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Spray-Drying Optimization for Dunaliella salina and Porphyridium cruentum Biomass

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Abstract

The compositions and cultivation advantages of microalgae increase their importance as sustainable food and feed sources. However, drying and encapsulation processes are needed for widespread use. In this study, *Dunaliella salina* and *Porphyridium cruentum* biomass were encapsulated by using spray-dryer (SD) and combined D-optimal methods. The independent variables were SD inlet temperature (170-190°C), maltodextrin (25-75%, w/w, in dm) and microalgae biomass (25-75%, w/w, in dm). Prior to spray drying, *P. cruentum* and *D. salina* were cultivated in a pilot scale tubular photobioreactor (PBR) and than harvested using a conical plate centrifuge. Significant models were determined for the effects of independent variables on total carotenoids, chlorophyll-a, crude protein, moisture content and encapsulation yield, water activity, average particle size, wettability, hygroscopity, L* and C* properties for both microalgae species ($P<0.05$). It was determined that biochemical and cell properties and composition need to developed unique spray-drying process for each alga. Also, due to the low moisture content (>6.27 g 100 g^{-1}) and water activity (>0.277), the average particle sizes (>143.7 µm) of the samples with high stability were advantageous for various food applications and storage. However, due to the low encapsulation yield (11.1-33.1%), we recommend encapsulation and drying of *P. cruentum* biomass with alternative methods to spray dryer. The extracellular, as well as the cell wall and storage polysaccharides released into the culture medium of these microalgae are possible reasons for the low encapsulation yield.

1. Introduction

The interest and demand for microalgae in food and feed technologies is increasing day by day. The main reasons for this situation are that they are sustainable sources for various nutrients as well as bioactive components and various ingredients in food technology (Balti et al. 2018; Rebolloso Fuentes et al. 2000; Durmaz et al. 2020; Yucel et al. 2021). It is an important advantage that their biomass is rich in various macro-molecules as well as containing bioactive and minor-components. However, this situation reveals the need to develop complex processes (Ljubic et al. 2021; Lafarga et al. 2021; Mehariya et al. 2021; Konar et al. 2022).

Studies are focused on the optimization of growing methods and conditions, bioreactor types, stress conditions, especially to optimize various pigments, polyunsaturated fatty acids, proteins contents and biomass for microalgae species (Francavilla et al. al. 2010; Bernaerts et al. 2018; Durmaz et al. 2020). The motivations in microalgae studies related to food technology are; (i) purification of macro- and micro-components, (ii) drying and encapsulation for widespread use, (iii) effect on stability and quality properties of algal components in food matrices, (iv) interactions with conventional components, (v) cost and quality improvement, (vi) responding to consumer demands and expectations, (vii) identifying alternative and sustainable ingredients. However, for all these studies, the biochemical composition of the microalgae biomass, the necessary post-harvest processes and their stability characteristics during their application, cultivation efficiency and compliance with food safety conditions should be considered. Direct consumption of *Dunaliella salina* (Depra et al. 2020; Yucel et al. 2021) and *Porphyridium cruentum* (Durmaz et al. 2020) included in this study were categorized as GRAS (Generally Recognized as Safe) by the FDA. Therefore, there is the advantage of applying the findings of thi study directly in food technology. Considering the industrial demands and needs, *D. salina* (Rammuni et al. 2019)d *cruentum* (Bernaerts et al. 2018) stand out as critically important microalgae to meet these demands sustainably. However, drying and encapsulation studies of them are limited.

