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REVIEW ARTICLES

Nanoencapsulation of *Spirulina* biomass by electrospraying for development of functional foods – a review

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Highlights
- Nanoparticles by electrospraying improve the bioactivity of functional compounds;
- Nanoencapsulation reduces the undesirable flavors and odors of compounds;
- Nanoencapsulated *Spirulina* biomass increases the nutritional value of food products.

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KEYWORDS
Bioactive compounds;
GRAS;
Microalgae;
Nutritional supplement;
Polymeric nanoparticles.

Abstract: The food industry has been looking to incorporate bioactive compounds in foods aiming at nutritional and functional benefits to the health of consumers. The *Spirulina* biomass contains bioactive compounds with a high biological value, such as proteins, vitamins, carbohydrates, pigments, fatty acids and biopeptides. The advance of nanobiotechnology allows the development of functional food products. Nanoencapsulation contributes to the reduction of undesirable flavors and odors of the compounds. The development of polymeric nanoparticles by electrospraying supports these compounds, improving stability and controlled delivery. In this context, the article addresses the use of nanoparticles as an encapsulating material for bioactive compounds and/or *Spirulina* biomass by the electrospraying method. The application of nanoencapsulated *Spirulina* for the development of functional foods has promising potential to increase the quality, bioactivity and nutritional value of products.

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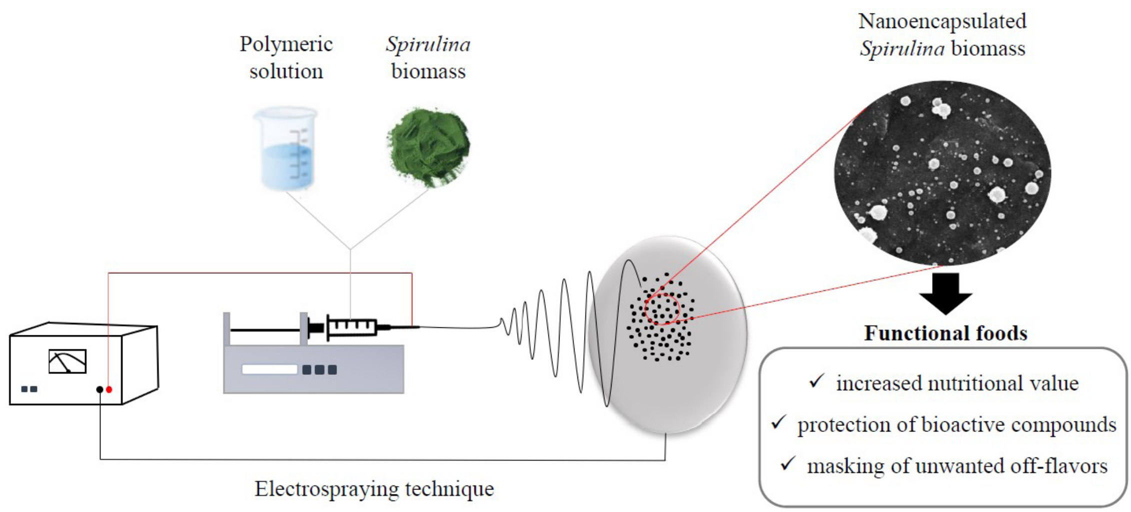
GRAPHICAL ABSTRACT



Introduction

The food industries have been looking for innovations in food production due to the demand for healthy products (Chopde et al., 2020). Nanotechnology is the science that allows the manipulation, organization and measurement of materials at the nanoscale. In this dimension, nanomaterials are developed with enhanced physical, chemical and biological properties due to the larger contact surface area and greater interaction that the nanomaterial allows, due to size reduction. Thus, nanotechnology is a promising technique for the development of new food products because it can improve the nutritional value and protection of active compounds without changing the physical. Moreover, the food's sensory characteristics increase shelf life and food safety (Kuang et al., 2020).

Nanoparticles are used as delivery systems based on the physicochemical properties of materials reduced to the nanoscale. The nanomaterials provide greater bioavailability of nanoencapsulated bioactive compounds due to their faster digestion (Zambrano-Zaragoza et al., 2018). Electrospraying is a versatile and practical method for the production of nanoparticles that allows the direct incorporation of the bioactive compound in a polymeric solution.

