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Encapsulation of bioactive compounds of food interest: applications, current advances, challenges, and opportunities

**Fabela-Morón, Miriam F.^{1*}; Pérez-Ruiz, Rigoberto V.¹; Ruíz-Hernández, Rafael¹;
Arce-Vázquez, María B.¹; Aguilar-Toalá, José E.¹; Jiménez -Guzmán, Judith¹;
García-Garibay, José M.¹**

¹ Universidad Autónoma Metropolitana, Unidad Lerma. Departamento de Ciencias de la Alimentación. Av. de las Garzas No. 10, Col. El Panteón, Municipio Lerma de Villada, Estado de México, México. C.P. 52005.

* Correspondence: mf.fabela@correo.uer.uam.mx; qa.miriamfabela@gmail.com

ABSTRACT

Objective: The encapsulation of bioactive compounds of food interest provide protection against ambiental factors and degradation reactions. Therefore, the encapsulation of these compounds, was studied and analyzed considering the applications, current advances, challenges, and opportunities on the topic.

Design/methodology/approach: Wall materials, bioactive compounds of food interest, encapsulation methods, applications, current advances, challenges, and opportunities in encapsulation of bioactive compounds were explored, described, and discussed considering the principal literature on the topic, and scientific databases were used for the bibliographic research.

Results: Encapsulation process is a novel technology that allows the increasing the stability of aromas, flavors, pigments, and microorganisms, beside of improve the sensory, physical chemical and functional properties, quality, and the extend the shelf-life.

Limitations on study/implications: Foods contain bioactive compounds that are susceptible to oxidation and degradation, which can reduce their quality and shelf life. To preserve these compounds, is important to develop other encapsulation systems considering alternative wall materials from different sources that can be applied under different process conditions from laboratory, pilot to industrial scale.

Findings/conclusions: Encapsulation process provide protection to bioactive compounds enhancing the sensory, physical chemical and functional properties, quality, and extend the shelf-life considering the integral and sustainable use of agricultural products.

Keywords: encapsulation, bioactive compounds, food interest, applications

INTRODUCTION

Food systems are susceptible to degradation making them unacceptable for its consumption and shelf-life. Bioactive compounds from foods require to be protected to extend the shelf-life, to improve its physical chemical, and sensorial properties, quality and stability in food science and technology. Exist an increasing interest in the development of food products containing natural compounds with antioxidant activity and other valuable properties. However, due to their structure and nature certain bioactive compounds such as polyphenols, flavonoids, carotenoids, among others, are not stable when are incorporated in food systems. The stability and shelf-life of bioactive compounds increase when are protected against chemical and physical factors prior to their application. In this sense, encapsulation process provides protection due to its potential for stabilization

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and controlled release of sensitive bioactive compounds, increasing the bio accessibility of bioactive molecules during digestion, and raising the water solubility of bioactive ingredients of food interest in different applications (Hcini *et al.*, 2021; Jayaprakash *et al.*, 2023; Komijani *et al.*, 2022).

Encapsulation technology

Encapsulation process is the technology by which a material or mixture of materials is entrapped with another material in the form of micro- and/or nanostructures through entrapment of a bioactive core with another substance called wall materials to provide protection to bioactive compounds as flavors, colorants, among others (Finney *et al.*, 2002; Jayaprakash *et al.*, 2023). This technology is widely used in the pharmaceutical, chemical, cosmetic and food industries. In the food industry, is used to encapsulates oils, fats, aromatic compounds, oleoresins, vitamins, minerals, colorants, flavors, antioxidants, and enzymes (Madene *et al.*, 2006). The material inside the microcapsule is called “core”, “inner phase” or “filler”, while the wall is referred to as “shell”, “coating”, “wall material” or “membrane”. Wall material does not react with the encapsulated compound (Gharsallaoui *et al.*, 2007).

Wall materials as encapsulant agents

Several food grade biopolymers have been used as wall materials in encapsulation of bioactive compounds, such as gum arabic, alginates, carrageenan, mesquite gum, proteins (milk or whey proteins, gelatin, soy, pea), maltodextrins with different dextrose equivalents, waxes and their blends (Mohan *et al.*, 2015; Wandrey *et al.*, 2010; Yang & McClements, 2013).

Physical chemical properties such as solubility, molecular weight, glass transition, crystallinity, diffusivity, film formation and emulsion properties, compatibility with the food product, dissolution release, among others, are very important to select the encapsulant agents (Madene *et al.*, 2006). Carbohydrates such as starches, corn syrup solids and maltodextrins are frequently employed as encapsulating agents. These materials exhibit low viscosities at high solids concentrations and good solubility (Da Costa *et al.*, 2012; Madene *et al.*, 2006), due to reduced interfacial properties of these materials are employed with mixtures of proteins or gums (Jayasundera *et al.*, 2011; Vélez-Erazo *et al.*, 2021). Starch and starch-based ingredients (modified starches, maltodextrins and cyclodextrins) act as carrier agents for flavor encapsulation, fat replacers and emulsion stabilizers (Falcão *et al.*, 2022; Madene *et al.*, 2006). Maltodextrin is a polysaccharide obtained by partial hydrolysis of corn, potato, or rice flour by means of acids or enzymes. Its chemical composition consists of D-glucose units linked with bonds (1-4) and with a low number of bonds (1-6) in random position. It has been determined that Maltodextrin with 10-20 DE are more effective for microencapsulation (Šturm *et al.*, 2019; Vidović *et al.*, 2014). Pectin is a polymer that produces stable emulsions due to its emulsifying properties related to the protein residues present with the pectin chains and to its chemical composition characterized by a high content of acetyl groups (Braccini & Pérez, 2001; Popoola-Akinola *et al.*, 2022). Gums and thickeners decrease sweetness in encapsulation process (Madene *et al.*, 2006), being used

in encapsulation for their emulsion-stabilizing and film-forming properties; the most used is gum arabic (Krishnan *et al.*, 2005). Gum arabic is a branched heteropolysaccharide consisting of D-glucoronic acid, L-rhamnose, D-galactose and L-arabinose (F. C. da Silva *et al.*, 2013). This material has emulsifying properties due to the presence of arabinogalactan structure (Archaina *et al.*, 2019; Mcnamee *et al.*, 1998). Proteins as natural encapsulant matrix have functional properties (solubility, film formation, ability to interact with water, emulsion formation and stability properties), proteins play a role as potential ingredients for the development of novel encapsulant systems. In recent years, protein-based carrier agents like whey protein and soy protein isolate are reported to be more effective and to produce higher product yields even when used at low concentrations (Jayasundera *et al.*, 2011; Nesterenko *et al.*, 2013).

