Italian Journal of Food Science, 2025; 37 (2): 423–439

Effect of microencapsulation by spray drying on the protein content of Spirulina (*Arthrospira platensis*)

Angie Castillo-Barzola[1], Henry L. Paisig[1,2], Marco Faieta[3], Oscar Jordán-Suárez[4], Emilio Porras-Sosa[1], Tarsila Tuesta[1]*

[1]Grupo de Investigación en Alimentos, Facultad de Ingeniería Química y Textil, Universidad Nacional de Ingeniería (GIA-FIQT-UNI), Av. Túpac Amaru, Rímac, Lima, Perú; [2]Laboratorio de Investigación en Biopolímeros y Metalofármacos (LIBIPMET), National University of Engineering, Av. Tupac Amaru, Rimac, Lima, Peru; [3]University of Teramo, Faculty of Bioscience and Technology for Food Agriculture and Environment, Teramo, Italy; [4]Universidad Le Cordon Bleu, Facultad de Ciencias de los Alimentos. Lima – Perú

***Corresponding Author:** Grupo de Investigación en Alimentos, Facultad de Ingeniería Química y Textil, Universidad Nacional de Ingeniería (GIA-FIQT-UNI), Av. Túpac Amaru 210, Rímac, Lima, Perú. Email: tarsilat@uni.edu.pe

Academic Editor: Prof. Marco Dalla Rosa, University of Bologna, Italy

Received: 26 October 2024; Accepted: 23 March 2025; Published: 8 April 2025
© 2025 Codon Publications

OPEN ACCESS

ORIGINAL ARTICLE

Abstract

Nowadays, there is a great demand for sustainable and nutritious foods, and fresh spirulina is a highly valuable source of protein. However, its use is limited because of its sensitivity to environmental stress conditions and distinctive flavor. Nevertheless, microencapsulation offers an effective solution to enhance stability and mask undesirable sensory properties. This study optimized *Spirulina* microencapsulation via spray drying, employing maltodextrin (MD) as the coating agent. By factorial design, inlet temperature (160–180°C) and *Spirulina*:MD ratios (1:2–1:4) were evaluated, identifying optimal conditions (174.7°C, 1:4 ratio) that achieved 46% yield and 31.65% protein content while preserving its native amino acid profile.

Keywords: Amino acids, factorial design, maltodextrin, optimization, *Spirulina*, spray drying

Introduction

Malnutrition is a public health concern caused by the deficiencies, excesses, or imbalances of vital nutrients, such as vitamins, minerals, lipids, proteins, among others (Ahmed *et al.*, 2022; Allen and Saunders, 2023; Padhani *et al.*, 2022), or because of the lack of an essential amino acid (EAA) (Olson *et al.*, 2020; Scholes, 2022). Nevertheless, this problem has still not been fully explained, so it is a field of great interest for the scientific community (Ersado, 2022). Since proteins play a crucial role in various biochemical processes, protein deficiency can lead to several functional disorders (Dolganyuk *et al.*, 2023) such as unintentional weight loss and muscle wasting, although it can be reversed with a balanced diet (Olson *et al.*, 2020; Scholes, 2022). Currently, meat, fish, eggs, nuts, legumes, and dairy products are considered the main sources of protein in human nutrition (Pintado and Delgado-Pando, 2020; Semba *et al.*, 2021). However, the production and transportation of animal-derived protein demands large areas of dedicated land, water, nitrogen, and fossil fuels, and their overconsumption greatly contributes to greenhouse gas emissions generating environmental impacts

(Ramírez-Rodrigues *et al.*, 2021; Semba *et al.*, 2021). In addition, the world population has increased at an unprecedented rate, with estimates projecting it to exceed 9 billion by 2050 (United Nations, 2017). Indeed, the demand for protein is expected to double in the coming decades (Garcia *et al.*, 2020; Sadigov, 2022; Shaghaghian *et al.*, 2022). Therefore, there is a great necessity to find an alternative and sustainable source of protein to meet the challenges of adequate nutrition (Raja *et al.*, 2022; Ramírez-Rodrigues *et al.*, 2021). In that sense, Spirulina represents a potential alternative because of its composition that is rich in protein, vitamins, minerals, pigments, and bioactive compounds such as polyphenols (Guarienti *et al.*, 2021).

Arthrospira Platensis, marketed as Spirulina, is a spiral-shaped, green-blue, photosynthetic and filamentous cyanobacterium, also called microalgae (Arahou *et al.*, 2021; Guidi *et al.*, 2021) that has created significant interest in several sectors, including pharmaceuticals, medicine, and food. Besides its high protein content (60–70%), it is also considered a complete and high-quality protein source because of its high digestibility, ranging between 83% and 90% (Pootthachaya *et al.*, 2023), which is better compared to other plant sources because of the presence of mucopolysaccharide, instead of cellulose, in the cell wall (Mohammadi *et al.*, 2024; Raczyk *et al.*, 2022; Ragaza *et al.*, 2020). Furthermore, from a qualitative perspective, spirulina offers a well-balanced amino acid composition (Ragaza *et al.*, 2020), which is aligned with FAO requirements (Raczyk *et al.*, 2022; Tessier *et al.*, 2021). However, spirulina presents certain limitations for its application in the food industry. Spirulina's high moisture content (Özyurt *et al.*, 2023; Silva *et al.*, 2023; Stramarkou *et al.*, 2021), dark green color, stemming from pigments such as chlorophyll, phycocyanin, and carotenes, and the fishy odor imparted by acids and sulfides (Jia *et al.*, 2024), make it unappealing to most consumers (Almeida *et al.*, 2021; Maag *et al.*, 2022).

Therefore, various preservation methods have been explored to overcome these challenges, and microencapsulation by spray drying is as an effective technique to protect sensitive compounds against stressing environmental factors, besides masking undesirable color and flavors of some active compounds. This process allows rapid, continuous, and scalable production of dry microspherical powder with consistent quality in a single step (Chen *et al.*, 2021; Guarienti *et al.*, 2021; Özyurt *et al.*, 2023). On the other hand, although the high drying temperatures involved in the spray-drying process may induce protein denaturation (Chen *et al.*, 2021), this technology is suitable for heat-sensitive compounds because of the brief exposure to high temperatures. In addition, the cooling effect of latent heat of evaporation may mitigate the high temperature processing conditions (Lu *et al.*, 2021; Samborska *et al.*, 2022). In this sense, the coating material adopted for microencapsulation by spray drying could contribute to limiting protein denaturation as well (Jiménez-González and Guerrero-Beltrán, 2021; Luo *et al.*, 2024). Among different encapsulation agents, maltodextrin (MD) is commonly used because of its low cost and large availability. Likewise, it is a good delivery system that can prevent thermal degradation of bioactive compounds, and it has been successfully applied for phycocyanin stabilization, which is the most abundant protein in spirulina (Faieta *et al.*, 2020).

MD is a starch-derived compound, obtained by acid and/or controlled enzymatic hydrolysis. Likewise, it can also be a whey protein isolate (Xiao *et al.*, 2022; Zhao *et al.*, 2022). This material is considered as a D-glucose polymer joined by α-(1,4) and α-(1,6) linkages. Moreover, it is commonly used as a drying or encapsulating agent, known for its high-water solubility, low cost, low viscosity, colorlessness, retarded crystallization, and decreased stickiness and hygroscopicity of mixture. Nevertheless, it forms stable microcapsules that maintain the integrity of sensitive flavors and fragrances under diverse environmental storage conditions (Chaudhary *et al.*, 2024; Kosasih *et al.*, 2023; Xiao *et al.*, 2022). In summary, the present study focuses on the microencapsulation of spirulina by spray drying testing different processing conditions (i.e., Spirulina:MD ratio and inlet temperature) for minimizing protein denaturation and maximizing process yield, utilizing a factorial design.

Materials and Methods

Materials

Spirulina (*Arthrospira platensis*) biomass (SP) was obtained from the producer Intipacha Microalgas (Ica, Peru). Food-grade MD (Dextrose equivalent DE: 11.3) was bought from IFF (Peru). Bradford reagent (Lt: SLCK1933), bovine serum albumin (Lt: 0000289566), and sodium hydroxide pellets were bought from Merck.

Proximal analysis of SP

Ash (AOAC 940.26), fat (AOAC 920.177), and protein (AOAC 920.152) contents were determined for SP, while carbohydrate content was estimated by the difference method.

Elemental analysis of SP

Elemental analysis was performed using Inductively Coupled Plasma Optical Emission Spectroscopy

ICP-OES (Avio 550 MAX, Perkin Elmer, USA) to evaluate the nutritional composition and ensure safety standards. The instrument was operated with a plasma gas flow rate of 8 L/min and a nebulizer flow rate of 1.7 L/min, following the protocol described by Proch and Niedzielski (2021) with little modifications.

Spray drying microencapsulation

SP and MD were mixed in different proportions (SP:MD ratio) according to a factorial design. At first, a domestic four-blade immersion blender (FPSTHB460A, Oster, China) was used at the lowest speed for 1 minute. Subsequently, the mixture, at pH: 7–7.5, was stirred at 300 rpm for 10 minutes. The aforementioned procedure was repeated three times to keep the SP in suspension and avoid agglomeration. The suspension was sprayed through the ATM3000 Spray Dryer (PIGNAT, Genas, France) at a feed flow rate of about 12 mL min^{-1}, and spray air flow pressure of 40 psi with different inlet temperatures, according to the conditions listed in Table 1. Subsequently, the spirulina microencapsulated in MD (SP-MD powder) was vacuum-sealed in embossed bags and stored in a desiccator at room temperature.

Protein quantification

Protein content was determined for each of the treatments performed. SP-MD powder (75 mg) was mixed with 5 mL of NaOH 0.5 N and shaken vigorously at 2400 rpm using a Vortex (model ZX-classic, Velp Scientifica, Italy) for 1 minute at room temperature. Subsequently, it was stirred at 300 rpm with a magnetic agitator in a water bath at boiling point for 20 minutes and afterward centrifuged at 4265 × g for 15 minutes. The supernatant obtained was used for protein determination (Papalia *et al.*, 2019; Saxena *et al.*, 2022). Finally, 250 µL of the solution extracted was mixed with 2.50 mL of Bradford's reagent and shaken at 2400 rpm for 1 minute, incubated for 6 minutes at room temperature, and the absorbance of the solution was measured at 595 nm wavelength using a UV/Visible spectrophotometer (UV-1700, Shimadzu, Japan). The amount of protein was calculated based on bovine serum albumin calibration curve (concentration range of 2.5 to 40 mg L^{-1}; R^2= 0.988) (Saxena *et al.*, 2022). Subsequently, the protein content relative to dried spirulina was determined using Equation 1 and reported as gram of protein/100 g of dried spirulina.

$$\text{Protein}\left(\frac{\text{g}}{100\text{g dry spirulina}}\right) = \left(\left(\text{Protein (mg L}^{-1}) * \text{DF}\right) * \frac{1 - \%\text{Moisture}}{\text{Dried} - \text{spirulina}}\right) * 100 \quad (1)$$

Where DF = 0.06 is the dilution factor, %Moisture = 5% is the moisture of SP-MD powder, and dried-spirulina content refers to the amount (mg) of dried spirulina expected in the sample under consideration.