The *Spirulina* microalga is a source of proteins with high biological value, amino acids, micronutrients, antioxidant compounds, carbohydrates, vitamins, and minerals (Abu-Taweel et al., 2019). This genus has received Generally Recognized As Safe (GRAS) certification by the Food and Drug Administration (FDA), where is authorized for consumption as a food or dietary supplement (Boukid & Castellari, 2021). Various foods were produced with *Spirulina* biomass: supplements (Carvalho et al., 2017; Freitas et al., 2019), snack (Lucas et al., 2018), energy gel (Moreira et al., 2018) and shake (Santos et al., 2016). However, biomass can transmit unpleasant odor and flavor, loss of bioactivity, and the appearance of green color in the product. In this context, the nanoencapsulation of bioactive compounds for application in foods can improve the industrial sector and generate benefits to products and consumers. The technique contributes to reducing undesirable sensory attributes, allowing an increase in the concentration of microalgal biomass added to the product, in addition to stabilizing the bioactive compounds, allowing controlled delivery of the substance to the target site and efficient absorption by the digestive system (Jafari & Mcclements, 2017).

In this sense, the review addresses nanoparticles as an encapsulating material for bioactive compounds by the electrospraying method. In addition, it describes the potential application of nanoencapsulated *Spirulina* biomass for the development of functional foods.

Nanotechnology

Nanotechnology is a technology that allows the manipulation of atoms, molecules or macromolecules for the development of materials with new shapes and sizes that can vary between 1-1000 nm. This technology has increasingly attracted the attention of the food industries, showing the potential to revolutionize the development of food systems (Khan et al., 2017). From nanotechnology, intelligent food packaging materials (Kuntzler et al., 2018), food nanosensors (Silva et al., 2019) and food additives (Sahani & Sharma, 2021) can be developed. Thus, designing materials on a nanometric scale can provide food products with new and better physicochemical, nutritional and sensory properties, in terms of flavor, texture, appearance, stability, nutrient bioavailability and gastrointestinal fate (Singh et al., 2017).

Polymeric nanoparticles

Nanoparticles are defined as colloidal solid particles with diameters ranging from 10-100 nm. Based on its morphology the term nanoparticle is classified as nanospheres and nanocapsules. The nanocapsules are composed of a polymeric shell around the core. The compound can be dissolved in this core and/or adsorbed to the polymeric wall. The nanospheres are formed by a dense polymeric matrix. In this case, the bioactive compound can be adsorbed on the surface or dispersed in the matrix (Zambrano-Zaragoza et al., 2018).

The nanoparticles have gained attention in the food area with potential application to be used as delivery systems for bioactive compounds in food and drinks. The increased bioavailability of nutrients and the encapsulation of bioactive compounds within nanoparticles are the main benefits. Thus, there is protection against chemical or biochemical degradation, prevention against adverse interactions and masking the unwanted flavor. These improvements in food quality increase the degree of acceptance of the products by consumers (Pathakoti et al., 2017).

Natural and synthetic polymers can be used for nanoencapsulation of active compounds. The polymer used in the food area must be biodegradable, non-toxic, and should not cause damage when coming into contact with food and subsequent human consumption.. Some examples of biodegradable polymers that can be applied in food products: polylactic acid, polyhydroxybutyrate, chitosan, polycaprolactone, polyethylene glycol, poly(glycolic acid) (Amulya et al., 2021). Studies with chitosan in the food area were cited by Raza et al. (2020) for encapsulation of active compounds to provide increased nutritional value, as well as protection of the compounds. Polylactic acid was used to nanoencapsulate bioactive compounds with antioxidant activity from sweet potato peel (Guerrero-León et al., 2021).

Different methods can be used for encapsulation, such as spray drying, emulsification, and solvent evaporation (Araiza-Calahorra et al., 2018). The main disadvantage of these techniques is that they involve several steps, high temperatures, or require large amounts of organic solvents, resulting in the degradation of bioactive compounds. Besides, homogeneous particles are not produced, and the process has low efficiency (Rostamabadi et al., 2021).

