparticle particles (Cruz, et al., 2020). The process, called supercritical particle emulsification (SFEE), combines conventional emulsification technique with the unique properties of the supercritical fluid to produce micro- and nanoparticles (De Aguiar, et al., 2016). An example of the above is shown in **Figure 8** when working with leaf extracts.

Several techniques based on supercritical fluids have been proposed to explore the solvent power handling characteristics and high diffusivity that are characteristic of fluids near the critical point (Cruz, et al., 2020). An advantage of SFEE over other supercritical fluid deposition methods is the correlation between the emulsion droplet diameter distribution and the final diameter distribution of the suspended solid. Therefore, the particle size of the final suspension can be controlled by several parameters that directly affect the final size of the resulting emulsion droplets (Aguiar, et al., 2016).

Supercritical fluid based technology offers many preeminences for the production of natural compounds such as quercetin.

Many techniques based on $scCO_2$ allow the production of sensitive materials at moderate temperature and unfavorable conditions, while avoiding contamination and degradation of the components (Dong, et al., 2019).

There are other supercritical fluid encapsulation methods using CO_2 as catalyst or solvent, as well as rapid expansion of supercritical solutions and critical solution process using CO_2 acts as solvent; however, it is used in the gas liquid saturated gas saturated (PGSS) process with CO_2. On the other hand, precipitation and supercritical antisolvents (SAS) or supercritical fluid extraction emulsions (SFEE) use CO_2, as an antisolvent (Cerro, et al., 2023).

Quercetin nanocapsules encapsulated in polysorbate 80, a nonionic emulsifier and surfactant which, widely used in food and cosmetics, were prepared by supercritical fluid emulsion extraction method of emulsion extraction, according to the study (Dong, et al., 2019).

Research to date has focused on supercritical fluid technology in the production of ingredients in various industries such as pharmaceuticals, cosmetics in particle formation in different fields, cosmetology, pharmaceuticals, and food.

The different supercritical fluid processes available to produce encapsulations of bioactive compounds, with respect to many investigations were discussed.

Quercetin is a bioflavonoid found in fruits, vegetables and oils. In addition to quercetin it is widely researched for its anti-inflammatory, anticancer and antioxidant (Dong, et al., 2019)

FUTURE TRENDS

Research in recent years has confirmed that tocotrienols possess effective anticancer, cholesterol-lowering and antioxidant capacities, sometimes even more effectively than α-tocopherol (Ribeiro, et al (b)). This is why encapsulated pigments are employed for functional products in foods (Ghosh, et al., 2022).

Future technological challenges depend mainly on research to increase the color intensity and stability of natural pigments through microencapsulation and nanoencapsulation methods, as well as the design of pigment blends to enhance desired nutritional properties (Ghosh, et al., 2022). In addition, with the increasing demand for compounds with antioxidant properties, research in the search for new antioxidant products and their incorporation into foods, medicines and cosmetics is always beneficial (Ribeiro, et al., 2020; Alu'datt, et al., 2022).

Encapsulation of bioactive compound from agri-food sources has become a promising alternative not only to create new functional food products but also to increase the use of agro-industrial by-products as food, for the boost of food circular economy (Alu'datt, et al., 2022).

In the food industry, color encapsulation masks flavor or aroma, maintain stability and add functionality to foods. They offer many advantages, such as nutritional and biofunctional and inspected release of encapsulated pigments in specific areas (Ghosh, et al., 2022).

Many studies have justified that valuable bioactive compounds can be extracted from processed food by-products and their solubility, stability, and biochemical properties can be improved (Alu'datt, et al., 2022).