Process yield (%)

The process yield was determined as the ratio of the mass of SP-MD powder to the mass of solids contained in the feed solution. This calculation is represented in Equation 2, as described by Duran Barón *et al.* (2021).

$$\text{Yield (\%)} = \frac{\text{Mass of dried particles}}{\text{Mass of solid in feed solution}} \times 100\ \% \quad (2)$$

Experimental design

All the experiments were carried out by triplicate, using a factorial design with two independent variables: SP:MD ratio (X_1) and temperature (X_2) (see Table 1). A one-way analysis of variance (ANOVA) was used to determine significant differences between the response variables at a confidence level of 95% ($p < 0.05$). In addition, the response surface methodology (RSM) enabled us to define the optimal conditions for preparing the SP-MD powder. The response variables analyzed were protein content (Y1) and process yield (Y2). The relationship between the independent variables and the response variables was modeled using a second-order polynomial equation, expressed as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \beta_4 X_1^2 + \beta_5 X_2^2 \quad (3)$$

where Y represented the response variable, and β coefficients represented the effects of the factors and their interactions.

Table 1. Treatments according to factorial design.

Treatment	SP:MD ratio	Inlet temperature (°C)
T1	1:2	160
T2	1:3	160
T3	1:4	160
T4	1:2	170
T5	1:3	170
T6	1:4	170
T7	1:2	180
T8	1:3	180
T9	1:4	180

Moisture content and water activity

Moisture content (%) of SP biomass and SP-MD powders was determined thermogravimetrically using a moisture analyzer (Model QL-720A, Eurotech, Taiwan). The analysis was performed using 0.50 g of sample placed into the aluminum sample plate and heated at 105°C until constant weight was reached. Each measurement was performed in triplicate. Water activity measurement was carried out on SP and SP-MD powders at 24°C using a water activity meter (CH8853, Novasina, Switzerland) according to the method proposed by Konar *et al.* (2022).

Amino acid concentration

Amino acid profile was determined for both SP and the SP-MD powder. Analysis was conducted using an HPLC system (Shimadzu, Japan) equipped with a UV/VIS detector, following the method described in Francioso *et al.* (2017). Quantification of amino acids was made by comparison with calibration curves generated, and data were reported as milligram of amino acid per gram of dry sample.

Color evaluation

Color determination was performed using a colorimeter (CR-20, Konica Minolta, Japan), according to the method described by García *et al.* (2021). First, the sample holder was half-filled with SP, then the equipment was turned over ensuring that the lens pointed upward toward the plate which was placed on the top, and the measurement was performed in triplicate. Color data were collected according to the CIELAB color space, with values of L*, a*, and b* representing lightness, red-green, and yellow-blue pair, respectively. Moreover, a comparison of the SP-MD powder samples, obtained from the different treatments, and the liquid mixture before drying against the original fresh biomass was conducted using the CIELAB color difference (calculated, as shown in equation 4. For the analysis, approximately 0.5 g of the sample was placed in the dish and compacted to ensure complete coverage of the base of the dish.

$$\begin{aligned}\Delta E^* &= \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \\ &= \sqrt{(L_i^* - L_0^*)^2 + (a_i^* - a_0^*)^2 + (b_i^* - b_0^*)^2}\end{aligned} \quad (4)$$

where L_0^*, a_0^*, and b_0^* were the color parameters of SP while L_i^*, a_i^*, and b_i^* were the measurements of the liquid samples and all the microencapsulated treatments. Color parameters of chroma (C*) and hue (h*) were calculated using Equations 5 and 6, respectively (Faieta *et al.*, 2020).

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (5)$$

$$h^* = \tan^{-1}\frac{b^*}{a^*} \quad (6)$$

Fourier-transform infrared (FTIR) analysis

The identification of the functional groups in the structure and interaction between SP, MD, and the optimal treatment of SP-MD powder were performed by Fourier transform infrared spectroscopy (IR21 Prestige FTIR, Shimadzu, Japan). Previously, SP was dehydrated at 40°C for 72 hours in an oven. The spectra were obtained by scanning the region between 4000 and 400 cm^{-1} by the attenuated total reflectance (ATR) sampling technique (Yadav *et al.*, 2022).

Morphology, particle size, and zeta potential of microcapsules

The microstructure and surface morphology of SP-MD powder were assessed by scanning electronic spectroscopy (SEM, Quanta 650 FEG, FEI, USA), as described by (Galván-Colorado *et al.*, 2024). Moreover, particle size and zeta potential were performed by dynamic light scattering (DLS, Brookhaven 90 plus, Holtsville, USA), using a 658 nm laser and 90° scattering angle. Samples were diluted in deionized water at 1000 mg L^{-1} and then sonicated for 3 minutes (Das *et al.*, 2022). Finally, an aliquot was placed in the cell for measurement.

Release kinetic in vitro of spirulina

The study of the in vitro release assay was conducted for the optimal treatment of microencapsulated spirulina following the method described by Tuesta-Chavez *et al.* (2022) with some modifications. The microcapsules (0.20 g) were added to a glass beaker containing 50 mL of water and stirred continuously using an orbital shaker (Model SHO-2D, WiseShake®, Germany) at 100 rpm for 8 hours at room temperature. During the kinetic study, 2 mL of sample was withdrawn from the beaker and analyzed by UV-VIS spectrophotometry (PharmaSpec UV-1700 model, Shimadzu®, Japan) at different time intervals. After analysis, the aliquots were returned to the dissolution vessel. Spirulina released concentrations were determined at 380 nm, using a linear calibration curve (R^2 = 0.9949, Abs = 0.0007(C)–0.0539) within a range of 100 to 1000 mg L^{-1}. All experiments were conducted in triplicate.

Data analysis

Moisture, color (L*, a*, b*, Chroma and Hue), and protein content were determined by triplicate and expressed as

the average ± S.D. (Standard deviation). These data were analyzed by ANOVA (Analysis of variance) followed by a multiple comparison (Tukey 95%) test. Optimum parameters for SP:MD and temperature were determined using the factorial design mentioned before.

Results and Discussions

Raw material

The overall composition of spirulina varies depending on the algal strain used for cultivation, environmental conditions, and seasonal factors (Alfadhly *et al.*, 2022). In this research, SP (*Arthrospira platensis*) was cultivated at alkaline pH range of 8–11, temperatures between 20 and 35ºC, and salinity levels of 12–20 g L^{-1} in raceway ponds or closed greenhouse systems. Under these conditions, the biomass exhibited a protein content of 66% dry weight (DW), which is consistent with values reported by Arahou *et al.* (2021), who found protein levels between 64 and 71% in biomass grown in the Zarrouk medium at 35°C. Likewise, de Morais *et al.* (2022) reported an increase in spirulina protein content up to 76% by cultivating the strain with crude glycerol as an organic carbon source. Furthermore, Bleakley and Hayes (2021) and Nunes *et al.* (2024) reported protein levels ranging from 70 to 76%, comparable to those found in meat and significantly higher than soybean (40%).

Regarding carbohydrate content, SP contained 16.81% DW, which aligns with the findings of Priyanka *et al.* (2023), who reported carbohydrate levels between 15% and 25% DW. Unlike plant-based carbohydrate, spirulina lacks cellulose and instead contains a diverse array of saccharides, including glucose, mannose, galactose, and xylose, as well as glycogen. Because of this composition, the carbohydrates present in spirulina exhibit high bioavailability and rapid digestibility, making them particularly suitable for populations such as older adults and individuals with intestinal malabsorption disorders (Alfadhly *et al.*, 2022).

Concerning the lipid content, SP contained 9.64% DW, slightly exceeding the 7.72% reported in the USDA Food Data Central results (Taiti *et al.*, 2023). However, previous studies have reported lipid content ranging from 5% to 10% DW (Alfadhly *et al.*, 2022). This lipid fraction is particularly relevant because of its nutritional and functional properties, as microalgal lipids have gained significant attention in human health and nutrition. Among these, glycolipids are the most abundant and serve as a key source of polyunsaturated fatty acids (PUFAs), which are known for their anti-inflammatory properties and potential therapeutic applications (Jung *et al.*, 2022). The lipid and carbohydrate profile of spirulina is influenced by cultivation parameters such as nutrient availability, light intensity, and pH, which can modulate their relative abundance (Rosero-Chasoy *et al.*, 2022; Saxena *et al.*, 2022). In particular, nitrogen limitation redirects carbon from protein synthesis to the metabolic pathways for carbohydrate or lipid production, resulting in accumulation (Saxena *et al.*, 2022).

In addition, the ash content in SP was 7.38% DW, which is slightly lower than the previously reported values ranging from 8% to 18% DW (Ramírez-Rodrigues *et al.*, 2021). Ash content is an indicator of the total mineral composition of a food product and plays a crucial role in determining its nutritional value (Costa *et al.*, 2024). Among all the nutritional components found in SP, microelements are also of nutritional interest (Rubio *et al.*, 2021). In this study, spirulina exhibited a large amount of minerals, as is shown in Table 2, with Potassium (K) (2128.49 mg kg^{-1}) being the most abundant followed by Phosphorus (P) (1165.91 mg kg^{-1}), Sodium (Na) (1106.52 mg kg^{-1}), and Sulfur (S) (918.67 mg kg^{-1}), which is consistent with the results obtained by Janda-Milczarek *et al.* (2023). Moreover, iron, calcium, and zinc content were 28.14, 72.07, and 1.94 mg kg^{-1}, in agreement with the results reported by Koli *et al.* (2022). However, spirulina can also be affected by pollution and be susceptible to accumulation of metals with high binding affinity (Wang *et al.* 2024). According to Rzymski *et al.* (2019) and USDA Foreign Agricultural Service (2018), heavy metals such as Lead (Pb), Nickel (Ni), and Cadmium (Cd) are toxic elements with established limits in spirulina: Pb < 3.00 and Cd < 3.00 mg kg^{-1}. These contaminants are of particular concern because they can cause harm during critical periods of brain development. In addition, other trace elements were analyzed, including As (< 0.1), B (< 10.00), Ba (< 0.30), Cd (< 1.0), Hg (< 0.1), Li (< 0.30), Ni (< 2.00), V (< 1.00), Al (< 7.00), and Pb (< 3.00) mg kg^{-1} DW, consistent with findings by Rubio *et al.* (2021) and Al-Dhabi (2013) for commercial spirulina products intended for human consumption.