Chitosan is other wall material derived from chitin, that can be found in the cell wall of fungi, exoskeleton of arthropods, and crustaceans. Is environmentally friendly, non-toxic, and has excellent antimicrobial and film-forming properties to be used in encapsulation process (Ashfaq *et al.*, 2022; Chausali *et al.*, 2022; Ré, 2006). Hydrogels and nanocarriers, also can be used as natural carrier agents for encapsulation as three-dimensional (3D) colloidal systems contained of physically or chemically bonded linear or branched polymer chains that can retain and absorb considerable amounts of water or bioactive compounds owing to hydrophilic features in the substitutional gaps between chains with amide ($-\text{CONH}-$), carboxyl ($-\text{COOH}$), hydroxyl ($-\text{OH}$), and sulfonic acid ($-\text{SO}_3\text{H}$) inside chains (Do *et al.*, 2022). Principal coating materials that can be used in hydrogels are polysaccharides, proteins, and lipids (Amiri *et al.*, 2022; Wen *et al.*, 2022). On the other hand, when polymers are used in mixtures of two or more encapsulating agents, the encapsulate structure can exhibit excellent physical characteristics and properties. The synergistic effect resulting from the mixture of carbohydrates, gums and proteins offers a significant application in bioactive compounds encapsulation, cost reduction in price and to create new macro, micro and nanostructures (Carneiro *et al.*, 2013; Du *et al.*, 2014; V. M. Silva *et al.*, 2014). For example, mixtures of whey proteins with maltodextrin, corn syrup and lactose; soy proteins with maltodextrin; sodium caseinate with lactose; whey protein concentrates with maltodextrin, increase the retention of volatile compounds and the efficiency of encapsulation of food oils by spray-drying (Rodea-González *et al.*, 2012).

Bioactive compounds of food interest

Among the bioactive compounds of food interest to encapsulate, stand out ingredients that provide flavor, color, beside of antioxidants, polyunsaturated fatty acids, polyphenols, etc. Table 1 indicates the principal bioactive compounds of food interest to be encapsulated:

Flavors. Flavors whether liquid or solid, are a complex mixture of volatile substances and labile components, susceptible to oxidation, chemical interactions, or volatilization and consequently affect sensory perception. To minimize damage, microencapsulation is used to trap liquid flavor substances: essential oils, oleoresins, aroma blends and acidulants. In this regard, research has been conducted to evaluate the wall material composition and operational conditions in relation to the retention and control of the release of encapsulated flavors (Buffo *et al.*, 2002; Goula & Adamopoulos, 2010). Enzymes. One of

Table 1. Principal bioactive compounds of food interest

Bioactive compounds	Source	Application	References
Bioactive peptides	Spirulina	Peptide based foods.	(Ovando <i>et al.</i> , 2018)
Phenolic compounds	Agroindustrial waste of mango	Food products with antioxidant activity	(Castro-Vargas <i>et al.</i> , 2019)
Antioxidants, phenolics, flavonoids carotenoids, anthocyanins, pectin	Tropical fruit, agri-food by-products	In functional foods and nutraceuticals	(Cádiz-Gurrea <i>et al.</i> , 2020; Gullón <i>et al.</i> , 2020)
Aminoacids, phenolics	Beans (<i>Phaseolus vulgaris</i>), (<i>Phaseolus lunatus</i>), (<i>Phaseolus coccineus</i>)	Development of functional foods with nutraceutical potential.	(Alcázar-Valle <i>et al.</i> , 2021)
Polyphenols	<i>Citrus pomace</i>	As nutraceuticals in functional foods and beverages	(Caballero <i>et al.</i> , 2021)
Phenolics, pectin, oils	Pomegranate fruit biowastes	Industrial application	(El-Shamy & Farag, 2021)
Vitamins, carotenoids, polyphenols	Kiwi fruit, byproducts	Development of novel valuable foods	(Sanz <i>et al.</i> , 2021)
Phenolics, oils	Olive byproducts	Foods packaging systems.	(Khwaldia <i>et al.</i> , 2022)
Carotenoids, pigments	Agrowastes from fruits, vegetables	Red, orange, and yellow colorants in food industry	(Cassani <i>et al.</i> , 2022)
Unsaturated fatty acids, amino acids, carotenoids, chlorophylls, phycocyanins, phenolic compounds	Spirulina	For use as colorants, antioxidants and functional ingredients in food products.	(Bortolini <i>et al.</i> , 2022)
Capsaicinoids, phenolics, pigments	Habanero chili pepper, Bell pepper wastes	Ingredient in food products.	(Fabela-Morón <i>et al.</i> , 2020; Razola-Díaz <i>et al.</i> , 2022)
Anthocyanins, ellagic acid, tocopherols, tannins, polyphenols	Jabuticaba (<i>Myrciaria</i> spp. or <i>Plinia</i> spp.)	As a food supplement in beverages, bakery products, and biodegradable film	(Fernandes <i>et al.</i> , 2022)
Flavonols, phenols and anthocyanins	Berries agroindustrial waste	Development of protective films.	(Romero <i>et al.</i> , 2022)
Amino acids, phenolic, flavonoids compounds	<i>Moringa oleifera</i> Lam.	Agroindustrial and food products uses.	(Ruiz-Hernandez <i>et al.</i> , 2022)
Antioxidants	Legumes	Chemopreventive agents in foods	(Sánchez-Chino <i>et al.</i> , 2022)

Source: own elaboration.

the main advantages of enzymes encapsulation by spray drying is the short times of this process. Due to the thermosensitivity of enzymes, the duration of this process is used to microencapsulate without causing severe damage to the enzyme structure. In addition, the incorporation of proteins as encapsulant agents increases porosity, surface flexibility, mechanical strength, and water evaporation (Jayaprakash *et al.*, 2023; Wen *et al.*, 2022).

Antioxidants. In food industry, antioxidant compounds have become of great interest due to their potential benefits as important nutraceuticals ingredients, because they have a protective effect on oxidative process (Fang & Bhandari, 2010).