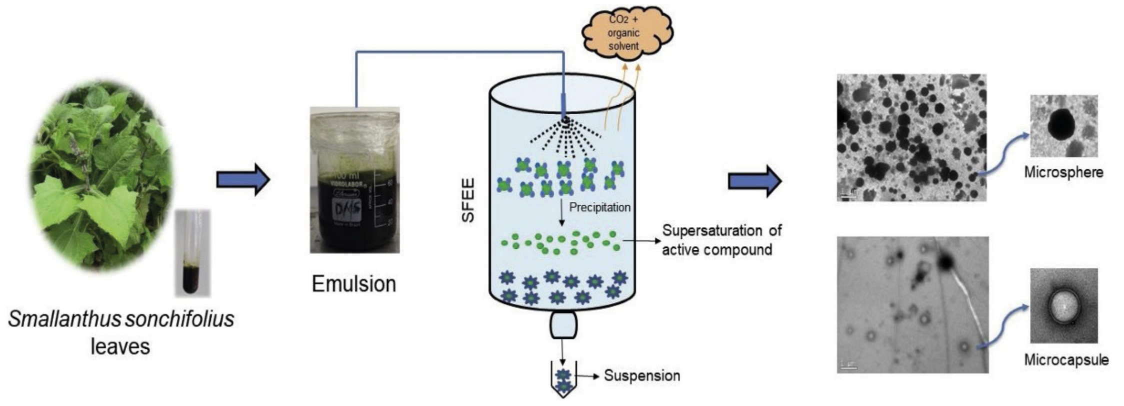

Figure 8: Encapsulation of *Smallanthus* sonchifolius leaf extract**.**

Source: Cruz, et al., (2020).

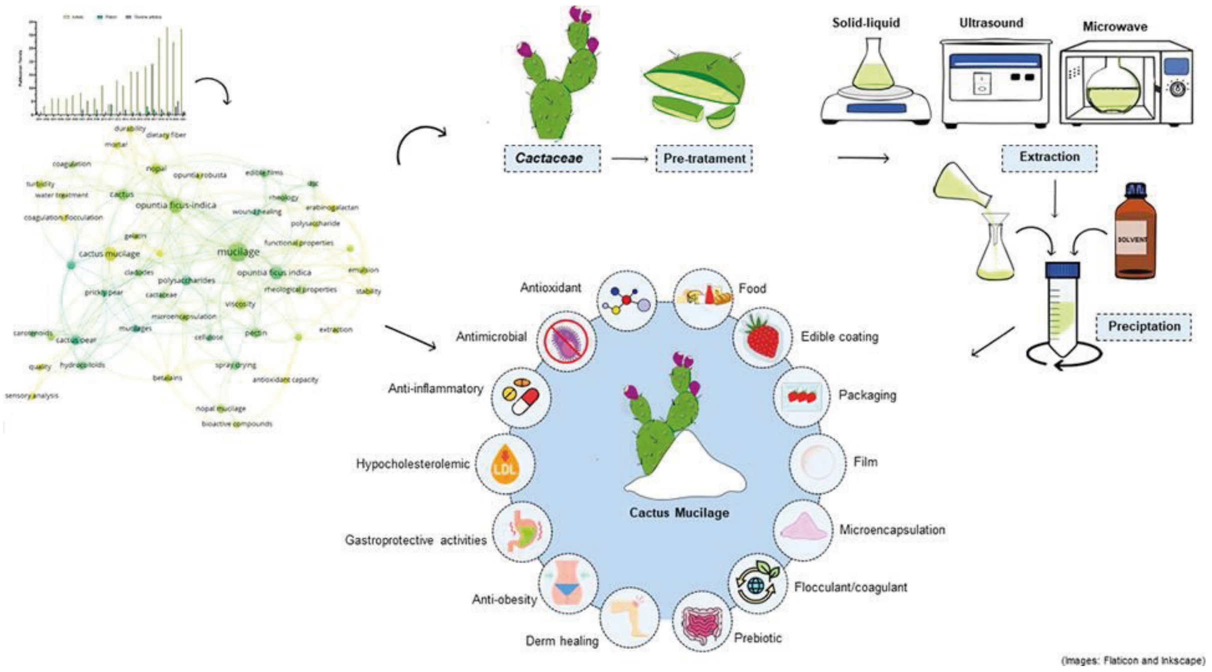

Figure 9. Biopotential use of cactus mucilage.

Source: Vieira & de Magalhães (2023).