Protein quantification of spirulina microencapsulated

The protein content, in the conditions tested, decreased from 66 g per 100 g of dried spirulina (initial biomass) to a range of 21.9–34.6 g per 100 g in the SP-MD powder. These values are comparable with those reported by Batista de Oliveira *et al.* (2021) who found a protein content of 27 g/100g in microencapsulated Spirulina sp. LEB-18, whose initial biomass protein content was 60 g/100 g DW. In the current research, the reduction in protein content is attributed to denaturation factors, particularly the mechanical stress caused by shear forces during mixing process in the preparation, as well as the elevated inlet temperatures during the spray-drying process. These high

Table 2. Elemental analysis on spirulina biomass.

Trace elements	Value (mg kg^{-1} DW)	Microelements	Value (mg kg^{-1} DW)
Aluminum. Al	<7.00	Potassium. K	2128.49
Antimony. Sb	<3.00	Phosphorus. P	1165.91
Arsenic. As	<3.00	Sodium. Na	1106.52
Barium. Ba	<0.30	Sulfur. S	918.67
Beryllium. Be	<0.10	Magnesium. Mg	291.98
Bismuth. Bi	<0.10	Calcium. Ca	72.07
Boron. B	<10.00	Iron. Fe	28.14
Cadmium. Cd	<0.30	Manganese. Mn	3.21
Cerium. Ce	<6.67	Zinc. Zn	1.94
Chromium. Cr	<1.00	Strontium. Sr	0.73
Cobalt. Co	<1.00		
Copper. Cu	<1.00		
Lead. Pb	<3.00		
Lithium. Li	<0.30		
Mercury. Hg	<3.00		
Molybdenum. Mo	<1.00		
Nickel. Ni	<2.00		
Selenium. Se	<7.00		
Silica. SiO_2	<0.50		
Silver. Ag	<0.70		
Thallium. Tl	<0.30		
Tin. Sn	<2.33		
Titanium. Ti	<6.67		
Uranium. U	<3.00		
Vanadium. V	<1.00		

temperatures could favor protein denaturation, through the disruption of bonds and forces that maintain the secondary, tertiary, and quaternary structures (Blanco A. and Blanco G., 2022; Butreddy *et al.* 2021). Haque *et al.* (2018) suggested that atomization and the air–water interface could introduce additional stress factors. Moreover, the combination of these factors with shear stress can synergistically amplify the destabilization of protein structures (Amaya-Farfan, 2020). In addition, a significant portion of the dried feed adhered to the spray dryer chamber walls during processing, contributing to protein losses. Hence, the results suggest that encapsulation optimization should extend beyond just the spray drying parameters but include sample preparation conditions.

As shown in Table 3, the highest protein content was T6, followed by T9. Moreover, a positive correlation was observed between the amount of MD and protein content ensuring the protective effect of the coating agent. These results are consistent with that reported by Zhang *et al.* (2022), who suggested that an increased solid content may act as a barrier for the biomass during processing, thereby preserving the protein portion. In addition, the best conditions to obtain the higher protein content in SP-MD powder was at 170ºC and an encapsulant ratio of 1:4. Therefore, it could be considered that the exposure to this temperature for short periods is negligible on the preservation of the phycocyanin, the most abundant protein in spirulina (Faieta *et al.* 2020; Özyurt *et al.* 2023). On the other hand, SP had a moisture content of 76.15% and a water activity of 0.85, which makes a highly perishable food, according to Silva *et al.* (2023) and Stramarkou *et al.* (2021). This disadvantage is a key challenge when handling SP, since high moisture content accelerates microbial growth and spoilage. However, the spray-drying process significantly reduced the moisture content of SP-MD powder under 8.70%, as is shown in Table 3, which is within safe microbiological limits (Özyurt *et al.* 2023).

Process efficiency

Regarding the process yield, a positive correlation between the amount of coating material and the process yield was observed with T8 and T9 exhibiting the highest

Table 3. Protein content of the SP-MD powder, process yield (%) and moisture.

Treatment	Dependent variables		Moisture (%)
	Protein content (g/100g dried spirulina)	Process yield (%)	
T1 (160, 1:2)	21.87 ± 0.23[f]	39.00 ± 0.82[c]	8.70 ± 0.49[a]
T2 (160, 1:3)	25.51 ± 0.43[c,d,e]	41.33 ± 1.70[b,c]	8.00 ± 0.66[a]
T3 (160, 1:4)	25.56 ± 2.45[c,d,e]	43.33 ± 0.94[a,b,c]	7.16 ± 0.29[b,c]
T4 (170, 1:2)	25.14 ± 0.05[d,e]	44.67 ± 3.09[a,b]	6.85 ± 0.24[b,c,d]
T5 (170, 1:3)	26.88 ± 0.20[c,d]	44.67 ± 1.25[a,b]	5.71 ± 0.65[d]
T6 (170, 1:4)	34.62 ± 0.68[a]	45.33 ± 0.94[a,b]	5.82 ± 0.51[d]
T7 (180, 1:2)	24.10 ± 1.82[e,f]	42.67 ± 3.09[a,b,c]	7.14 ± 0.19[b,c]
T8 (180, 1:3)	27.84 ± 0.53[c]	46.00 ± 3.56[a]	5.90 ± 0.60[d]
T9 (180, 1:4)	31.55 ± 0.83[b]	46.67 ± 0.94[a]	6.46 ± 0.97[c,d]

Protein content in SP-MD powder is regarded only on dry spirulina.

yields, with statistically equivalent values. This can be attributed to the higher initial solid content found in these formulations (Zhang *et al.* 2022). Higher MD concentration would lead to an increase of glass transition temperature (Tg) of the particles, reducing droplet adhesion to the dryer chamber walls (Decker *et al.* 2024; Xiao *et al.* 2022), leading to higher spirulina content in the SP-MD powder. These treatments, along with T6, also showed higher protein content, highlighting the critical role that the solid matrix plays in maintaining protein integrity in microencapsulation. On the other hand, the temperature did not show a clear trend in influencing the process yield. However, T6 (170°C) and T9 (180°C) achieved high values for both protein content and yield, with no statistical differences, suggesting T6 for scale-production because of other benefits such as energy savings, thermal efficiency, and production costs (Tay *et al.* 2021).

Water activity and moisture content analysis of spirulina microencapsulated

In the current study, SP had an initial moisture content of 76.15% and a water activity of 0.85, which makes a highly perishable food according to Silva *et al.* (2023) and Stramarkou *et al.* (2021). This is a key challenge when handling SP, as high moisture content accelerates microbial growth and spoilage. However, the spray-drying process significantly reduced the moisture content of SP-MD powder under 6.70%, which is within safe microbiological limits (Özyurt *et al.* 2023). In addition, the water activity values ranged from 0.33 to 0.45, well below the critical threshold of 0.61, indicating that the powder was not susceptible to microbial proliferation (Barbosa-Cánovas *et al.,* 2020). In fact, low moisture and water activity values ensure the effectiveness of spray drying, which enhances the shelf-life and stability of the spirulina. According to the moisture results, a negative correlation was observed with the temperature, indicating that as the inlet temperature increased, the moisture content in the SP-MD powder decreased. Likewise, treatments at 160°C showed a negative correlation with the amount of MD, suggesting that higher concentrations lead to the reduction in moisture content. Similar results were also reported by Tay *et al.* (2021).

Experimental design and model fitting

Table 4 presents the regression coefficients of the quadratic polynomial model, and the corresponding p-values obtained from the ANOVA analysis, which was used to determine the significant variables influencing the dependent variables. Moreover, the efficacy of the model was evaluated through the R^2 value. According to the results, X_1, X_2 (SP:MD ratio and spray drying inlet temperature, respectively), and the quadratic coefficient of X_2 significantly influence protein content ($p < 0.05$), whereas the R^2 value obtained was 0.819. In addition, the response

Table 4. Estimated regression coefficients of the second-order polynomial equation and analysis of variance (ANOVA) of the model for the response variables.

Regression coefficients	Protein content		Yield process	
	Effect	p	Effect	p
β_0	–772.278		–558.747	
$\beta_1(X_1)$	–7.471	0.0000*	1.351	0.0339*
$\beta_2(X_2)$	9.449	0.0006*	6.843	0.0059*
$\beta_3(X_1X_2)$	0.047	0.1054	–0.002	0.9583
$\beta_4(X_1^2)$	0.099	0.6176	–0.027	0.9198
$\beta_5(X_2^2)$	–0.028	0.0013*	–0.019	0.0784
R^2	0.819		0.461	

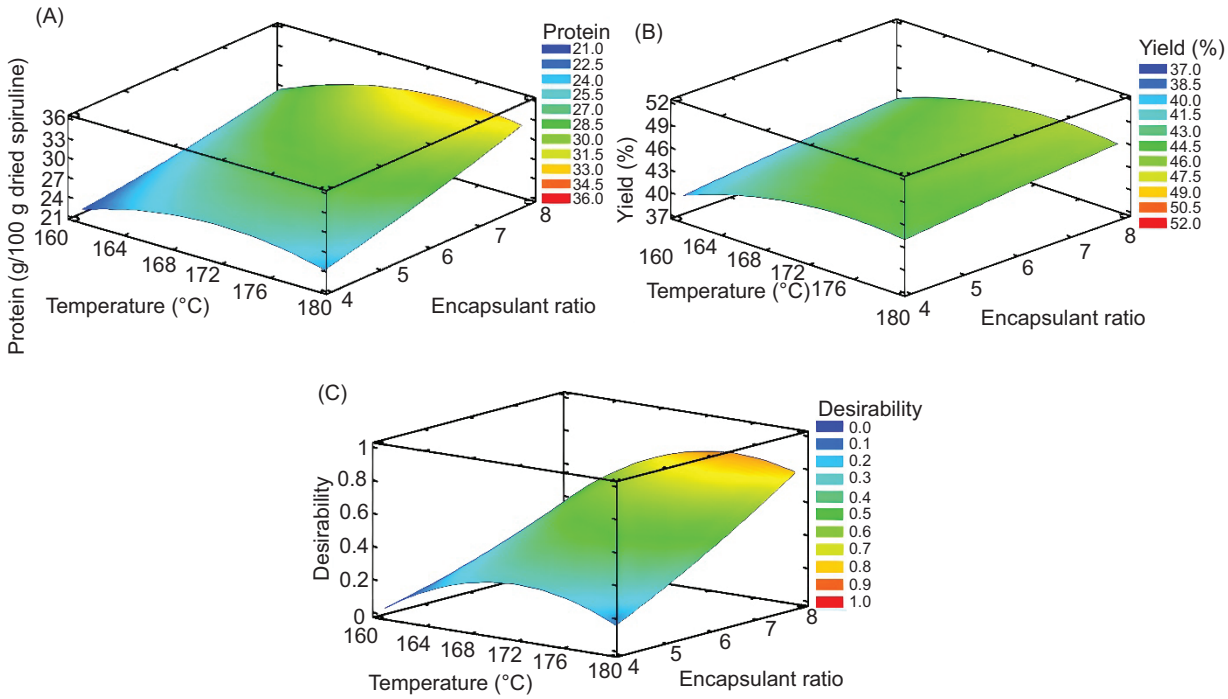

Figure 1. Response surface graphs of protein content (A), process yield (B), and desirability of the nine treatments (C).

surface plot (Figure 1A) showed that the optimal combination of temperature and SP:MD ratio—174.8°C and 1:4, respectively—resulted in the highest protein content, reaching 33.1 g/100 g dried spirulina. Regarding the responding surface plot of the yield process, Figure 1B showed that the optimal combination was 174.7°C and SP:MD ratio was 1:4. The model response indicates that higher temperatures as well as encapsulant agent amount increases the yield process. According to the ANOVA, both X_1 and X_2, as well as the quadratic effect of X_2, had a significant influence on the process yield ($p < 0.05$). However, the R^2 value was 0.461, which was lower compared to the model for residual protein content. Finally, the optimization results were integrated using a desirability function (0.83), as shown in Figure 1C, finding that the ideal conditions for both protein content and yield were found to be 174.8°C of X_1 with 1:4 of X_2. These results show the significant impact of both temperature and encapsulant/bioactive ratio on preserving protein content and maximizing process efficiency during spray drying.