Polyphenols. The consumption of polyphenols (anthocyanins, catechins, tannins and flavonoids) reduces cardiovascular damage and the risk of cancer. The effectiveness of these compounds depends on the stability, bioactivity, and bioavailability of the active compound. Due to their sensitivity to environmental factors such as light, heat and oxygen, encapsulation is an effective process for their preservation (Bakowska-Barczak & Kolodziejczyk, 2011; Koop *et al.*, 2022) to a large extent, due to its content of bioactive nutrients and their importance as dietary antioxidants. There is a growing demand for delivery of antioxidants through functional foods with the related challenge of protecting their bioactivity during food processing and subsequent passage through the gastrointestinal tract. This study focuses on the evaluation of concentration of bioactive compounds in black currant berries (*Ribes nigrum* L.).

Carotenoids. Composed of the hydrophobic carbon chain and are defined as natural pigments synthesized by plants, algae, bacteria, and fungi sources, which are related to the yellow, orange, and red colors (Luana Carvalho de Queiroz *et al.*, 2022).

Polyunsaturated fatty acids. Encapsulation of polyunsaturated fatty acids as omega-3 and omega-6 fatty acids, is commonly used in food fortification for their considerable health benefits to preserve their characteristics such as odor, flavor and oxidative stability (Carneiro *et al.*, 2013; Khwaldia *et al.*, 2022; Quintanilla-Carvajal *et al.*, 2010).

Encapsulation methods

There are different encapsulation methods that can be used to encapsulate bioactive compounds of food interest, which are indicated in Figure 1:

Spray drying. Is an encapsulation method that provides maximum protection of the encapsulated compounds in dried and stable form (Fang & Bhandari, 2010), improving flavor, aroma, stability, nutritional value and appearance, and allowing the complete release of the bioactive ingredient from wall material (Adamiec & Kalembera, 2006; Krishnan *et al.*, 2005). These process achieves microparticles or microcapsules with particular characteristics and properties (Burgain *et al.*, 2011).

Spray chilling. Is a variant of spray drying, which consists of cooling or freezing, where the material to be encapsulated is mixed with the carrier and atomized by means of nebulization of the emulsion or suspension containing the wall material and the solid or liquid active substance (sensitive pigments, flavors, and aromas, antioxidants, and natural preservatives) in cold air (Figueiredo *et al.*, 2022; Yáñez *et al.*, 2002). The coatings usually used are vegetable oils in the case of cooling spraying or hydrogenated vegetable oil for freeze spraying; thus, heat-sensitive liquids and materials that are not soluble in conventional solvents can be encapsulated.

Freeze drying. Is the widely used method for the encapsulation of thermosensitive substances, because minimizes thermal degradation reactions for carotenoids encapsulation (Šereglej *et al.*, 2021). Coacervation. involves the separation from solution of colloid particles which then agglomerate into separate, liquid phase called coacervate, the core material

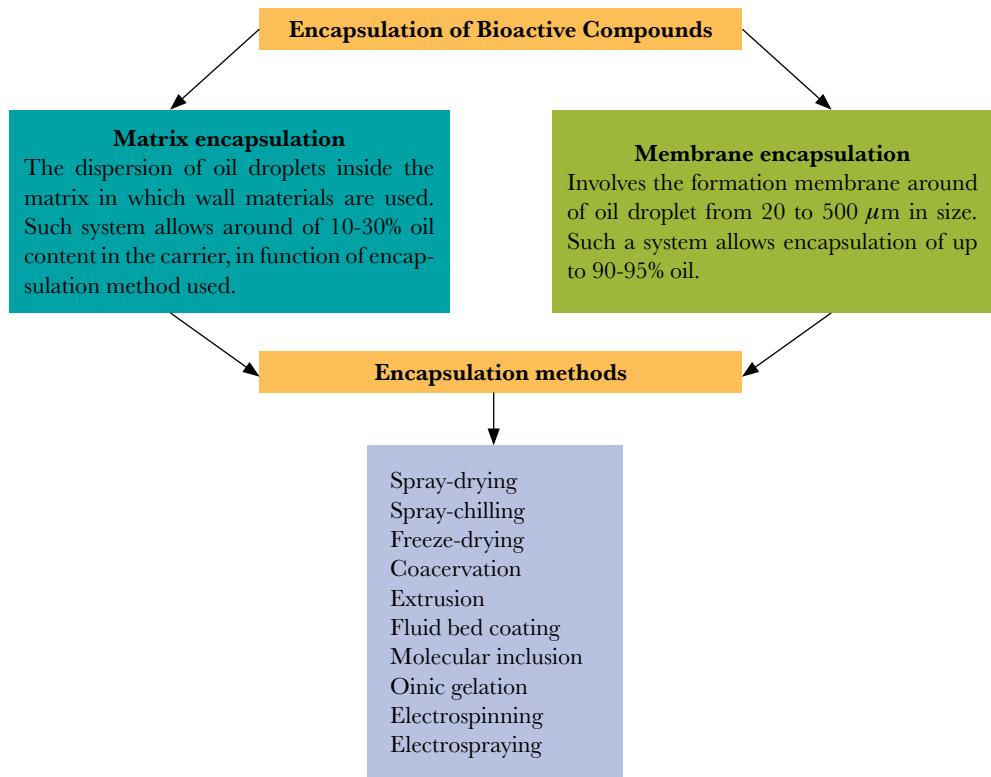


Figure 1. Classification of encapsulation methods. Source: own elaboration.

used must be compatible with the receiver polymer and be insoluble or partially soluble in the coacervation medium. Simple coacervation involves only one type of polymer with the addition of strongly hydrophilic agents to the colloidal solution. For complex coacervation, two or more kind of oppositely charged polymers are used to protect bioactive compounds (Madene *et al.*, 2006; Ré, 2006).

Extrusion. is based on the gelation of an anionic polysaccharide, when in contact with calcium or any other multivalent ion, immobilizing microorganisms or bioactive compounds. Alginate, k-carrageenan and whey proteins can be used to obtain capsules (beads) by this method.

Fluid bed coating. Consists of suspending solid particles in air at high velocity in a temperature and humidity controlled chamber, where the wall material is atomized with hot air to encapsulate bioactive ingredients using hydrogenated vegetable oils, stearins, fatty acids, emulsifiers, waxes, starches, gums and maltodextrins (Yáñez *et al.*, 2002).