Electrospraying technique

Electrospraying is an effective technique to obtain particles with diameters on the nanometer scale, as it does not involve severe conditions of temperature, pressure, or the use of aggressive chemicals (Niu et al., 2020). In addition, this process produces nanoparticles with high porosity and surface area to volume ratio (Coelho et al., 2021). The equipment is composed of a high electrical potential source, a positive displacement pump and an electrically grounded collector for the deposition of electrosprayed nanoparticles (Niu et al., 2020) (Figure 1).

The size and shape of nanoparticles are controlled by process, solution and environmental parameters. The properties of the polymeric solution comprise a solvent, viscosity, surface tension, electrical conductivity, molecular weight, and polymer concentration. The process parameters correspond to electrical potential, feed rate, capillary diameter, and distance between capillary and collector.

The main environmental conditions are relative humidity and temperature (Coelho et al., 2021). Thus, electrospraying is a versatile technique applied to material development.

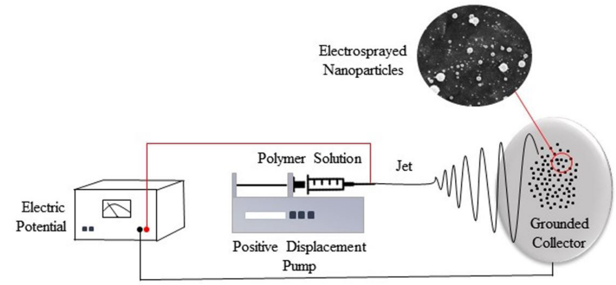


Figure 1. Schematic diagram of the electrospraying process.

In this process, nanomaterials can be obtained through adjustments in the process parameters and properties of the polymer solution. The process has advantages, such as operating at room temperature and the efficient evaporation of the solvent. Moreover, there is the possibility of expanding the scale of the process. These advantages are important to maintain the bioactivity of the nanoencapsulated active compounds (Niu et al., 2020; Coelho et al., 2021).

Microalgae

Microalgae are unicellular microscopic organisms, photosynthetic, physiologically they can be eukaryotic or prokaryotic and are capable of developing in aquatic environments (Costa et al., 2020). It is estimated that there are 50,000 known species with applications in various areas of science such as pharmaceutical, food, agriculture and medical (Mobin et al., 2019).

Microalgae are able to accumulate molecules and bioactive compounds in their microalgal biomass, especially proteins, carbohydrates and lipids. In addition, they have the ability to synthesize compounds such as carotenoids, long-chain fatty acids, essential and non-essential amino acids, enzymes, vitamins and minerals (Mobin et al., 2019).

The microalgal biomass produced has potential for applications in the development of food (Freitas et al., 2019), medicines (Hu et al., 2019), biopesticides (Costa et al., 2019), biofuels (Nagappan et al., 2019) and environmental bioremediation (Kumar et al., 2014).

Spirulina sp.

Spirulina (scientific name *Arthospira*) is a blue-green microalga belonging to the group of *Cyanophytas*, with a helical shape. This microalga presents a prokaryotic cell organization, with the absence of most of the cell organelles. *Spirulina* is found in alkaline lakes and develops as multicellular cylindrical trichomes (Abu-Taweel et al., 2019). The interest in *Spirulina* mainly derives from its chemical composition, which varies between 50-70% of protein, 10-20% of carbohydrate, 5-10% of lipid (Rosa et al., 2016). Moreover, *Spirulina* stands out for being a source of vitamin A and C, vitamins of the B complex (B1, B2, B6 and B12), vitamin E, biotin, folic acid and pantothenic acid, pigments (carotenoids,

Table 1. Bioactive activities from the microalgae of the *Spirulina* genus.

Microalga	Bioactive activity	Reference
Spirulina sp.	Anti-inflamatory	Abu-Taweel et al. (2019)
Spirulina platensis	Antitumor	Wang & Zhang (2016)
Spirulina máxima	Antihypertensive	Suliburska et al. (2016)
Spirulina platensis	Anticancer	Czerwonka et al. (2018)
Spirulina platensis	Anti-obesity	Shariat et al. (2019)
Spirulina platensis	Antidiabetic	Hu et al. (2019)

phycocyanin and chlorophyll), minerals and trace elements, iron, calcium, magnesium, phosphorus and potassium being the most important (Abu-Taweel et al., 2019). In this way, microalga biomass stands out as a nutritionally important raw material developing new food products. In addition, intracellular and extracellular metabolites of cyanobacteria present potential biological activities (Table 1).