Amino acid profile comparison

SP is a well-known source of protein with its quality determined by the quantification and proportion of EAA (Alfadhly *et al.*, 2022; Kumar *et al.*, 2022; Markou *et al.*, 2023). Table 5 exhibited all EAA, with a total amino acid (TAA) content of SP of 600.2 g kg^{-1} DW, constituting 41.5% of TAA. In addition, glutamic acid was the most abundant amino acid representing approximately 15% of TAA. Other amino acids included are: aspartic acid (9.9%), leucine (8.8%), alanine (7.5%), arginine (7.2%), and valine (6.6%), which were notable because they significantly contributed to the TAA and the nutritional value of a food product. Similarly, Gentscheva *et al.* (2023) found that spirulina contains glutamic acid (8.15%), aspartic acid (5.34%), alanine (4.54%), leucine (4.84%), arginine (3.96%), and valine (3.34%). Therefore, based on the results, fresh spirulina whose protein content is dominated by glutamic acid has attracted a huge interest because of its high potential to develop umami ingredients (Pratama *et al.*, 2022). On the other hand, SP-MD powder at optimal conditions preserved all amino acids with slight reduction from 600.2 to 584.44 g kg^{-1} DW. The most abundant EAA on SP-MD powder was leucine with 11.8% of TAA, while the amino acid which presented a major reduction was aspartic acid with 34.05% of the initial content, followed by arginine (31.23%) and threonine (30.76%). Overall, it has been noticed that EAA rose from 248.90 to 298.59 g kg^{-1} DW, and non-EAA (NEAA) was reduced from 351.3 to 285.86 g kg^{-1} DW. Moreover, EAA represented a major percentage of TAA on SP-MD powder (51.10%) in comparison with the EAA on biomass (41.5%). In conclusion, although the protein content was reduced, the product maintained its nutritional property because of the presence of all EAA.

Table 5. Amino acid profile of spirulina biomass and SP-MD powder.

		Spirulina biomass (g kg^{-1} DW)	SP-MD powder (g kg^{-1} DW)
Essential amino acids	Isoleucine	35.30	39.62
	Leucine	52.70	68.69
	Valine	39.90	49.40
	Phenylalanine	27.90	41.04
	Tryptophan	11.50	10.45
	Histidine	11.50	10.07
	Lysine	30.20	39.43
	Threonine	29.50	20.43
	Methionine	10.40	19.48
Nonessential amino acids	Alanine	45.30	39.24
	Glycine	31.90	29.93
	Proline	23.70	20.14
	Tyrosine	25.10	20.43
	Aspartic acid	59.20	39.05
	Glutamic acid	90.90	67.83
	Arginine	43.10	29.64
	Serine	25.90	29.74
	Cysteine	6.20	9.88
Total amino acids (TAA)		600.20	584.44
EAA		248.90	298.59
NEAA		351.30	285.86

Color assessment

The color parameters of SP, liquid samples, and treatments of SP-MD powder are shown in Table 6. It is worth mentioning that liquid samples are divided into three groups: liquid samples 1 (LS1) is the mixture of spirulina and MD in a ratio of SP:MD equal to 1:2 which corresponded to T1, T4, and T7 according to Table 1. The luminosity parameter (L*) has significantly increased for all the samples after the drying process because of the addition of the coating material. According to the L* values of the treatments (T1–T9), a positive correlation between MD content and L* was found, while temperature did not exhibit a significant variation. A similar result was found in the study made by (Özyurt *et al.* (2023), where the highest whiteness values (L*) were observed with increasing concentrations of MD. This is also attributed to the capacity of protection of MD which is proved with major values of protein content (Table 3). Moreover, the greenness (–a*) and yellowness (+b*) of the SP were lower than the microencapsulated samples. In fact, the SP used was dark with greenish shades and blue with color parameters relatively like those reported by Demarco *et al.* (2022).

On the other hand, it is known that values of CIELAB color difference (ΔE*) lower than 3.00 are difficult to be perceived by the human eye and are considered as the same color (García *et al.*, 2021). In this context, the color difference of liquid samples as well as microencapsulated samples was noticeable. Regarding color parameters of liquid samples, they were also dark with little changes in color index in comparison to SP, with the LS3 sample resulting as the one with the highest color difference among the liquid samples. For the SP-MD powder, the microencapsulated samples (T1–T9) exhibited a major average color difference of 49.20, highlighting T3, T6, and T9 whose values were higher. Regarding the C* values of the treatments, they ranged 12.65 to 15.20, indicating low color saturation. The lowest values were observed in T3, T6, and T9, which correspond to treatments with the highest encapsulant ratio. However, no significant correlation was found between temperature and encapsulant ratio. Finally, h* of the treatments ranged from

Table 6. Color parameters (CIELAB-color system) for spirulina biomass and changes in color indexes of the liquid samples and microencapsulated samples.

Samples	L*	a*	b*	C*	Hue	ΔE*ab
SP	15.37 ± 0.10[c]	–2.80 ± 0.06[d]	–0.87 ± 0.05[f]	2.93 ± 0.08	197.21 ± 1.02	
LS 1	13.47 ± 0.04[f]	0.60 ± 0.15[b]	–1.17 ± 0.02[f]	1.32 ± 0.10	296.92 ± 4.85	3.91
LS 2	13.80 ± 0.21[f]	–1.17 ± 0.07[c]	–0.80 ± 0.23[f]	1.50 ± 0.27	211.18 ± 18.97	2.26
LS 3	8.07 ± 0.24[g]	1.90 ± 0.12[a]	2.00 ± 0.21[e]	2.80 ± 0.23	45.63 ± 9.96	9.14
T1 (160, 1:2)	61.60 ± 0.33[c]	–12.90 ± 0.33[f,g]	4.37 ± 0.26[c]	13.62 ± 0.23	161.28 ± 1.46	47.61
T2 (160, 1:3)	63.97 ± 0.21[b]	–13.97 ± 0.29[h,i]	3.67 ± 0.12[d]	14.44 ± 0.25	165.28 ± 0.76	50.07
T3 (160, 1:4)	66.37 ± 0.90[a]	–11.80 ± 0.41[e]	4.53 ± 0.29[b,c]	12.65 ± 0.28	158.94 ± 1.88	52.07
T4 (170, 1:2)	59.60 ± 1.00[d]	–14.37 ± 0.29[i]	4.97 ± 0.26[b]	15.20 ± 0.34	160.94 ± 0.68	46.09
T5 (170, 1:3)	63.07 ± 0.74[b]	–12.70 ± 0.54[f,g]	4.93 ± 0.12[b]	13.63 ± 0.48	158.73 ± 1.17	49.06
T6 (170, 1:4)	65.43 ± 0.45[a]	–12.17 ± 0.39[e,f]	4.70 ± 0.00[b,c]	13.04 ± 0.36	158.86 ± 0.60	51.24
T7 (180, 1:2)	60.03 ± 1.19[d]	–12.77 ± 0.87[f,g]	5.77 ± 0.12[a]	14.02 ± 0.77	155.60 ± 1.77	46.24
T8 (180, 1:3)	62.87 ± 0.68[b,c]	–13.20 ± 0.43[g,h]	6.20 ± 0.08[a]	14.59 ± 0.36	154.82 ± 1.01	49.13
T9 (180, 1:4)	65.43 ± 0.48[a]	–12.77 ± 0.41[f,g]	4.40 ± 0.14[c]	13.51 ± 0.35	160.96 ± 1.08	51.32

SP: Spirulina biomass, LS: Liquid sample refers to the mixture of spirulina and maltodextrin before it was spray dried. LS1 corresponds to T1, T4, and T7; LS2 corresponds to T2, T5, and T8; and LS3 corresponds to T3, T6, and T9.

154.82 to 165.28, which correspond to the cyan-green region according to Rong *et al.* (2024).

FTIR spectroscopy

The FTIR analysis highlights the presence of key functional groups and interactions in both the SP and the encapsulating MD, offering an insight into the chemical interactions that play a role in the encapsulation process and protein protection. Figure 2 presents the FTIR spectra corresponding to the functional groups and chemical interaction of SP, MD, and the protein encapsulated within MD. The infrared spectrum of spirulina (Figure 2, spectrum A) exhibited characteristic peaks at 3279 cm^{-1}, attributed to the symmetric stretching vibration of the –OH group, overlapping with N-H stretching. In addition, two bands at 2961 cm^{-1} and 2920 cm^{-1} were observed, corresponding to the asymmetric C-H stretching vibrations in aliphatic groups (-CH_3 and -CH_2, respectively). A notable peak at 1635 cm^{-1} was identified, consistent with the stretching vibration of C=O in amide I, while bands at 1544 cm^{-1} and 1239 cm^{-1} were attributed to the vibrations in amide II and III, respectively. Furthermore, the stretching vibration of the C-O group was detected at 1034 cm^{-1}, aligning with similar results reported in the literature (Buhani *et al.*, 2019; da Silva *et al.*, 2019; Golmakani *et al.*, 2024). On the other hand, in the MD spectrum (Figure 2), peaks at 3271 cm^{-1} and 2920 cm^{-1} were attributed to the -OH and C-H stretching vibrations, respectively. The band at 1639 cm^{-1} was associated with the water–MD interaction, likely because of moisture content, a typical feature in polysaccharides (da Silva *et al.*, 2019; Pais *et al.*, 2021). In addition, signals at 1358 cm^{-1}, 1147 cm^{-1}, and 992 cm^{-1} were linked to asymmetric -CH_2 scissoring vibrations, the asymmetric and symmetric stretching of the glycosidic bond (C-O-C), and the asymmetric stretching of C-O, respectively (Pais *et al.*, 2021; Yu *et al.*, 2021). The infrared spectrum of the microencapsulate (Figure 2, spectrum C) showed a slight shift in the band associated to the -OH group (from 3279 cm^{-1} to 3285 cm^{-1}) because of the hydrogen bridge interactions that occurred between these groups with those of the MD; likewise, it was noted in the band of 1635 cm^{-1} that shifted to 1649 cm^{-1}. Also, the presence of bands associated with amide II at 1544 cm^{-1} and amide III at 1240 cm^{-1} were identified, suggesting that the structural integrity of spirulina is maintained, as well as that of MD, since peaks at 1148 cm^{-1} and 1016 cm^{-1} were found, attributed to the vibrations of the C-O-C and C-O glycosidic bond, respectively. The results clearly show that spirulina maintains its chemical and functional characteristics, as does the encapsulant (MD), indicating that the SP remains encapsulated in the MD, generally through intermolecular Van der Waals forces and hydrogen bonds.