Molecular inclusion. Encapsulation of compounds is performed using cyclodextrins and maltodextrin as biopolymer matrix (Yáñez *et al.*, 2002).

Ionic gelation. Process that encapsulates by means of extrusion dripping, is an efficient and low-cost method that does not require specialized equipment, high temperature, or organic solvents, making it appropriate for hydrophobic or hydrophilic compounds using calcium alginates (Arriola *et al.*, 2019).

Immobilized cell technology. In this process, the material to encapsulate as probiotics, enzymes, is trapped throughout the matrix, but not necessarily inside it by

extrusion or emulsification. Involves the entrapment of living cells in spherical gel beads and was initially designed to improve continuous fermentation processes, especially in the dairy industry, as well as to enhance cell protection against undesirable conditions (Frakolaki *et al.*, 2021).

Electrospraying. Is used in food and nutraceutical applications, based on electrohydrodynamic process using high voltage electrical field without heating, offers high product quality, encapsulation efficiency, short drying time and economical as novel alternative method (Jayaprakash *et al.*, 2023). Electrostatic spray drying has recently been introduced as novel process, which uses electrostatic charge technology, and achieve low drying temperatures, higher encapsulation efficiency, and reduced bioactive compounds degradation (Jayaprakash *et al.*, 2023).

Applications and current advances in encapsulation of bioactive compounds

Table 2 shows the applications and current advances of encapsulated bioactive compounds using different wall materials. The advantages of encapsulating these compounds are related to retard auto-oxidation, increase stability, enhance flavor, mask the bitter taste of lipidic substances, and to reduce the risk of oxidation.

Challenges and opportunities in the encapsulation of bioactive compounds of food interest

Meat and seafood products contain compounds like polyunsaturated fatty acids and fat-soluble vitamins that are susceptible to oxidation, which can reduce their quality and shelf-life. Therefore, there is interest in developing antioxidant packaging materials to preserve these sea products as part of principal challenges in encapsulation technology for their preservation. Respect to fruits and vegetables, have been protected with nanostructured wall materials, alginate-based films, cellulose nanocrystals, and polylactic acid/gelatin/polylactic acid multilayer films, among others. Consequently, in food products is being of interest the development of another encapsulant systems to improve their protection, properties, and shelf-life considering the different alternatives that encapsulation methods and wall materials provide.

In addition, the development of encapsulation process suitable for different applications in the food industry has some challenges and opportunities to be investigated and improved, which need to be addressed in the future research of encapsulation of bioactive compounds.

The current development of novel encapsulation systems is mainly focused on the preparation step in the laboratory, and most of the research developed does not take into consideration the cost and production conditions process. Also, other challenges and opportunities in the encapsulation of bioactive compounds include the exploration of alternative wall materials from different sources that can be used in different foods stuffs and food matrices to improve the performance in the creation of microparticles. Therefore, is necessary to extend the research developing of manufacturing processes to encapsulate bioactive compounds with different wall materials and selecting the kind of encapsulation method from pilot-scale to industrial scale. Additionally, is important to evaluate and establish the possible effects of encapsulant agents and process conditions

Table 2. Applications of bioactive compounds encapsulated.

Bioactive compounds	Wall materials	Encapsulation method	Application	References
Aqueous extract of pink-fleshed guava fruit	Maltodextrin, gum arabic, and their mixtures.	Spray-drying	Product that can be incorporated into different food products in powder form.	(Osorio <i>et al.</i> , 2011)
Paprika oleoresin	Modified starch Capsul®	Spray-drying	Carotenoids, antioxidants protection.	(Rascón <i>et al.</i> , 2015)
Phenolic and antioxidant compounds from Roselle (<i>Hibiscus sabdariffa</i> L.)	Maltodextrin, gum arabic	Spray-drying	Instant beverage powder to extend shelf-life.	(Archaina <i>et al.</i> , 2019)
Non-dewaxed Propolis and antioxidants from honey	Maltodextrin, gum arabic, inulin	Freeze-drying Spray-drying	Water-dispersible propolis powder and phenols protection.	(Šturm <i>et al.</i> , 2019)
Antioxidants from Bottle Gourd (<i>Lagenaria siceraria</i>) juice	Maltodextrin, whey protein isolate, soy protein isolate	Spray-drying	Beverage powder to extend shelf-life and bioactive compounds protection.	(Bhat <i>et al.</i> , 2021)
Antioxidants from food sources	Gelatin, whey, soy proteins, cellulose, starch, chitosan, alginate, lipids, beeswax, palm wax, fats, and oils.	Nanotechnology process	Active food materials as nanoparticles, nanofibers, nanocrystals, and nanoemulsions with antioxidants properties.	(Cheng <i>et al.</i> , 2022)
Phenolic compounds	Tunisian Rosemary (<i>Rosmarinus officinalis</i> L.) Extracts	Coprecipitation	Nanoparticles for use in food technology.	(Hcini <i>et al.</i> , 2021)
<i>Capsicum oleoresin</i>	Gum arabic, modified corn starch (EMCAP™), modified malt (MALT)	Spray-drying	<i>Capsicum oleoresin</i> protection with capsaicin retention, and antioxidant activities.	(da Silva Anthero <i>et al.</i> , 2022)
Asthaxanthin	Carageenan, chitosan, lupin protein isolate	Spray-drying	Functional ingredient in Foods.	(Morales <i>et al.</i> , 2021)
Cinnamon esential oil	Sodium alginate, chitosan powder,	Droplet-based millifluidic technique	Food engineering.	(Farahmand, Emadzadeh, <i>et al.</i> , 2022)
Probiotics	Prebiotics matrices	Immobilized cell technology, Extrusion, Spray-drying, Freeze-drying	For food products to enhance microbial balance.	(Frakolaki <i>et al.</i> , 2021)
Lycopene	Basil gum, zein	Electrospinning	Functional nanofibers.	(Komijani <i>et al.</i> , 2022)
Probiotics	Low molecular chitosan powders	Ionic gelation	Probiotics protection and controlled release.	(Farahmand, Ghorani <i>et al.</i> , 2022)
Phenolics, probiotics	Chitosan, fructans, whey protein, alginate, gelatin, oils	Electrospraying, spray-drying	Use in food products.	(Jayaprakash <i>et al.</i> , 2023)

Source: own elaboration.

on sensory, physical chemical, and tecno-functional properties, human health, and the environmental impact in a sustainable perspective (Cassani *et al.*, 2022; Cheng *et al.*, 2022; Figueiredo *et al.*, 2022; Šeregelj *et al.*, 2021).