D. salina, one of the richest natural sources of carotenoids, is a unicellular, halophilic, biflagellate green microalgae (Prieto et al. 2011; Khadim et al. 2018; Colusse et al. 2020;). *D. salina* cells are ovoid, ellipsoid, or spherical in shape, with a length of 5–25 µm and a width of 3–13 µm. Among the intracellular pigments of *D. salina*, the main ones are carotenoids and chlorophyll (Hosseini et al. 2017). Its high fatty acid, protein and pigment contents make this microalga an attractive option for the feed and food industry (Morowvat and Ghasemi, 2016; Khadim et al. 2018). *P. cruentum* (Rodophyta) is a eukaryotic red marine microalga with spherical and insufficiently walled cells (Balti et al. 2018; Rebolloso Fuentes et al. 2000). Considering the diversity and amount of different components in the composition of *P. cruentum* biomass, it is recommended to be used for nutritional purposes (Rebolloso Fuentes et al. 2000). It is also noteworthy that it has a high competitive advantage in terms of economy. Because the unit production volume of this microalgae is high and the production cycle is short (Oh et al. 2009; Balti et al. 2018). *D. salina* can also adapt quickly and easily to various conditions. One of the subjects that aquaculture studies focus on is the production of *D. salina* with low cost and high efficiency (Colusse et al. 2020).

In general, among the priority issues in microalgae technology is the development of ingredients for food, feed and cosmetics production by developing technologies and applications with high economic feasibility. Different techniques can be used in microalgae cultivation. These include open and closed methods. Although microalgae are fast growing microorganisms, their high volume production can be carried out under controlled conditions (Ljubic et al. 2021). In addition, considering the effect of stress conditions on the components, it is advantageous to provide optimally controlled conditions for microalgae cultivation for certain purposes. There are several risks to microalgae cultivation in open ponds and other systems; low efficiency, high CO_2 consumption, contamination risks, insufficient control of some environmental factors, such as high salt and water requirement (Garcia-Gonzalez et al. 2005). Therefore, the use of photobioreactor is remarkable (Prieto et al. 2011). Photobioreactor design and scale-up studies, which are highly efficient and can be used for different species, are an important part of microalgae studies (Khadim et al. 2018). In addition, microalgae cultivation studies should be carried out for the control of environmental conditions and for different target uses. This control is more important in situations where stress and environmental conditions have a significant effect on their biochemical composition, such as in *D. salina*.

Selection of appropriate microalgae for certain purposes is important because there are many microalgae species and their biomass shows high biochemical variation. However, even the same microalgae species are cultured with biomasses with compositions that vary according to various factors (Bernaerts et al. 2018). For example, *D. salina* has high-quality protein content, and the amount and composition of essential amino acids, which vary depending on the culture conditions, are also important (Colusse et al. 2020). Oh et al. (2009) determined that the total lipid amount of *P. cruentum* changed depending on the carbon source in the culture medium. Cultivation technique and stress conditions have important effects on the composition of microalgae biomass. These stress conditions include the type and concentration of carbon source, temperature, light intensity, salinity, nutrient deficiencies, and residence time in the bioreactor (Prieto et al. 2011; Morowvat and Ghasemi, 2016; Hosseini et al. al., 2017; Colusse et al. 2020; Rammuni et al. 2019; Rebolloso Fuentes et al. 2000; Ljubic et al.

2021). However, the change in these conditions does not have the same effect on all components. For example, for *D. salina*, UVB light exposure increased vitamin D3 production and decreased protein accumulation (Ljubic et al. 2021). For some microalgae, stress conditions provide more than one advantage. For example, *Dunaliella* species show optimal growth, especially with an increase in salinity. These features provide advantages in terms of industrial applications. Because with the increase in salinity, there is a significant decrease in the number and species of other microorganisms that it will compete with (Garcia et al. 2007). However, optimization of cultivation conditions increases the production of certain biomolecules, making it difficult to compare different microalgae biomass profiles (Bernaerts et al. 2018).