Spirulina as a food source and bioactive compounds

Spirulina is applied as a functional ingredient in the development of various products to increase the nutritional quality and therapeutic effect in chronic diseases (Alterthum et al., 2019). The development of foods with *Spirulina* has become a global trend in the food industry through the high consumer demand for healthy products. Most of *Spirulina* biomass is marketed as a nutritional supplement in powder, tablet, or capsule form. However, studies have been incorporating microalgal biomass in products such as sauces (Almeida et al., 2021), kefir (Atik et al., 2021), among others.

In Brazil, since 1996, the Biochemical Engineering Laboratory at the Federal University of Rio Grande (FURG, Rio Grande, RS) develops food products with the addition of *Spirulina* sp. LEB 18 as shake for elderly population (Santos et al., 2016), supplements for athletes (Freitas et al., 2019; Carvalho et al., 2017), energy gel (Moreira et al., 2018), and snacks (Lucas et al., 2018). In addition to these products, cookies, powdered cake mix, powdered milk, powdered gelatine, pudding, instant soups, cereal bars, isotonic drinks, instant noodles were also produced (Figure 2) and capsules of *Spirulina* sp. LEB 18 as a food supplement for commercialization (Olson Microalgas Macronutrição, Camaquã, RS). In addition, *Spirulina* foods have been developed with a view to supplementing children's meals. All foods are developed at the *Spirulina* Food Preparation Center, located at FURG.

Spirulina's proven ability to produce bioactive compounds highlights these biotechnologically microorganisms for applications in many areas. However, adding biomass to food requires some challenges for commercialization that need to be overcome, especially its green color intensity and fish flavor and aroma (Lafarga, 2019). In this way, the nanoencapsulation of biologically active microalgal compounds has the potential to meet these challenges. Thus, it is possible to reduce or eliminate odors, control the release of bioactive compounds at the target site and increase the bioavailability of these compounds.

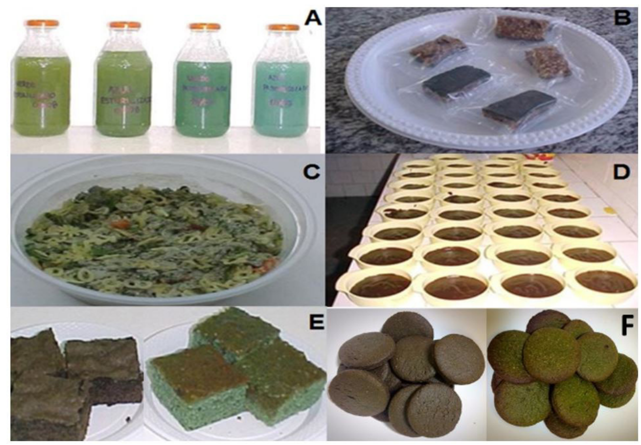


Figure 2. Food products with *Spirulina* sp. LEB: isotonic beverages (A), cereal bars (B), instant soups (C), pudding (D) cake powder mix (E) and biscuits (F). Source: Vaz et al. (2016).

Conclusion and future perspectives

The bioactive compounds from the *Spirulina* microalga are important for the food industry as they can offer health benefits, such as nutraceutical, anti-inflammatory, antioxidant and antimicrobial properties. However, the direct incorporation of the compounds into foods is limited, as it can alter the sensory characteristics of the product, such as odor, flavor, and appearance. Furthermore, bioactive compounds are affected by environmental factors, pH and gastric digestion. The polymeric nanoparticles produced by electrospraying play an important role in the encapsulation of the compounds. They allow an increase in the nutritional value of the products, protect the bioactive compounds from anticipated degradation and promote their controlled release. Thus, the nanoencapsulation of *Spirulina* microalgal biomass is a promising and effective alternative for the development of functional foods. In addition, there is an increase in the quality, stability, and bioactivity of the compounds during the processing, storage, and transport steps.

Conflict of interests

The authors declare that there are no conflicts of interest.

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