CONCLUSIONS

Encapsulation process is a novel technology with many advantages for its applications in a food science and technology, that allows the increasing the stability of aromas, flavors, pigments, and microorganisms, cover undesirable odors and flavors, allow controlled release, and increase the bioavailability of bioactive compounds, with health benefits for consumers. This process has avoided the development of wall materials for different uses in food science and technology. The physical and chemical properties of wall materials can improve the antioxidant and functional properties of active ingredients encapsulated, thus inhibiting the oxidative and degradation reactions in foods. Consequently, encapsulation processes of bioactive compounds can improve the sensory, physical chemical and functional properties, beside of quality, in addition to extend the shelf-life considering the integral and sustainable use of agricultural products within the applications, challenges and opportunities to improve the encapsulation of bioactive compounds of food interest from laboratory, pilot to industrial scale.

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REFERENCES

Adamiec, J., & Kalember, D. (2006). Analysis of Microencapsulation Ability of Essential Oils during Spray Drying. *Drying Technology*, 24(9), 1127–1132. <https://doi.org/10.1080/07373930600778288>

Alcázar-Valle, M., García-Morales, S., Mojica, L., Morales-Hernández, N., Sánchez-Osorio, E., Flores-López, L., Enríquez-Vara, J. N., & Lugo-Cervantes, E. (2021). Nutritional, antinutritional compounds and nutraceutical significance of native bean species (*Phaseolus* spp.) of mexican cultivars. *Agriculture (Switzerland)*, 11(11). <https://doi.org/10.3390/agriculture11111031>

Amiri, S., Nezamdoost-Sani, N., Mostashari, P., McClements, D. J., Marszalek, K., & Mousavi Khaneghah, A. (2022). Effect of the molecular structure and mechanical properties of plant-based hydrogels in food systems to deliver probiotics: an updated review. *Critical Reviews in Food Science and Nutrition*, 0(0), 1–27. <https://doi.org/10.1080/10408398.2022.2121260>

Archaina, D., Vasile, F., Jiménez-Guzmán, J., Alamilla-Beltrán, L., & Schebor, C. (2019). Physical and functional properties of roselle (*Hibiscus sabdariffa* L.) extract spray dried with maltodextrin-gum arabic mixtures. *Journal of Food Processing and Preservation*, 43(9), 1–9. <https://doi.org/10.1111/jfpp.14065>

Arriola, N. D. A., Chater, P. I., Wilcox, M., Lucini, L., Rocchetti, G., Dalmina, M., Pearson, J. P., & de Mello Castanho Amboni, R. D. (2019). Encapsulation of *Stevia rebaudiana* Bertoni aqueous crude extracts by ionic gelation – Effects of alginate blends and gelling solutions on the polyphenolic profile. *Food Chemistry*, 275(September 2018), 123–134. <https://doi.org/10.1016/j.foodchem.2018.09.086>

Ashfaq, A., Khursheed, N., Fatima, S., Anjum, Z., & Younis, K. (2022). Application of nanotechnology in food packaging: Pros and Cons. *Journal of Agriculture and Food Research*, 7(September 2021), 100270. <https://doi.org/10.1016/j.jafr.2022.100270>

Bakowska-Barczak, A. M., & Kolodziejczyk, P. P. (2011). Black currant polyphenols: Their storage stability and microencapsulation. *Industrial Crops and Products*, 34(2), 1301–1309. <https://doi.org/10.1016/j.indcrop.2010.10.002>

Bhat, S., Saini, C. S., Kumar, V., & Sharma, H. K. (2021). Spray Drying of Bottle Gourd Juice: Effect of Different Carrier Agents on Physical, Antioxidant Capacity, Reconstitution, and Morphological Properties. *ACS Food Science and Technology*, 1(2), 282–291. <https://doi.org/10.1021/acsfoodscitech.0c00041>

Bortolini, D. G., Maciel, G. M., Fernandes, I. de A. A., Pedro, A. C., Rubio, F. T. V., Branco, I. G., & Haminiuk, C. W. I. (2022). Functional properties of bioactive compounds from *Spirulina* spp.: Current status and future trends. *Food Chemistry: Molecular Sciences*, 5(August). <https://doi.org/10.1016/j.foodchms.2022.100134>

Braccini, I., & Pérez, S. (2001). Molecular basis of Ca^{2+} -induced gelation in alginates and pectins: The egg-box model revisited. *Biomacromolecules*, 2(4), 1089–1096. <https://doi.org/10.1021/bm010008g>

Buffo, R. A., Probst, K., Zehentbauer, G., Luo, Z., & Reineccius, G. A. (2002). Effects of agglomeration on the properties of spray-dried encapsulated flavours. *Flavour and Fragrance Journal*, 17(4), 292–299. <https://doi.org/10.1002/ffj.1098>

Burgain, J., Gaiani, C., Linder, M., & Scher, J. (2011). Encapsulation of probiotic living cells: From laboratory scale to industrial applications. *Journal of Food Engineering*, 104(4), 467–483. <https://doi.org/10.1016/j.jfoodeng.2010.12.031>

Caballero, S., Li, Y. O., McClements, D. J., & Davidov-Pardo, G. (2021). Encapsulation and delivery of bioactive citrus pomace polyphenols: a review. *Critical Reviews in Food Science and Nutrition*, 62(29), 8028–8044. <https://doi.org/10.1080/10408398.2021.1922873>

Cádiz-Gurrea, M. de la L., Villegas-Aguilar, M. del C., Leyva-Jiménez, F. J., Pimentel-Moral, S., Fernández-Ochoa, Á., Alaón, M. E., & Segura-Carretero, A. (2020). Revalorization of bioactive compounds from tropical fruit by-products and industrial applications by means of sustainable approaches. *Food Research International*, 138(July). <https://doi.org/10.1016/j.foodres.2020.109786>

Carneiro, H. C. F., Tonon, R. V., Grosso, C. R. F., & Hubinger, M. D. (2013). Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials. *Journal of Food Engineering*, 115(4), 443–451. <https://doi.org/10.1016/j.jfoodeng.2012.03.033>

Cassani, L., Marcovich, N. E., & Gomez-Zavaglia, A. (2022). Valorization of fruit and vegetables agro-wastes for the sustainable production of carotenoid-based colorants with enhanced bioavailability. *Food Research International*, 152(December 2021), 110924. <https://doi.org/10.1016/j.foodres.2021.110924>