With various demands and expectations, optimization studies are needed for both cultivation and post-harvest processes in microalgae technology. Conditions in post-harvest processes are critical both for productivity sustainability and for different application areas. The process following harvest for microalgae is dehydration. This process should be applied considering the end-use aim (Depra et al. 2020). Multi-effects can be achieved with the use of dried and encapsulated whole microalgae biomass (Durmaz et al. 2020). In addition to being economical and high efficiency of post-harvest processes, their effects on end product characteristics should be investigated. It should be noted that the methods to be used shoul be applicable for scale-up. Microalgae dehydration can be completed using various methods. However, based on commercial and industrial scale, process conditions have significant effects on end product properties and process cost. For example, the pigment compositions of microalgae can be modified using different drying and other post-harvest techniques. In addition, encapsulation can be used to improve the stability of pigments against external factors such as temperature, pH and light (Durmaz et al. 2020). Variation in cell structures are also factors to consider. For example, the properties of the cell wall can affect the stability of various bioactive compounds during dehydration. Drying and encapsulation with a spray-dryer is advantageous due to its economic and widespread use (Konar et al. 2022).

In general, nutritionally important components are stored in the microalgae cell and are protected by a cell wall. Therefore, the cell wall limits the extraction of target substances and/or their bioavailability properties. As a result, cell walls may need to be broken down by various methods (such as thermal, sonication, mechanical and/or chemical) in microalgae processing (Bernaerts et al. 2018). However, this is not valid for all microalgae. *D. salina* and *P. cruentum* are advantageous microalgae in this sense. Because *D. salina* does not have a rigid cell wall (Pereira and Otero, 2019). For example, *D. salina* cell wall property provides advantage for the extraction of carotenoids (Chen et al. 2020). Also, the cell wall of *P. cruentum* is more fragile than other microalgae (Rebolloso Fuentes et al. 2000). For example, no change was detected in the amount of extractable protein after ultrasonication (Gonzalez-Lopez et al. 2010). This may be advantageous for the extraction of various substances from biomass.

The non-rigid cell wall structure for microalgae increases the potential for direct consumption or use in foods after post-harvest processes such as drying (Yucel et al. 2021). However, this feature should also be taken into account in determining the conditions and method in the post-harvest processes to be applied. Because exposures such as temperature and oxygen stress may be responsible for losses for various components. Therefore, it is important to optimize both the type and amount of carrier material and the process conditions.

One of the approaches used in microalgae drying and encapsulation is the application of these processes to whole biomass. By this process, it may be possible to produce a natural material that can be used in various applications. We can also obtain multi-functional products as a result of whole microalgae biomass drying and/or encapsulation (Bernaerts et al. 2018; Durmaz et al. 2020; Konar et al. 2022). The need for additional applications that arise during the extraction of different components is eliminated and advantages are provided for loss and stability problems that may occur during these processes. For example, the presence of chlorophyll in *D. salina* biomass may adversely affect the efficiency of carotenoid extraction (Rammuni et al. 2019). In this study, the drying of the whole biomass of two microalgae *(D. salina* and *P. cruentum*), which can be widely consumed as food and also food ingredient, was optimized by a widely used and low-cost method (spray-dryer) and carrier agent (maltodextrin) considering scale-up advantages. For this aim, the effects of process conditions (spray dryer inlet temperature) and feed composition (microalgae biomass:maltodextrin) on process efficiency and final product composition and characteristics were investigated.

2. Materials And Methods

2.1. Materials

Dunaliella salina (UTEX 2538) and *Porphyridium cruentum* (UTEX 161) from The Culture Collection of University of Texas (Austin, USA) were cultivated in a pilot scale tubular photobioreactor (PBR) (Ege University Fisheries Faculty, Izmir, Turkey). The tubular PBR with 200 L capacity consisted of a solar tube made of transparent plexiglass material with a diameter of 0.05m (wall thickness 0.002 m) and in a steel tank consisted of a double walled on which an algal suspension was circulated, gas changed and heat changed. Illumination was measured on the surface of tube as 200 µmol photons $m^2 s^{-1}$ (Philips TLM 40W/54RS and metalhalide bulb; Sylvania Britelux MH 250W) light intensity.