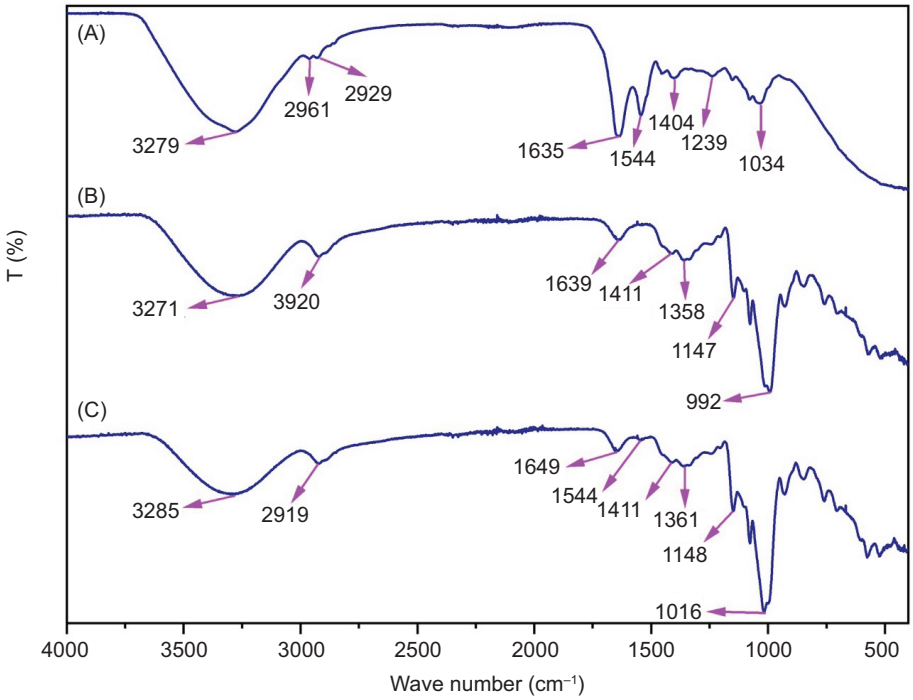

Figure 2. FTIR of spirulina biomass (A), maltodextrin (B), and SP-MD powder (C).

SEM and DLS analysis

In Figure 3, the micrographs show spherical microparticles of irregular sizes with the presence of cavities. This morphology could be defined as irregular shape with single core and wall (Corrêa-Filho *et al.*, 2019; Xiao *et al.*, 2022), primarily influenced by the presence of MD (Faieta *et al.*, 2020). The formation of rough surfaces, dents, and concavities is attributed to the rapid and drastic evaporation of moisture during the initial stages of spray drying, as the droplets enter the drying chamber. This is followed by the subsequent cooling of the microparticles, which contributes to their final shape and surface characteristics (Norkaew *et al.*, 2019). In this study, the surface integrity of the spray-dried samples maintained a continuous surface without visible cracks or fissures, indicating that the spray drying conditions effectively preserved the structural integrity of the microcapsules (Van *et al.*, 2024). This is likely because of the protective role of MD as the wall material, which contributes to lower oxygen permeability, improved protection, and enhanced retention of core materials (Valková *et al.*, 2022) These factors play a significant role in the functional properties of the microcapsules, such as their release kinetics. Nevertheless, previous studies have suggested that using MD with a higher DE value could act as a plasticizer, preventing irregular shrinkage and promoting the formation of a smoother surface (Ghani *et al.*, 2017).

Particle size mainly depends on the encapsulating agent and drying conditions (Ozdemir *et al.,* 2021). The powder obtained in this study had an average size of 5.21 ± 0.54 µm, as measured using ImageJ software. This falls within the typical size range for food powders produced by spray drying, which generally varies between 5 and 25 µm and is classified as medium-sized by Piñón-Balderrama *et al.* (2020).

The hydrodynamic particle size measured by DLS was found to be 441 nm in diameter. In addition, the zeta potential was recorded at −23.7 mV, indicating that the microcapsules exhibit moderate stability over time. According to Jacob and Mullar, a zeta potential of ±30 mV is required for electrostatic stabilization, while ±20 mV is sufficient for steric stabilization (Kamble *et al.*, 2022). However, at more alkaline pH levels, the zeta potential is expected to become more negative because of the gradual deprotonation of carboxyl and amino groups present in the encapsulated proteins (Lee *et al.*, 2021). This increase in negative charge could enhance electrostatic repulsion between particles, reducing the tendency for aggregation and sedimentation.

In vitro release study

The release profile of spirulina from the microcapsules in an aqueous medium is shown in Figure 4. The release

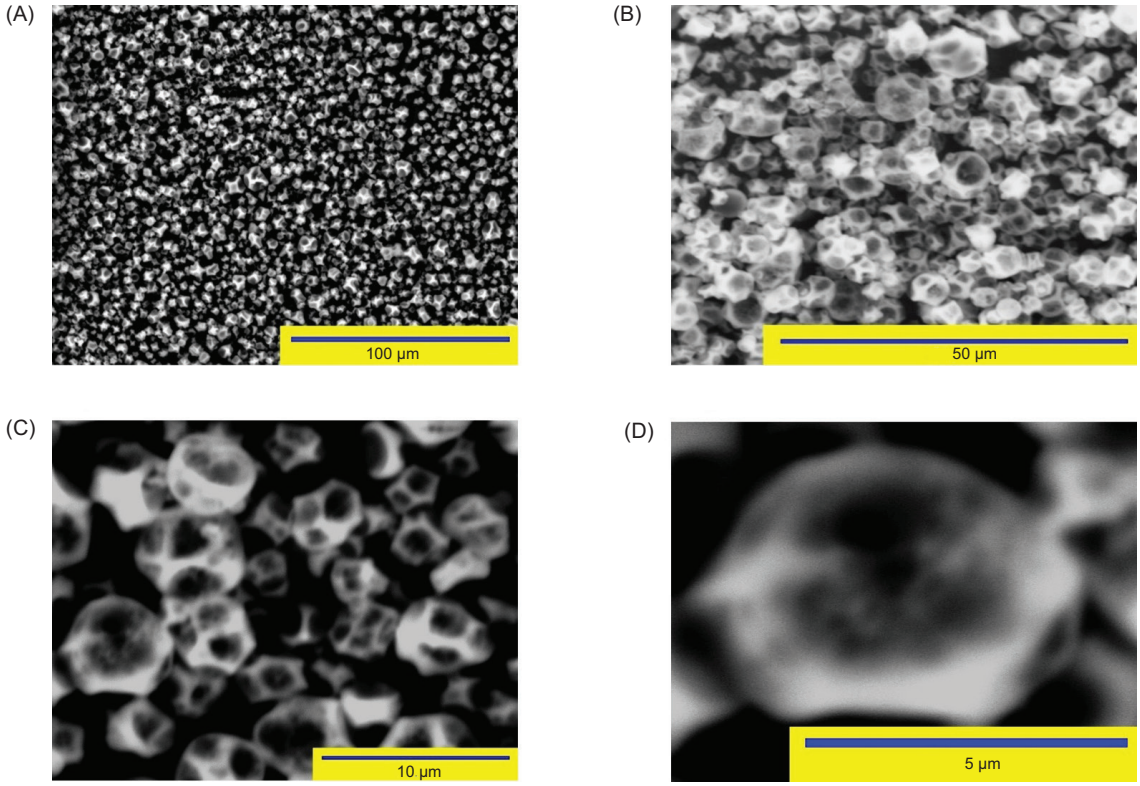

Figure 3. SEM images of optimal treatment SP-MD powder at magnifications of (A) 500×, (B) 1500×, (C) 6000×, and (D) representative particle.

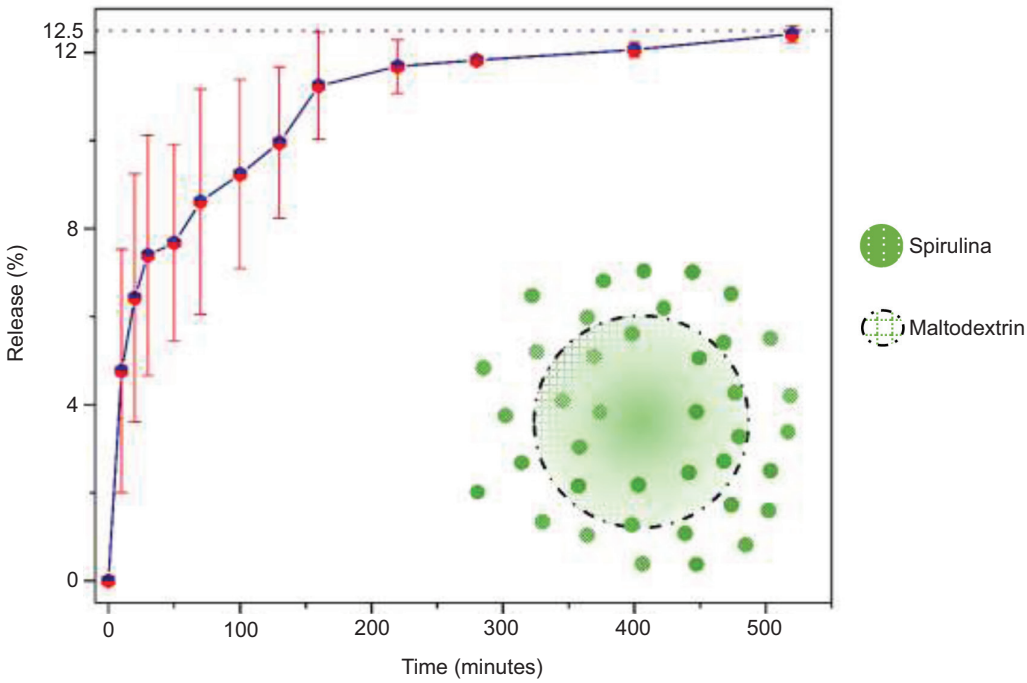

Figure 4. Release profile of spirulina from microcapsules at pH 6 in water medium.

occurs in three distinct phases: an initial rapid release during the first 30 minutes (7.40 ± 2.23%), attributed to nonencapsulated spirulina present on the surface of the microcapsules. This behavior is similar to findings reported by Ozdemir *et al.* (2021), which examined the release of basil essential oil from a combined matrix of gum Arabic, whey protein isolate, and MD. The following phase is slower (between 50 and 160 minutes, 11.25 ± 0.99%), attributed to the spirulina produced by the partial microcapsule's erosion and the final phase where the release percentage remains relatively constant (12.42 ± 0.15%), associated with the low solubility in water presented by the microparticles and is also attributed to the desorption of spirulina, produced by the erosion of microcapsules. The latter behavior is a positive parameter for the industry, since it allows the material's incorporation in matrices with different humidity levels and also to be used in liquid products without promoting the immediate release of encapsulated spirulina (Guarienti *et al.*, 2021).