Castro-Vargas, H. I., Vivas, D. B., Barbosa, J. O., Medina, S. J. M., Gutiérrez, F. A., & Parada-Alfonso, F. (2019). Bioactive phenolic compounds from the agroindustrial waste of Colombian mango cultivars 'sugar mango' and 'tommy atkins'—An alternative for their use and valorization. *Antioxidants*, 8(2), 1–19. <https://doi.org/10.3390/antiox8020041>

Chausali, N., Saxena, J., & Prasad, R. (2022). Recent trends in nanotechnology applications of bio-based packaging. *Journal of Agriculture and Food Research*, 7, 100257. <https://doi.org/10.1016/j.jafr.2021.100257>

Cheng, H., Chen, L., McClements, D. J., Xu, H., Long, J., Xu, Z., Meng, M., & Jin, Z. (2022). Recent advances in the application of nanotechnology to create antioxidant active food packaging materials. *Critical Reviews in Food Science and Nutrition*, 0(0), 1–16. <https://doi.org/10.1080/10408398.2022.2128035>

Da Costa, S. B., Duarte, C., Bourbon, A. I., Pinheiro, A. C., Serra, A. T., Martins, M. M., Januário, M. I. N., Vicente, A. a., Delgadillo, I., Duarte, C., & Da Costa, M. L. B. (2012). Effect of the matrix system in the delivery and *in vitro* bioactivity of microencapsulated Oregano essential oil. *Journal of Food Engineering*, 110(2), 190–199. <https://doi.org/10.1016/j.jfoodeng.2011.05.043>

da Silva Anthero, A. G., Maria Tomazini Munhoz Moya, A., Souza Torsoni, A., Baú Betim Cazarin, C., & Dupas Hubinger, M. (2022). Characterization of *Capsicum oleoresin* microparticles and *in vivo* evaluation of short-term capsaicin intake. *Food Chemistry: X*, 13(December), 100179. <https://doi.org/10.1016/j.foodchx.2021.100179>

da Silva, F. C., da Fonseca, C. R., de Alencar, S. M., Thomazini, M., Balieiro, J. C. D. C., Pittia, P., & Favaro-Trindade, C. S. (2013). Assessment of production efficiency, physicochemical properties and storage stability of spray-dried propolis, a natural food additive, using gum Arabic and OSA starch-based carrier systems. *Food and Bioproducts Processing*, 91(1), 28–36. <https://doi.org/10.1016/j.fbp.2012.08.006>

Do, N. H. N., Truong, Q. T., Le, P. K., & Ha, A. C. (2022). Recent developments in chitosan hydrogels carrying natural bioactive compounds. *Carbohydrate Polymers*, 294(June), 119726. <https://doi.org/10.1016/j.carbpol.2022.119726>

Du, J., Ge, Z. Z., Xu, Z., Zou, B., Zhang, Y., & Li, C. M. (2014). Comparison of the Efficiency of Five Different Drying Carriers on the Spray Drying of Persimmon Pulp Powders. *Drying Technology*, 32(10), 1157–1166. <https://doi.org/10.1080/07373937.2014.886259>

El-Shamy, S., & Farag, M. A. (2021). Novel trends in extraction and optimization methods of bioactives recovery from pomegranate fruit biowastes: Valorization purposes for industrial applications. *Food Chemistry*, 365(June), 130465. <https://doi.org/10.1016/j.foodchem.2021.130465>

Fabela-Morón, M. F., Cuevas-Bernardino, J. C., Ayora-Talavera, T., & Pacheco, N. (2020). Trends in Capsaicinoids Extraction from Habanero Chili Pepper (*Capsicum Chinense* Jacq.): Recent Advanced Techniques. *Food Reviews International*, 36(2), 105–134. <https://doi.org/10.1080/87559129.2019.1630635>

Falcão, L. de S., Coelho, D. B., Veggi, P. C., Campelo, P. H., Albuquerque, P. M., & de Moraes, M. A. (2022). Starch as a Matrix for Incorporation and Release of Bioactive Compounds: Fundamentals and Applications. *Polymers*, 14(12). <https://doi.org/10.3390/polym14122361>

Fang, Z., & Bhandari, B. (2010). Encapsulation of polyphenols - A review. *Trends in Food Science and Technology*, 21(10), 510–523. <https://doi.org/10.1016/j.tifs.2010.08.003>

Farahmand, A., Emadzadeh, B., Ghorani, B., & Poncelet, D. (2022). Droplet-based millifluidic technique for encapsulation of cinnamon essential oil: Optimization of the process and physicochemical characterization. *Food Hydrocolloids*, 129(February), 107609. <https://doi.org/10.1016/j.foodhyd.2022.107609>

Farahmand, A., Ghorani, B., Emadzadeh, B., Sarabi-Jamab, M., Emadzadeh, M., Modiri, A., & Tucker, N. (2022). Millifluidic-assisted ionic gelation technique for encapsulation of probiotics in double-layered polysaccharide structure. *Food Research International*, 160(June), 111699. <https://doi.org/10.1016/j.foodres.2022.111699>

Fernandes, I. D. A., Arruda, Maria, G., Volpato, W., Gonçalves, D., Cristina, A., Windson, C., & Haminiuk, I. (2022). Measurement : Food Bioactive compounds , health-promotion properties and technological applications of Jabuticaba : A literature overview. *Measurement: Food*, 8(January), 100057. <https://doi.org/10.1016/j.meafoo.2022.100057>

Figueiredo, J. de A., Silva, C. R. de P., Souza Oliveira, M. F., Norcino, L. B., Campelo, P. H., Botrel, D. A., & Borges, S. V. (2022). Microencapsulation by spray chilling in the food industry: Opportunities, challenges, and innovations. *Trends in Food Science and Technology*, 120(October 2021), 274–287. <https://doi.org/10.1016/j.tifs.2021.12.026>

Finney, J., Buffo, R., & Reineccius, G. a. (2002). Effects of Type of Atomization and Processing Temperatures on the Physical Properties and Stability of Spray-Dried Flavors. *Journal of Food Science*, 67(3), 1108–1114. <https://doi.org/10.1111/j.1365-2621.2002.tb09461.x>