The *D. salina* were cultured in sterilized seawater enriched with salt (6.0 g L^{-1} NaCl) and F/2 medium (Guillard, 1975). Salinity was 6.0 g L^{-1}. The *P. cruentum* were grown in seawater (2.8 g L^{-1} NaCl) in Porphyridium medium (Vonshak 1988). The medium contained 10.4×10^{-3} M of nitrogen (KNO_3) and 5.5×10^{-4} M of phosphate (KH_2PO_4). All reagents, except otherwise stated, were obtained from Merck (Germany) and standards from Sigma- Aldrich (USA).

The microalgal culture circulated at a velocity of 0.6 m s^{-1} using a centrifugal pump located between the bubble column and the solar receiver. All cultures were maintained at 20.0 ± 1.00°C under 16/8 hours of light/dark photoperiod. The temperature of system controlled by an internal heat exchanger placed in titanium tubes with a water flow of 100 L h^{-1} of sea water. pH of microalgae culture in the system were controlled by Seko Control 40 pH/redox meter (Turkey). This device was connected with solenoid valve for culture pH which was controlled automatically by injection of pure industrial grade CO_2 gas at 5 L min^{-1}. After reaching the maximum value of the biomass growth phase, the algal biomass was harvested using a conical plate centrifuge (ENKA separator Turkey; 4863 g), obtaining slurry with 20% dry weight content, and then stored at – 20°C. prior to encapsulation by using maltodextrin (12–16 DE, Tayas Food,

Kocaeli, Istanbul) as carrier. After separation, algal biomass with an average of 12% and 15% dry matter for *D. salina* and *P. cruentum*, respectively was obtained.

2.2 Study model

A combined D-optimal method by a statistical package, Design-Expert (Stat-Ease Inc. version 12.0, Minneapolis) was used in order to determine the influence of three independent variables on the model system. The effect of spray dryer inlet temperature (170.0-190.0°C, A, X1) 170–190, ratio of C. vulgaris biomass (25.0%-75.0%, B, X2) and maltodextrin (25.0%-75.0%, C, X3) in total solid content of feed solution on the crude protein, pigment and moisture contents, particle size, wettability, hygroscopity, color properties and encapsulation yield of samples were investigated.

2.3 Encapsulation by using a spray dryer

For the preparation feed solution with, 8.0 g 100 mL^{-1} and 15.0 g 100 mL^{-1} for *D. salina* and *P. cruentum*, respectively, soluble solid content, wall material (maltodextrin, 12–16 DE) and *C. vulgaris* were mixed with distilled water at 25°C acording to study model and shaken at 250 rpm in a refrigerated incubator for 30 min (De Oliveria et al. 2021). Encapsulation of microalgae samples by spray drying process was performed with a laboratory scale spray dryer (B15, Unopex, Izmir, Turkey), with a nozzle atomization system including 1.0 µm nozzle diameter. The main parameters important for the spray drying process were as inlet air temperature (170.0-190.0°C) and outlet air temperature (95.0°C) and feed rate (7.00–9.00 mL min^{-1}). The residence time of the drying air within the spray chamber was about 1.5 seconds (Konar et al. 2022).

2.4 Encapsulation yield

The encapsulation yield (EY, %) was calculated by determining the mass in the initial solution and the dried product. EY was calculated by using Eq. 1 (Nunes & Mercadante, 2007);

$$\mathrm{EY}\,(\%) = 100\mathrm{x}\frac{[\mathrm{EncapsulatedMass}\,(\mathrm{indm}) - \mathrm{TotalMassofFeedSolution}\,(\mathrm{indm})]}{\mathrm{TotalMassofFeedSolution}\,(\mathrm{indm})} (1)$$

2.5 Water activity, protein and moisture contents

Protein and moisture contents of encapsulated microalgae were performed according to method used by Durmaz et al. (2020). Crude protein content (N 6.25) was determined by the Kjeldahl method after acid digestion. To determine moisture content, samples were dried at 105°C by drying oven (Memmert UF110, Germany) until a constant weight was achieved. The water activity (aw) of the samples was measured using a Lab- Master aw (Novasina, Switzerland). aw value of each sample was measured in triplicate after a follow-up day of sample preparation.