Conclusions

SP reported a protein content of 66 g/100 g dried spirulina based on the proximal analysis, confirming its status as a complete protein source containing all EAA. While the microencapsulated sample (SP-MD powder) presented a reduced protein content on an average of 31.65 g/100 g dried-spirulina, it still retained all EAA with a slight variation. Notably, the optimum operating conditions were 174.7ºC and an SP:MD ratio of 1:4, which resulted in higher protein content and process yield (46%). In addition, the FTIR and SEM analyses confirmed microencapsulation of spirulina within MD, validating its effectiveness as a protective coating material. Moreover, SP showed a release profile in three stages, reaching a maximum release of 12.5% at 8 hours. Further studies should focus on the optimization of biomass pretreatment before spray drying to preserve higher amounts of protein. The stability of the powder synthesized will also need to be investigated as well as its impact on food formulation from a sensory standpoint.

Authors Contributions

Angie Castillo-Barzola did conceptualization, methodology, validation, investigation, resources, writing – review & editing, supervision, project administration, and funding acquisition. Henry L. Paisig was concerned with methodology, validation, investigation, formal analysis, and writing – review & editing. Marco Faieta was responsible for validation, investigation, and writing – review & editing. Oscar Jordán-Suárez did methodology, resources, writing – review & editing, formal analysis, and data curation. Emilio Porras-Sosa looked into conceptualization, validation, and supervision. Tarsila Tuesta was concerned with conceptualization, methodology, investigation, resources, and writing – review & editing, supervision, and funding acquisition.

Acknowledgments

Authors are grateful to PROCIENCIA for the funding as well as for the technical and financial support provided by Erika Saavedra and Giancarlo Caballero. ACB is grateful to the research laboratory of the Faculty of Bioscience and Technology for Food Agriculture and Environment of Università degli Studi di Teramo for the consultancy; the Laboratorio de Operaciones Unitarias of the Universidad Nacional de Ingeniería, especially Mr. Victor Rojas and Mr. Elmer Ordaya, for their technical contribution and support in the operation of the spray-dryer; the laboratory of Universidad Le Cordon Bleu for their technical support on the use of spray-drying equipment; the IFAPA of the Universidad de Almería for the approach to technology in terms of spirulina production at pilot plant level; the company Intipacha Microalgas for their contributions and for providing the main raw material of this study, the spirulina; and Grupo de Investigación en Alimentos of the Universidad Nacional de Ingeniería, mainly to Jaime Walas Levano, Jonnatan Bañon, and Eng. Gilberto García.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research work was financially supported by the Funding Program Nº. PE501084735-2023-PROCIENCIA, assigned to the project "Diseño del proceso de producción de complemento alimenticio a partir de la microalga espirulina a nivel planta piloto".

References

Ahmed M.H., Vasas D., Hassan A., Molnár J. 2022. The impact of functional food in prevention of malnutrition. PharmaNutrition. 19: 100288. https://doi.org/10.1016/J.PHANU.2022.100288

Al-Dhabi N.A. 2013. Heavy metal analysis in commercial spirulina products for human consumption. Saudi. J. Biol. Sci. 20(4): 383–388. https://doi.org/10.1016/J.SJBS.2013.04.006

Alfadhly N.K.Z., Alhelfi N., Altemimi A.B., Verma D.K., Cacciola F., Narayanankutty A., et al. 2022. Trends and technological advancements in the possible food applications of spirulina and

their health benefits: A review. Molecules. 27(17): 5584. https://doi.org/10.3390/MOLECULES27175584

Allen B. and Saunders J. 2023. Malnutrition and undernutrition: Causes, consequences, assessment and management. Medicine. 51(7): 461–468. https://doi.org/10.1016/J.MPMED.2023.04.004

Almeida L.M.R., Cruz L.F. da S., Machado B.A.S., Nunes I.L., Costa J.A.V., Ferreira E. de S., et al. 2021. Effect of the addition of Spirulina sp. biomass on the development and characterization of functional food. Algal Research. 58: 102387. https://doi.org/10.1016/J.ALGAL.2021.102387

Amaya-Farfan J. 2020. Denaturation of proteins, generation of bioactive peptides, and alterations of amino acids. In *Chemical Changes During Processing and Storage of Foods: Implications for Food Quality and Human Health* (pp. 21–84). Elsevier. https://doi.org/10.1016/B978-0-12-817380-0.00002-6

Arahou F., Hassikou R., Arahou M., Rhazi, L., Wahby, I. 2021. Influence of culture conditions on Arthrospira platensis growth and valorization of biomass as input for sustainable agriculture. Aquaculture International. 29(5): 2009–2020. https://doi.org/10.1007/S10499-021-00730-5/METRICS

Barbosa-Cánovas G.V, Fontana A.J., Schmidt S.J., Labuza T.P. 2020. "Water Activity in Foods: Fundamentals and Applications" (Ed.). 2020. John Wiley & Sons.

Batista de Oliveira T.T., Miranda dos Reis I., Bastos de Souza M., da Silva Bispo E., Fonseca Maciel L., Druzian J.I., et al. 2021. Microencapsulation of Spirulina sp. LEB-18 and its incorporation in chocolate milk: Properties and functional potential. LWT. 148: 111674. https://doi.org/10.1016/J.LWT.2021.111674

Blanco A. and Blanco G. 2022. Proteins. *Medical Biochemistry*, pp. 21–75. https://doi.org/10.1016/B978-0-323-91599-1.00004-3

Bleakley S. and Hayes M. 2021. Functional and bioactive properties of protein extracts generated from Spirulina platensis and Isochrysis galbana T-Iso. Applied Sciences. 11(9): 3964. https://doi.org/10.3390/APP11093964

Buhani S., Aditiya I., Al Kausar R., Sumadi R. 2019. Production of a Spirulina sp. algae hybrid with a silica matrix as an effective adsorbent to absorb crystal violet and methylene blue in a solution. Sustain. Environ. Res. 1(1): 1–11. https://doi.org/10.1186/s42834-019-0027-2

Butreddy A., Janga K.Y., Ajjarapu S., Sarabu S., Dudhipala, N. 2021. Instability of therapeutic proteins—An overview of stresses, stabilization mechanisms and analytical techniques involved in lyophilized proteins. Int. J. Biol. Macromol. 167: 309–325. https://doi.org/10.1016/J.IJBIOMAC.2020.11.188

Chaudhary M.N., Li X., Yang S., Wang D., Luo L., Zeng L., et al. 2024. Microencapsulation efficiency of carboxymethylcellulose, gelatin, maltodextrin, and acacia for aroma preservation in jasmine instant tea. Gels. 10(10): 670. https://doi.org/10.3390/GELS10100670/S1

Chen Y., Mutukuri T.T., Wilson N.E., Zhou Q. (Tony). 2021. Pharmaceutical protein solids: Drying technology, solid-state characterization and stability. Adv. Drug Deliv. Rev. 172: 211–233. https://doi.org/10.1016/J.ADDR.2021.02.016

Corrêa-Filho L.C., Moldão-Martins M., Alves V.D. 2019. Advances in the application of microcapsules as carriers of functional compounds for food products. Appl. Sci. 9(3): 571. https://doi.org/10.3390/APP9030571

Costa M.M., Spínola M.P., Prates, J.A.M. 2024. Microalgae as an alternative mineral source in poultry nutrition. Vet. Sci. 11(1): 44. https://doi.org/10.3390/VETSCI11010044

da Silva S.C., Fernandes I.P., Barros L., Fernandes Â., José Alves M., Calhelha R.C., et al. 2019. Spray-dried Spirulina platensis as an effective ingredient to improve yogurt formulations: Testing different encapsulating solutions. J. Funct. Foods. 60: 103427. https://doi.org/10.1016/j.jff.2019.103427

Das S., Thiagarajan V., Chandrasekaran N., Ravindran B., Mukherjee A. 2022. Nanoplastics enhance the toxic effects of titanium dioxide nanoparticle in freshwater algae Scenedesmus obliquus. Comp. Biochem. Physiol. C. Toxicol. Pharmacol. 256: 109305. https://doi.org/10.1016/J.CBPC.2022.109305

de Morais E.G., Nunes I.L., Druzian J.I., de Morais M.G., da Rosa A.P.C., Costa J.A.V. 2022. Increase in biomass productivity and protein content of Spirulina sp. LEB 18 (Arthrospira) cultivated with crude glycerol. Biomass Convers. Biorefin. 12(3): 597–605. https://doi.org/10.1007/s13399-020-00934-4

Decker B.L.A., Miguel E. de C., Fonteles T.V., Fernandes F.A.N., Rodrigues S. 2024. Impact of spray drying on the properties of grape pomace extract powder. Processes. 12(7): 1390. https://doi.org/10.3390/PR12071390

Demarco M., Moraes J.O. de, Ferrari M.C., Neves F. de F., Laurindo J.B., Tribuzi, G. 2022. Production of Spirulina (Arthrospira platensis) powder by innovative and traditional drying techniques. J. Food Process. Eng. 45(1): e13919. https://doi.org/10.1111/JFPE.13919

Dolganyuk V., Sukhikh S., Kalashnikova O., Ivanova S., Kashirskikh E., Prosekov A., et al. 2023. Food proteins: Potential resources. Sustainability. 15(7): 5863. https://doi.org/10.3390/SU15075863