Frakolaki, G., Giannou, V., Kekos, D., & Tzia, C. (2021). A review of the microencapsulation techniques for the incorporation of probiotic bacteria in functional foods. *Critical Reviews in Food Science and Nutrition*, 61(9), 1515–1536. <https://doi.org/10.1080/10408398.2020.1761773>

Gharsallaoui, A., Roudaut, G., Chambin, O., Voilley, A., & Saurel, R. (2007). Applications of spray-drying in microencapsulation of food ingredients: An overview. *Food Research International*, 40(9), 1107–1121. <https://doi.org/10.1016/j.foodres.2007.07.004>

Goula, A. M., & Adamopoulos, K. G. (2010). A new technique for spray drying orange juice concentrate. *Innovative Food Science and Emerging Technologies*, 11(2), 342–351. <https://doi.org/10.1016/j.ifset.2009.12.001>

Gullón, P., Gullón, B., Romaní, A., Rocchetti, G., & Lorenzo, J. M. (2020). Smart advanced solvents for bioactive compounds recovery from agri-food by-products: A review. *Trends in Food Science and Technology*, 101(May), 182–197. <https://doi.org/10.1016/j.tifs.2020.05.007>

Hcini, K., Lozano-Pérez, A. A., Luis Cenis, J., Quílez, M., & José Jordán, M. (2021). Extraction and Encapsulation of Phenolic Compounds of Tunisian Rosemary (*Rosmarinus officinalis* L.) Extracts in Silk Fibroin Nanoparticles. *Plants*, 10(11), 2312. <https://doi.org/10.3390/plants10112312>

Jayaprakash, P., Maudhuit, A., Gaiani, C., & Desobry, S. (2023). Encapsulation of bioactive compounds using competitive emerging techniques: Electrospraying, nano spray drying, and electrostatic spray drying. *Journal of Food Engineering*, 339(April 2022). <https://doi.org/10.1016/j.jfoodeng.2022.111260>

Jayasundera, M., Adhikari, B., Adhikari, R., & Aldred, P. (2011). The effect of protein types and low molecular weight surfactants on spray drying of sugar-rich foods. *Food Hydrocolloids*, 25(3), 459–469. <https://doi.org/10.1016/j.foodhyd.2010.07.021>

Khwaldia, K., Attour, N., Matthes, J., Beck, L., & Schmid, M. (2022). Olive byproducts and their bioactive compounds as a valuable source for food packaging applications. *Comprehensive Reviews in Food Science and Food Safety*, 21(2), 1218–1253. <https://doi.org/10.1111/1541-4337.12882>

Komijani, M., Mohebbi, M., & Ghorani, B. (2022). Assembly of electrospun tri-layered nanofibrous structure of zein/basil seed gum/zein for increasing the bioaccessibility of lycopene. *Lwt*, 161(September 2021), 113328. <https://doi.org/10.1016/j.lwt.2022.113328>

Koop, B. L., Nascimento da Silva, M., Diniz da Silva, F., Thayres dos Santos Lima, K., Santos Soares, L., José de Andrade, C., Ayala Valencia, G., & Rodrigues Monteiro, A. (2022). Flavonoids, anthocyanins, betalains, curcumin, and carotenoids: Sources, classification and enhanced stabilization by encapsulation and adsorption. *Food Research International*, 153(January), 110929. <https://doi.org/10.1016/j.foodres.2021.110929>

Krishnan, S., Bhosale, R., & S, R. (2005). Microencapsulation of cardamom oleoresin: Evaluation of blends of gum arabic, maltodextrin and a modified starch as wall materials. *Carbohydrate Polymers*, 61(1), 95–102. <https://doi.org/10.1016/j.carbpol.2005.02.020>

Luana Carvalho de Queiroz, J., Medeiros, I., Costa Trajano, A., Piuvezam, G., Clara de França Nunes, A., Souza Passos, T., & Heloneida de Araújo Morais, A. (2022). Encapsulation techniques perfect the antioxidant action of carotenoids: A systematic review of how this effect is promoted. *Food Chemistry*, 385(October 2021), 132593. <https://doi.org/10.1016/j.foodchem.2022.132593>

Madene, A., Jacquot, M., Scher, J., & Desobry, S. (2006). Flavour encapsulation and controlled release - a review. *International Journal of Food Science and Technology*, 41(1), 1–21. <https://doi.org/10.1111/j.1365-2621.2005.00980.x>

Mcnamee, B. F., O'Riordan, E. D., & O'Sullivan, M. (1998). Emulsification and Microencapsulation Properties of Gum Arabic. *Society*, 4551–4555. <https://doi.org/10.1021/jf9803740>

Mohan, A., Rajendran, S. R. C. K., He, Q. S., Bazinet, L., & Udenigwe, C. C. (2015). Encapsulation of food protein hydrolysates and peptides: a review. *RSC Adv.*, 5(97), 79270–79278. <https://doi.org/10.1039/C5RA13419F>

Morales, E., Burgos-Díaz, C., Zúñiga, R. N., Jorkowski, J., Quilaqueo, M., & Rubilar, M. (2021). Influence of O/W emulsion interfacial ionic membranes on the encapsulation efficiency and storage stability of powder microencapsulated astaxanthin. *Food and Bioproducts Processing*, 126, 143–154. <https://doi.org/10.1016/j.fbp.2020.12.014>

Nesterenko, A., Alric, I., Silvestre, F., & Durrieu, V. (2013). Vegetable proteins in microencapsulation: A review of recent interventions and their effectiveness. *Industrial Crops and Products*, 42(1), 469–479. <https://doi.org/10.1016/j.indcrop.2012.06.035>

Osorio, C., Forero, D. P., & Carriazo, J. G. (2011). Characterisation and performance assessment of guava (Psidium guajava L.) microencapsulates obtained by spray-drying. *FRIN*, 44(5), 1174–1181. <https://doi.org/10.1016/j.foodres.2010.09.007>

Ovando, C. A., Carvalho, J. C. de, Vinícius de Melo Pereira, G., Jacques, P., Soccol, V. T., & Soccol, C. R. (2018). Functional properties and health benefits of bioactive peptides derived from Spirulina: A review. *Food Reviews International*, 34(1), 34–51. <https://doi.org/10.1080/87559129.2016.1210632>

Popoola-Akinola, O. O., Raji, T. J., & Olawoye, B. (2022). Lignocellulose, dietary fibre, inulin and their potential application in food. *Heliyon*, 8(8), e10459. <https://doi.org/10.1016/j.heliyon.2022.e10459>