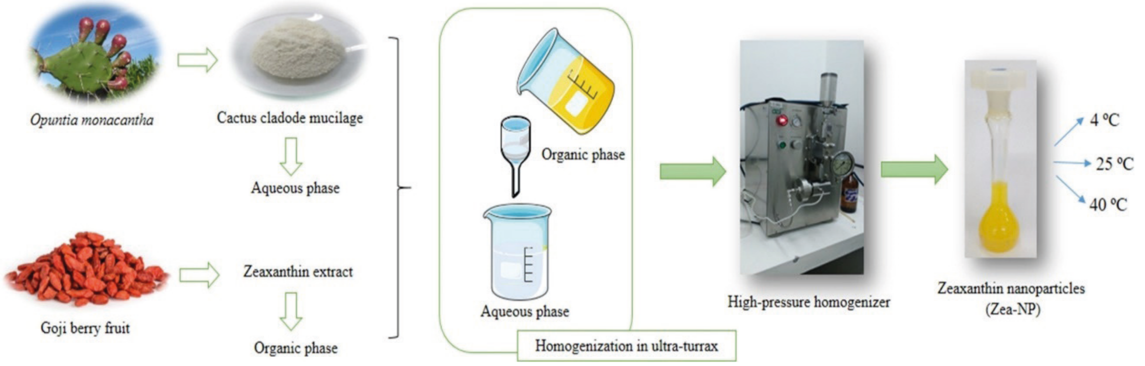

Figure10. Nanoencapsulation of zeaxanthin with *Opuntia monacantha* mucilage as a structuring material.

Source: De Campo et al., (2018).

OPUNTIAS

The Cactaceae is a family that rarely grows in other continents, are divided into 175 genera and there are more than 2,000 species and are native to all of the Americas (Vieira, & Magalhães, 2023).

OPUNTIA MUCILAGES

Mucilages are composed of plant-derived materials, especially water-soluble polysaccharides, and heterogeneous polysaccharide that are edible, bioactive and of natural origin, making them useful materials at the nanoscale (Nedovic, et al., 2011; Vieira, & Magalhães, 2023). Nopal cactus mucilage has been widely studied in various applications (Vieira, & Magalhães, 2023) and they are non-toxic and present an accessible cost (Prajapati, et al., 2013).

They are usually characterized as polysaccharides of the arabinogalactan type, which are a source of minerals, proteins, essential amino acids, fatty acids, proteins and phenolic compounds (Vieira, & Magalhães, 2023). It can be classified as native gum as it is derived from a natural source and its main advantages are non-toxic properties, flexibility, bioavailability, biodegradability and affordability (Taheri & Mahdi Jafari, 2019). These properties enable them to act as emulsifiers, stabilizers, foamers and thickeners. Therefore, they are used in dairy products, bakery products, emulsifiers and powdered products, as well as in microcapsule products, coatings and/or ecological films, focused on food and cosmetic products (Vieira, & Magalhães, 2023).

In addition, polysaccharides such as mucilage from the Cactaceae family, are raw materials used in the food industry and many of them have been used to improve the rheological properties of products (De Campo, et al., 2018). Its main beneficial properties are antioxidant, antimicrobial, prebiotic, healing, anti-ulcer, anti-inflammatory, hyperlipidemic and slimming effects (Vieira, & Magalhães, 2023). The process of obtaining and using cactus mucilage is shown in **Figure 9.**

STUDIES CARRIED OUT WITH OPUNTIAS

The cactus cladode mucilage protects *zeaxanthin* from degradation and has the potential to be used as a structural material for nanoencapsulation. The stability of nanoencapsulated and non-encapsulated *zeaxanthin* was evaluated in terms of particle size, pH, color and percent *zeaxanthin* retention during storage at 4, 25 and 40 °C for 28 days (**Figure 10.**) (De Campo, et al., 2018).

TUNA AYRAMPO (*Opuntia apurimacensis*)

Tuna ayrampo (*Opuntia apurimacensis*) is cultivated in warm climates and in different regions of Peru, such as Huancavelica, Ayacucho and Arequipa, including Lima, and also in the Apurimac region, between Andahuaylas and Abancay (Ostolaza C. 2004). No documented information on the various uses of ayrampo has been found and is lacking. It is also used as a natural medicine by villagers and is found in the district of San Miguel de Mayocc, Churcampa, in the Huancavelica region (Jorge, P. and Troncoso, L. 2016).