Duran Barón R., Valle-Vargas M.F., Quintero-Gamero G., Quintanilla-Carvajal M.X., Alean J. 2021. Encapsulation of citrulline extract from watermelon (Citrullus lanatus) by-product using spray drying. Powder Technol. 385: 455–465. https://doi.org/10.1016/J.POWTEC.2021.03.014

Ersado T.L. 2022. Causes of malnutrition. *Combating Malnutrition through Sustainable Approaches*. https://doi.org/10.5772/INTECHOPEN.104458

Faieta M., Corradini M.G., Di Michele A., D. Ludescher R., Pittia P. 2020. Effect of encapsulation process on technological functionality and stability of Spirulina platensis extract. Food Biophys. 15(1): 50–63. https://doi.org/10.1007/s11483-019-09602-1

Francioso A., Fanelli S., Vigli D., Ricceri L., Cavallaro R.A., Conrado A.B., et al. 2017. HPLC determination of bioactive sulfur compounds, amino acids and biogenic amines in biological specimens. Adv. Exp. Med. Biol. 975: 535–549. https://doi.org/10.1007/978-94-024-1079-2_42

Galván-Colorado C., Chamorro-Cevallos G.A., Chanona-Pérez J.J., Zepeda-Vallejo L.G., Arredondo-Tamayo B., González-Ussery S.A., et al. 2024. Phycobiliprotein from arthrospira maxima: Conversion to nanoparticles by high-energy ball milling, structural characterization, and evaluation of their anti-inflammatory effect. Int. J. Biol. Macromol. 275: 133679. https://doi.org/10.1016/J.IJBIOMAC.2024.133679

García A.B., Longo E., Bermejo R. 2021. The application of a phycocyanin extract obtained from Arthrospira platensis as a blue natural colorant in beverages. J. Appl. Phycol. 33(5): 3059–3070. https://doi.org/10.1007/S10811-021-02522-Z/TABLES/4

Garcia S.N., Osburn B.I., Jay-Russell M.T. 2020. One health for food safety, food security, and sustainable food production. Front. Sustain. Food Syst. 4: 481782. https://doi.org/10.3389/FSUFS.2020.00001/BIBTEX

Gentscheva G., Nikolova K., Panayotova V., Peycheva K., Makedonski L., Slavov P., et al. 2023. Application of Arthrospira platensis for medicinal purposes and the food industry: A review of the literature. Life. 13(3): 845. https://doi.org/10.3390/LIFE13030845

Ghani A.A., Adachi S., Shiga H., Neoh T.L., Adachi S., Yoshii H. 2017. Effect of different dextrose equivalents of maltodextrin on oxidation stability in encapsulated fish oil by spray drying. BBB. 81(4): 705–711. https://doi.org/10.1080/09168451.2017.1281721

Golmakani M.T., Hajjari M.M., Kiani F., Sharif N., Hosseini S.M.H. 2024. Application of electrospinning to fabricate phycocyanin- and Spirulina extract-loaded gliadin fibers for active food packaging. Food Chem. X*:* 22. https://doi.org/10.1016/j.fochx.2024.101275

Guarienti C., Bender L.E., Frota E.G., Bertolin T.E., Costa J.A.V., Richards N.S.P. dos S. 2021. Effects of microencapsulation on the preservation of thermal stability and antioxidant properties of Spirulina. J. Food Meas. Charact. 15(6): 5657–5668. https://doi.org/10.1007/S11694-021-01140-0/METRICS

Guidi F., Gojkovic Z., Venuleo M., Assunçao P.A.C.J., Portillo E. 2021. Long-term cultivation of a native arthrospira platensis (Spirulina) strain in pozo izquierdo (Gran Canaria, Spain): Technical evidence for a viable production of food-grade biomass. Processes. 9(8): 1333. https://doi.org/10.3390/PR9081333/S1

Haque A., Sheikh B., Rahman M. 2018. *Drying and Denaturation of Proteins in Spray Drying Process*. https://www.researchgate.net/publication/275100415

Janda-Milczarek K., Szymczykowska K., Jakubczyk K., Kupnicka P., Skonieczna-Żydecka K., Pilarczyk B., et al. 2023. Spirulina supplements as a source of mineral nutrients in the daily diet. Appl. Sci (Switzerland), 13(2): 1011. https://doi.org/10.3390/APP13021011/S1

Jia X., Cui H., Qin S., Ren J., Zhang Z., An Q., et al. 2024. Characterizing and decoding the key odor compounds of Spirulina platensis at different processing stages by sensomics. Food Chem. 461: 140944. https://doi.org/10.1016/J.FOODCHEM.2024.140944

Jiménez-González O. and Guerrero-Beltrán J.Á. 2021. Extraction, microencapsulation, color properties, and experimental design of natural pigments obtained by spray drying. Food Eng. Rev. 13(4): 769–811. https://doi.org/10.1007/S12393-021-09288-7

Jung F., Braune S., Jung C.H.G., Krüger-Genge A., Waldeck P., Petrick I., et al. 2022. Lipophilic and hydrophilic compounds from Arthrospira platensis and its effects on tissue and blood cells—An overview. Life. 12(10): 1497. https://doi.org/10.3390/LIFE12101497

Kamble S., Agrawal S., Cherumukkil S., Sharma V., Jasra R.V., Munshi P. 2022. Revisiting zeta potential, the key feature of interfacial phenomena, with applications and recent advancements. ChemistrySelect. 7(1). https://doi.org/10.1002/SLCT.202103084

Koli D.K., Rudra S.G., Bhowmik A., Pabbi S. 2022. Nutritional, functional, textural and sensory evaluation of Spirulina enriched green pasta: A potential dietary and health supplement. Foods. 11(7): 979. https://doi.org/10.3390/FOODS11070979

Konar N., Durmaz Y., Genc Polat D., Mert, B. 2022. Optimization of spray drying for Chlorella vulgaris by using RSM methodology and maltodextrin. J. Food Process. Preserv. 46(5): e16594. https://doi.org/10.1111/JFPP.16594

Kosasih E.A., Dzaky M.I., Zikri A., Rachmanudiputra A., Abizar F., Fauzi M., et al. 2023. Microencapsulation of maltodextrin and gelatin using spray drying with double-condenser compression refrigeration systems. Case Stud. Therm. Eng. 45: 102931. https://doi.org/10.1016/J.CSITE.2023.102931

Kumar R., Hegde A.S., Sharma K., Parmar P., Srivatsan V. 2022. Microalgae as a sustainable source of edible proteins and bioactive peptides – Current trends and future prospects. Food Res. Int. 157: 111338. https://doi.org/10.1016/J.FOODRES.2022.111338

Lee H.W., Lu Y., Zhang Y., Fu C., Huang D. 2021. Physicochemical and functional properties of red lentil protein isolates from three origins at different pH. Food Chem. 358: 129749. https://doi.org/10.1016/J.FOODCHEM.2021.129749

Lu W., Yang X., Shen J., Li Z., Tan S., Liu W., Cheng Z. 2021. Choosing the appropriate wall materials for spray-drying microencapsulation of natural bioactive ingredients: Taking phenolic compounds as examples. Powder Technol. 394: 562–574. https://doi.org/10.1016/J.POWTEC.2021.08.082

Luo G., Liu H., Yang S., Sun Z., Sun L., Wang L. 2024. Manufacturing processes, additional nutritional value and versatile food applications of fresh microalgae Spirulina. Front. Nutr. 11: 1455553. https://doi.org/10.3389/FNUT.2024.1455553

Maag P., Dirr S., Karslioglu Ö.Ö. 2022. Investigation of bioavailability and food-processing properties of Arthrospira platensis by enzymatic treatment and micro-encapsulation by Spray Drying. Foods. 11(13): 1922. https://doi.org/10.3390/FOODS11131922

Markou G., Kougia E., Arapoglou D., Chentir I., Andreou V., Tzovenis I. 2023. Production of Arthrospira platensis: Effects on growth and biochemical composition of long-term acclimatization at different salinities. Bioengineering. 10(2): 233. https://doi.org/10.3390/BIOENGINEERING10020233

Mohammadi M., Mahdavi-Yekta M., Reihani S.F.S., Khorshidian N., Habibi M., Mousavi Khaneghah A. 2024. Assessment of physicochemical properties of orange juice concentrate formulated with pectin, xanthan, and CMC hydrocolloids. Int. J. Food Sci. 2024(1): 7013553. https://doi.org/10.1155/2024/7013553

Norkaew O., Thitisut P., Mahatheeranont S., Pawin B., Sookwong P., Yodpitak S., Lungkaphin A. 2019. Effect of wall materials on some physicochemical properties and release characteristics of encapsulated black rice anthocyanin microcapsules. Food Chem. 294: 493–502. https://doi.org/10.1016/J.FOODCHEM.2019.05.086

Nunes E., Odenthal K., Nunes N., Fernandes T., Fernandes I.A., Pinheiro de Carvalho M.A.A. 2024. Protein extracts from microalgae and cyanobacteria biomass. Techno-functional

properties and bioactivity: A review. Algal Res. 82: 103638. https://doi.org/10.1016/J.ALGAL.2024.103638

Olson B., Marks D.L., Grossberg A.J. 2020. Diverging metabolic programmes and behaviours during states of starvation, protein malnutrition, and cachexia. J. Cachexia Sarcopenia Muscle. 11(6): 1429–1446. https://doi.org/10.1002/JCSM.12630

Ozdemir N., Bayrak A., Tat T., Altay F., Kiralan M., Kurt, A. 2021. Microencapsulation of basil essential oil: Utilization of gum Arabic/whey protein isolate/maltodextrin combinations for encapsulation efficiency and in vitro release. J. Food Meas. Charact. 15(2): 1865–1876. https://doi.org/10.1007/S11694-020-00771-Z/METRICS

Özyurt G., Uslu L., Durmuş M., Sakarya Y., Uzlaşir T., Küley E. 2023. Chemical and physical characterization of microencapsulated Spirulina fermented with Lactobacillus plantarum. Algal Res. 73: 103149. https://doi.org/10.1016/J.ALGAL.2023.103149

Padhani Z.A., Das J.K., Akhtar S., Ismail T., Bhutta Z.A. 2022. Tackling protein-calorie malnutrition during world crises. Ann. Nutr. Metab. 78(Suppl. 1): 27–38. https://doi.org/10.1159/000522242

Pais M., George S.D., Rao P. 2021. Interfacial adsorption of nanoparticles of maltodextrin for enhanced protection of metal surface. Surf. Interfaces. 26: 101418. https://doi.org/10.1016/j.surfin.2021.101418

Papalia T., Sidari R., Panuccio M.R. 2019. Impact of different storage methods on bioactive compounds in Arthrospira platensis biomass. Molecules. 24(15): 2810. https://doi.org/10.3390/MOLECULES24152810