2.6 Color analysis

Color properties (L*, a*, b*, C* and h°) of algal biomass after spray dryer process were determined by a colorimeter (CR-400, Konica Minolta, Japan). The L* (blackness-whiteness), a* (± red-green) and b* (± yellow-blue) values of the samples were measured and these values were used to determine the chroma (C*) and hue angle (h°) values by using Eqs. (2) and (3) (Konar et al. 2022). Analyzes were carried out in five replications.

$$C* = \sqrt{a*^2 + b*^2}$$

2

$$h* = \arctan\,(b*/a*)$$

3

2.7 Pigment analysis

Chlorophyll-a and total carotenoid contents were determined spectrophotometrically. 5 mL of samples were centrifuged, and supernatant was discarded. After that, 5 mL methanol and glass beads were added to the samples and mixed by vortex. Mechanical agitator was used for cell disruption. Samples were placed into the ultrasonic bath. Then, they were centrifuged, and supernatants were taken to determine absorbance values at defined wave-length by using a UV-VIS spectrophotometer (UV-1280, Schimadzu, Kyoto, Japan). Chlorophyll-a and total carotenoids were determined according to the Eqs. 4 and 5, respectively (Zou & Richmond, 2000; Sánchez et al. 2005);

Chlorophyll a (µg/mL) = 13.9 A_{665}* (4)

*A665; absorbance value at 665 nm

Total carotenoids (µg/ml) = 4.5 A_{475}* (5)

*A475; absorbance value at 475 nm

2.8 Mean Particle Size

The mean particle size of microalgae powders was determined by using a micrometer device (Mitutoyo, Manufacturing Co. Ltd., Japan, 0.001 mm accuracy). Mean values from 5 replicate assessments were assessed (Fidaleo et al. 2017).

2.9 Hygroscopicity

The hygroscopicity of samples was measured according to the method used by Fritzen-Freire et al. (2012). 1 g of encapsulated powder sample was taken in known weight (m_i) of petri dish and was placed in an airtight glass desiccator containing NaCl saturated solution of 75% RH and stored for 7 days at a room temperature of 25°C. At the end of storage period, the sample was weighed (m_f), and hygroscopicity was calculated by using Eq. 6;

Hygroscopicity (g H_2O/100 g sample) = $((m_f - m_i)/m_i) \times 100$ (6)

2.10 Wettability

The wettability time was evaluated by static wetting test method (Hammes, Englert, Norena, & Cardozo, 2015) in second (sec). 1 g of encapsulated probiotic powder was sprinkled over the surface of 100 mL distilled water at room temperature without agitation. Time taken for the powder particles to sediment, submerse and disappear from the water surface was recorded.

2.11 Statistical analysis

Design Expert (Stat-Ease Inc. trial version 13.0, Minneapolis, US) program was used for data analyses. Regression coefficients of quadratic models and interaction terms were determined ($p > 0.05$).

3. Results And Discussion

3.1 Encapsulation Yield

The relationship between feed and final product total masses, as well as variations in the concentrations of certain compounds, can be used to determine the efficiency of the drying and encapsulation processes. Variations in pigment concentrations are among the most used parameters (Iqbal & Hadiyanto, 2020). However, if the final product amount is low, it is not always sufficient to develop a process with only high component stability (Konar et al. 2022). As in this study, mass loss-based efficiency determination can be considered in processes where all microalgae biomass is dried. Of course, optimization studies can be carried out simultaneously based on the stability of different components and more than one response.