Rettir, R., Crook, Mottram (1995) *Opuntia apurimacensis* grows shrubby and presents an altitude of up to 1 meter. The shoots are 15 to 20 centimeters long with pointed tips, 1 to 2 centimeters thick and 6 to 10 centimeters wide. The oval to radial crowns sit in small bumps. The brownish-yellow glochids are up to 3 millimeters long. The slender spines are one or two, protruding and rectally whitish. They are 3 to 7 millimeters long.

The flowers have a lemon-yellow coloration from 6.5 to 7 centimeters long. The bright red fruits are up to 6 inches long.

BOTANICAL DESCRIPTION

Order	Similar to the lavo (*Caryophyllales*)
Family	Cactus family (*Cactaceae*)
Subfamily	Opuntioideae
Tribe:	Opuntieae
Genus	Opuntia (*Opuntia*)
Type:	*Opuntia apurimacensis*
Scientific name:	*Opuntia apurimacensis*
Common name:	*Ayrampo, Ayrampu, Airampo.*

Source: Rettir, R., Crook, Mottram (1995).

Chemical composition of the tuna ayrampo

The ayrampo has a high index of antioxidant capacity due to bioactive components such as Vitamin C, total polyphenols, betalains which are high concentrations, which are directly related to the flavor, astringency, aroma and color of food. For this reason, polyphenolic compounds make up a large group of natural antioxidants that are capable of neutralizing and trapping free radicals, which is why their consumption is recommended to prevent chronic diseases (Jorge, P. and Troncoso, L. 2016).

Variables	Ayrampo Tuna
Vitamin C (mg of ascorbic acid in 100 g of ff)	49,9 ± 6,3
Total polyphenols (mg gallic acid equivalents in 100 g of ff)	107,3 ± 10,6
FRAP (mmoles of Fe-II in 100 g of ff)	1.1 ± 0.1
Contribution of vitamin C to antioxidant capacity (percentage)	68.5

Table 1. Concentration of biocomponents of the ayrampo prickly pear cactus

Source: Jorge, P. and Troncoso, L. (2016).

Situation of the ayrampo prickly pear in Peru

Ostolaza, C. (2004) describes that the ayrampo prickly pear is cultivated in several regions of Peru, including Lima, and ayrampo is distributed in the Apurimac Region, between Andahuaylas and Abancay, and has a characteristic purple color.

Jorge, P. and Troncoso, L. (2016) mention about the ayrampo prickly pear and its culinary use that they prepare mazamorra, chicha, likewise the villagers use it as a natural medicine for the discomfort of fever and to prevent the increase or resurgence of eruptive diseases.

Opuntia monacantha

Opuntia monacantha belongs to the Opuntia species, is cultivated in the southern coastal region of Brazil (Carneiro, et al., 2016) and represents a good source to obtain mucilage. Mucilage obtained from the Opuntia genus was used to microencapsulate bioactive compounds (Otárola, et al., 2015; De Campo, et al., 2018). However, there are no reports on the use of mucilages obtained from Opuntia ssp. in nanoencapsulation (De Campo, et al., 2018).

In order to find new possibilities for synthetic polymers in nanoencapsulation and considering the importance of *zeaxanthin* for human health and the solubility and stability of nanoencapsulation, they are being investigated and designed for the use of cactus mucilage. *Zeaxanthin* encapsulated in a new natural polymer from *Opuntia monacantha*. In addition, the physicochemical properties and stability of encapsulated and non-encapsulated zeaxanthin at different temperatures were evaluated (De Campo, et al., 2018).

CONCLUSIONS

Micro- and nano-encapsulation of bioactive compounds, such as betalains and polyphenols present in the "ayrampo" prickly pear (Opuntia spp.), represent a crucial advance for the food and pharmaceutical industry. These technologies not only protect the compounds from degradation by environmental factors, but also improve their bioavailability and functionality. Encapsulation is not only a conservation strategy, but also a key tool for the development of innovative, healthier and value-added products. However, the industrial implementation of these techniques requires continuous optimization to ensure maximum efficacy and safety in the final products. The future of functional foods and nutraceuticals will depend on the ability to integrate these technological advances, making it possible to take full advantage of bioactive compounds, thus boosting sustainability and economic development in the agri-food sector.

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