Piñón-Balderrama C.I., Leyva-Porras C., Terán-Figueroa Y., Espinosa-Solís V., Álvarez-Salas C., Saavedra-Leos M.Z. 2020. Encapsulation of active ingredients in food industry by spray-drying and nano spray-drying technologies. Processes. 8(8): 889. https://doi.org/10.3390/PR8080889

Pintado T. and Delgado-Pando G. 2020. Towards more sustainable meat products: Extenders as a way of reducing meat content. Foods. 9(8): 1044. https://doi.org/10.3390/FOODS9081044

Pootthachaya P., Puangsap W., Bunchalee P., Plangklang P., Reungsang A., Yuangsoi B., Cherdthong A., et al. 2023. Investigation of nutritional profile, protein solubility and in vitro digestibility of various algae species as an alternative protein source for poultry feed. Algal Res. 72: 103147. https://doi.org/10.1016/J.ALGAL.2023.103147

Pratama A.I., Lioe H.N., Yuliana N.D., Ogawa M. 2022. Umami compounds present in umami fraction of acid-hydrolyzed Spirulina (Spirulina platensis). Algal Res. 66: 102764. https://doi.org/10.1016/J.ALGAL.2022.102764

Priyanka S., Varsha R., Verma R., Babu A.S. 2023. Spirulina: A spotlight on its nutraceutical properties and food processing applications. JMBFS. 12(6): e4785-e4785. https://doi.org/10.55251/jmbfs.4785

Proch J. and Niedzielski P. 2021. Iron species determination by high performance liquid chromatography with plasma based optical emission detectors: HPLC–MIP OES and HPLC–ICP OES. Talanta. 231: 122403. https://doi.org/10.1016/J.TALANTA.2021.122403

Raczyk M., Polanowska K., Kruszewski B., Grygier A., Michałowska D. 2022. Effect of Spirulina (Arthrospira platensis) supplementation on physical and chemical properties of semolina (Triticum durum) based fresh pasta. Molecules. 27(2): 55. https://doi.org/10.3390/MOLECULES27020355

Ragaza J.A., Hossain M.S., Meiler K.A., Velasquez S.F., Kumar V. 2020. A review on Spirulina: Alternative media for cultivation and nutritive value as an aquafeed. Rev. Aquac. 12(4): 2371–2395. https://doi.org/10.1111/RAQ.12439

Raja K., Kadirvel V., Subramaniyan T. 2022. Seaweeds, an aquatic plant-based protein for sustainable nutrition – A review. Future Foods. 5:100142. https://doi.org/10.1016/J.FUFO.2022.100142

Ramírez-Rodrigues M.M., Estrada-Beristain C., Metri-Ojeda J., Pérez-Alva A., Baigts-Allende D.K. 2021. Spirulina platensis protein as sustainable ingredient for nutritional food products development. Sustainability. 13(12): 6849. https://doi.org/10.3390/SU13126849

Rong A., Hansopaheluwakan-Edward N., Li D. 2024. Analyzing the color availability of AI-generated posters based on K-means clustering: 74% orange, 38% cyan, 32% yellow, and 28% blue-cyan. Color Res. Appl. 49(2): 234–257. https://doi.org/10.1002/col.22912

Rosero-Chasoy G., Rodríguez-Jasso R.M., Aguilar C.N., Buitrón G., Chairez I., Ruiz H.A. 2022. Growth kinetics and quantification of carbohydrate, protein, lipids, and chlorophyll of Spirulina platensis under aqueous conditions using different carbon and nitrogen sources. Bioresour. Technol. 346: 126456. https://doi.org/10.1016/J.BIORTECH.2021.126456

Rubio C., Dominik-Jakubiec M., Paz S., Gutiérrez Á.J., González-Weller D., Hardisson, A. 2021. Dietary exposure to trace elements (B, Ba, Li, Ni, Sr, and V) and toxic metals (Al, Cd, and Pb) from the consumption of commercial preparations of Spirulina platensis. Environ. Sci. Pollut. Res. Int. 28(17): 22146–22155. https://doi.org/10.1007/S11356-020-12260-3/METRICS

Rzymski P., Budzulak J., Niedzielski P., Klimaszyk P., Proch J., Kozak L., et al. 2019. Essential and toxic elements in commercial microalgal food supplements. J. Appl. Phycol. 31(6): 3567–3579. https://doi.org/10.1007/S10811-018-1681-1/FIGURES/3

Sadigov R. 2022. Rapid growth of the world population and its socioeconomic results. Sci. World J. 2022(1): 8110229. https://doi.org/10.1155/2022/8110229

Samborska K., Poozesh S., Barańska A., Sobulska M., Jedlińska A., Arpagaus C., et al. 2022. Innovations in spray drying process for food and pharma industries. J. Food Eng. 321:110960. https://doi.org/10.1016/J.JFOODENG.2022.110960

Saxena R., Rodríguez-Jasso R.M., Chávez-Gonzalez M.L., Aguilar C.N., Quijano G., Ruiz H.A. 2022. Strategy development for microalgae Spirulina platensis biomass cultivation in a bubble photobioreactor to promote high carbohydrate content. Fermentation. 8(8):374. https://doi.org/10.3390/FERMENTATION8080374

Scholes G. 2022. Protein-energy malnutrition in older Australians: A narrative review of the prevalence, causes and consequences of malnutrition, and strategies for prevention. HPJA. 33(1): 187–193. https://doi.org/10.1002/HPJA.489

Semba R.D., Ramsing R., Rahman N., Kraemer K., Bloem M.W. 2021. Legumes as a sustainable source of protein in human diets. GFSI. 28: 100520. https://doi.org/10.1016/J.GFS.2021.100520

Shaghaghian S., McClements D.J., Khalesi M., Garcia-Vaquero M., Mirzapour-Kouhdasht A. 2022. Digestibility and bioavailability

of plant-based proteins intended for use in meat analogues: A review. Trends Food Sci. Technol. 129: 646–656. https://doi.org/10.1016/J.TIFS.2022.11.016

Silva N.C., Freitas L.V.D., Silva T.C., Duarte C.R., Barrozo M.A.S. 2023. Use of refractance window drying as an alternative method for processing the microalga Spirulina platensis. Molecules. 28(2): 720. https://doi.org/10.3390/MOLECULES28020720

Stramarkou M., Papadaki S., Kyriakopoulou K., Tzovenis I., Chronis M., Krokida M. 2021. Comparative analysis of different drying techniques based on the qualitative characteristics of Spirulina platensis biomass. J. Aquat. Food Prod. Technol. 30(5): 498–516. https://doi.org/10.1080/10498850.2021.1900969

Taiti C., Di Vito M., Di Mercurio M., Costantini L., Merendino N., Sanguinetti M., Bugli F., Garzoli S. 2023. Detection of secondary metabolites, proximate composition and bioactivity of organic dried Spirulina (Arthrospira platensis). Appl. Sci. 14(1): 67. https://doi.org/10.3390/APP14010067

Tay J.B.J., Chua X., Ang C., Subramanian G.S., Tan S.Y., Lin E.M.J., et al. 2021. Effects of spray-drying inlet temperature on the production of high-quality native rice starch. Processes. 9(9): 1557. https://doi.org/10.3390/PR9091557/S1

Tessier R., Calvez J., Khodorova N., Gaudichon C. 2021. Protein and amino acid digestibility of 15N Spirulina in rats. Eur. J. Nutr. 60(4): 2263–2269. https://doi.org/10.1007/S00394-020-02368-0/METRICS

Tuesta-Chavez T., Monteza J., Silva Jaimes M.I., Ruiz-Pacco G.A., Changanaqui K., Espinoza – Suarez J.B., et al. 2022. Characterization and evaluation of antioxidant and antimicrobial capacity of prepared liquid smoke-loaded chitosan nanoparticles. J. Food Eng. 319: 110912. https://doi.org/10.1016/J.JFOODENG.2021.110912

United Nations. 2017. *World Population Prospects: The 2017 Revision*. Department of Economic and Social Affairs, Population Division, *Key Findings and Advance Tables*. Working Paper No. ESA/P/WP/248.

USDA Foreign Agricultural Service. 2018. *Maximum Levels of Contaminants in Foods*. China Releases the Standard for Maximum Levels of Contaminants in Foods. Global Agricultural Information Network. GAIN Report Number: CH18025

Valková V., Ďúranová H., Falcimaigne-Cordin A., Rossi C., Nadaud F., Nesterenko A., et al. 2022. Impact of freeze- and spray-drying microencapsulation techniques on β-Glucan powder biological activity: A comparative study. Foods. 11(15): 2267. https://doi.org/10.3390/FOODS11152267

Van C.K., Nguyen P.T.N., Nguyen T.T.T., Bach L.G. 2024. Microencapsulation of Citrus latifolia peel essential oil by spray-drying using maltodextrin: Characterization, antimicrobial activities, and release profile. LWT. 197: 115825. https://doi.org/10.1016/J.LWT.2024.115825

Wang X., Li Y., Zhang X., Chen X., Wang X., Yu D., et al. 2024. The extracellular polymeric substances (EPS) accumulation of Spirulina platensis responding to Cadmium (Cd2+) exposure. J. Hazard. Mater. 470: 134244. https://doi.org/10.1016/J.JHAZMAT.2024.134244

Xiao Z., Xia J., Zhao Q., Niu Y., Zhao D. 2022. Maltodextrin as wall material for microcapsules: A review. Carbohydr. Polym. 298: 120113. https://doi.org/10.1016/J.CARBPOL.2022.120113

Yadav M., Kumar V., Jain S., Sandal N., Chauhan M.K. 2022. *Assessment of Adsorption and Removal Efficacy of Spirulina Powder for Strontium and Thallium*. https://doi.org/10.21203/RS.3.RS-1539864/V1

Yu J.Y., Roh S.H., Park H.J. 2021. Characterization of ferulic acid encapsulation complexes with maltodextrin and hydroxypropyl methylcellulose. Food Hydrocoll. 111: 106390. https://doi.org/10.1016/j.foodhyd.2020.106390

Zhang H., Gong T., Li J., Pan B., Hu Q., Duan M., Zhang, X. 2022. Study on the effect of spray drying process on the quality of microalgal biomass: A comprehensive biocomposition analysis of spray-dried S. acuminatus biomass. Bioenergy Res. 15(1): 320–333. https://doi.org/10.1007/S12155-021-10343-8/METRICS

Zhao M., Cao W., Li L., Ren A., Ang Y., Chen J., et al. 2022. Effects of different proteins and maltodextrin combinations as wall material on the characteristics of Cornus officinalis flavonoids microcapsules. Front. Nutr. 9: 1007863. https://doi.org/10.3389/FNUT.2022.1007863/BIBTEX