Quintanilla-Carvajal, M. X., Camacho-Díaz, B. H., Meraz-Torres, L. S., Chanona-Pérez, J. J., Alamilla-Beltrán, L., Jiménez-Aparicio, A., & Gutiérrez-López, G. F. (2010). Nanoencapsulation: A New Trend in Food Engineering Processing. *Food Engineering Reviews*, 2(1), 39–50. <https://doi.org/10.1007/s12393-009-9012-6>

Rascón, M. P., Bonilla, E., García, H. S., Salgado, M. a., González-Arnao, M. T., & Beristain, C. I. (2015). Tg and aw as criteria for the oxidative stability of spray-dried encapsulated paprika oleoresin. *European Food Research and Technology*. <https://doi.org/10.1007/s00217-015-2446-6>

Razola-Díaz, M. D. C., Gómez-Caravaca, A. M., de Andrés, J. L., Voltes-Martínez, A., Zamora, A., Pérez-Molina, G. M., Castro, D. J., Marchal, J. A., & Verardo, V. (2022). Evaluation of Phenolic Compounds and Pigments Content in Yellow Bell Pepper Wastes. *Antioxidants*, 11(3), 1–17. <https://doi.org/10.3390/antiox11030557>

Ré, M. I. (2006). Formulating Drug Delivery Systems by Spray Drying. *Drying Technology*, 24(4), 433–446. <https://doi.org/10.1080/07373930600611877>

Rodea-González, D. A., Cruz-Olivares, J., & Román-Guerrero, A. (2012). Spray-dried encapsulation of chia essential oil (*Salvia hispanica* L.) in whey protein concentrate-polysaccharide matrices. <https://doi.org/10.1016/j.jfoodeng.2012.01.020>

Romero, J., Cruz, R. M. S., Díez-Méndez, A., & Albertos, I. (2022). Valorization of Berries' Agro-Industrial Waste in the Development of Biodegradable Pectin-Based Films for Fresh Salmon (*Salmo salar*) Shelf-Life Monitoring. *International Journal of Molecular Sciences*, 23(16). <https://doi.org/10.3390/ijms23168970>

Ruiz-Hernandez, R., Hernandez-Rodriguez, M., Cruz-Monterrosa, R. G., Diaz-Ramirez, M., Martinez-Garcia, C. G., Garcia-Martinez, A., & Rayas Amor, A. A. (2022). *Moringa oleifera* Lam.: A review of environmental and management factors that influence the nutritional content of leaves. *Tropical and Subtropical Agroecosystems*, 25(1). <https://doi.org/10.56369/taes.4053>

Sánchez-Chino, X. M., Corzo-Ríos, L. J., & Cid-Gallegos, M. S. (2022). Compuestos antioxidantes provenientes de leguminosas como agentes quimiopreventivos en cáncer de colon. Antioxidant compounds from legumes as chemopreventive agents in colon cancer. October. <https://doi.org/10.53331/teq.v5i15.5150>

Sanz, V., López-Hortas, L., Torres, M. D., & Domínguez, H. (2021). Trends in kiwifruit and byproducts valorization. *Trends in Food Science and Technology*, 107(June 2020), 401–414. <https://doi.org/10.1016/j.tifs.2020.11.010>

Šeregelj, V., Ćetković, G., Čanadanović-Brunet, J., Šaponjac, V. T., Vulić, J., Lević, S., Nedović, V., Brandolini, A., & Hidalgo, A. (2021). Encapsulation of carrot waste extract by freeze and spray drying techniques: An optimization study. *Lwt*, 138(December 2020), 1–10. <https://doi.org/10.1016/j.lwt.2020.110696>

Silva, V. M., Vieira, G. S., & Hubinger, M. D. (2014). Influence of different combinations of wall materials and homogenisation pressure on the microencapsulation of green coffee oil by spray drying. *Food Research International*, 61, 132–143. <https://doi.org/10.1016/j.foodres.2014.01.052>

Šturm, L., Osojnik Črnivec, I. G., Istenič, K., Ota, A., Megušar, P., Slukan, A., Humar, M., Levic, S., Nedović, V., Kopinč, R., Deželak, M., Pereyra Gonzales, A., & Poklar Ulrich, N. (2019). Encapsulation of non-dewaxed propolis by freeze-drying and spray-drying using gum Arabic, maltodextrin and inulin as coating materials. *Food and Bioproducts Processing*, 116(June), 196–211. <https://doi.org/10.1016/j.fbp.2019.05.008>

Vélez-Erazo, E. M., Bosqui, K., Rabelo, R. S., & Hubinger, M. D. (2021). Effect of ph and pea protein: Xanthan gum ratio on emulsions with high oil content and high internal phase emulsion formation. *Molecules*, 26(18). <https://doi.org/10.3390/molecules26185646>

Vidović, S. S., Vladi, J. Z., Va, G., Zekovi, Z. P., & Popovi, L. M. (2014). Maltodextrin as a carrier of health benefit compounds in *Satureja montana* dry powder extract obtained by spray drying technique. 258, 209–215. <https://doi.org/10.1016/j.powtec.2014.03.038>

Wandrey, C., Bartkowiak, A., & Harding, S. (2010). *Materials for Encapsulation*. In N. J. Zuidam & V. A. Nedović (Eds.), *Encapsulation Technologies for Active Food Ingredients and Food Processing* (p. 400). Springer New York. <https://doi.org/10.1007/978-1-4419-1008-0>

Wen, C., Zhang, J., Zhang, H., & Duan, Y. (2022). New Perspective on Natural Plant Protein Based Nanocarriers for Bioactive Ingredients Delivery. *Foods*, 11(12), 1–13. <https://doi.org/10.3390/foods11121701>

Yáñez, J. F., Salazar, J. a M., Chaires, L. M., Jiménez, J. H., Márquez, M. R., & Ramos, E. G. R. (2002). Aplicaciones biotecnológicas de la microencapsulación. *Avance y Perspectiva*, 21, 313–319.

Yang, Y., & McClements, D. J. (2013). Food Hydrocolloids Encapsulation of vitamin E in edible emulsions fabricated using a natural surfactant. *Food Hydrocolloids*, 30(2), 712–720. <https://doi.org/10.1016/j.foodhyd.2012.09.003>