According to Konar et al. (2022), in the study they used spray dryer and maltodextrin, the EY value for *Chlorella vulgaris* was 14.93–28.50%. In this study, EY values for *D. salina* and P. *cruentum* were determined as 50.8–70.2% and 11.3–33.1%, respectively (Table 1). For *P. cruentum*, significant effects of changing the feed composition on EY have not been determined. More dried biomass was obtained only at the lowest microalgae concentration and at relatively low temperature (Fig. 1). *D. salina* EY values were generally affected by both the feed concentration and the spray dryer inlet temperatures. The use of lower temperature and microalgae concentration resulted in higher EY (Fig. 2). Significant models for EY were determined for both microalgae species ($P < 0.05$). The R^2 values of these models for *D. salina* and *P. cruentum* were 0.7979 and 0.8549, respectively.

Table 1
Encapsulated *Dunaliella salina* and *Porphyridium cruentum* crude protein and pigment contents

Sample	SDI (°C)	Microalgae Biomass (%)	MD (%)	*Dunaliella salina*			*Porphyridium cruentum*		
				Total Carotenoid ($\mu g\ g^{-1}$)	Encapsulation Yield (%)	Chlorophyll-a ($\mu g\ g^{-1}$)	Total Carotenoid ($\mu g\ g^{-1}$)	Encapsulation Yield (%)	Chlorophyll-a ($\mu g\ g^{-1}$)
1	175	62.5	37.5	3189.7±15.5	64.0±1.12	5764.4±31.5	645.3±11.2	26.2±0.12	1065.3±11.4
2	185	37.5	62.5	6412.5±22.0	64.6±2.51	10474.6±46.9	379.5±21.0	13.3±1.04	1265.9±22.5
3	180	75.0	25.0	4275.0±34.5	65.7±0.90	8050.4±43.2	368.8±15.3	11.1±0.91	1533.4±17.1
4	190	75.0	25.0	2615.6±51.0	48.8±3.21	3770.4±32.9	249.2±9.50	12.7±1.03	1647.5±18.5
5	190	75.0	25.0	1240.2±21.4	50.8±1.47	1678.4±24.8	439.2±15.3	12.5±0.76	1577.1±20.5
6	175	25.0	75.0	1297.5±17.5	67.2±0.56	2038.7±21.0	258.0±8.75	31.9±0.17	464.9±21.1
7	170	75.0	25.0	1264.0±14.3	55.9±1.16	1962.4±15.0	342.5±15.1	11.3±0.56	1274.2±9.44
8	190	25.0	75.0	9267.2±41.0	70.2±2.05	14725.3±14.2	142.7±11.2	29.5±0.45	423.8±8.76
9	180	50.0	50.0	6292.7±56.0	59.9±1.54	9931.8±59.5	376.5±21.4	20.3±1.02	1127.6±12.0
10	190	50.0	50.0	2228.8±24.6	56.4±0.95	2793.1±19.9	295.9±9.55	18.1±1.10	933.0±9.51
11	185	62.5	37.5	2273.9±17.8	57.0±2.11	3273.8±33.7	598.7±15.4	22.2±0.75	1281.9±14.0
12	175	37.5	62.5	4900.0±32.0	64.3±2.05	8571.7±44.1	395.9±11.5	28.7±0.46	1605.5±12.5
13	170	25.0	75.0	5146.0±44.5	62.1±0.99	7667.5±48.5	262.5±14.3	33.1±1.04	482.7±5.75
14	170	50.0	50.0	1322.7±10.9	51.3±1.21	2085.0±20.9	406.7±22.2	20.4±0.89	1430.1±13.1
15	180	25.0	75.0	5737.5±28.5	64.0±1.56	8158.0±52.0	142.7±8.75	29.9±0.91	423.8±7.50
Model				Quadratic	Quadratic	Quadratic	Quadratic	Cubic	Cubic
p value				0.0286*	0.0059*	0.0329*	0.0080*	0.0003*	< 0.0001
Lack of fit F value				0.3970**	0.2789**	0.3661**	0.7999**	nd	0.2002**
R^2				0.6304	0.7979	0.6190	0.5527	0.8549	0.8732
Adjusted- R^2				0.4826	0.6857	0.4667	0.4782	0.7968	0.8386
Predicted- R^2				0.1538	0.3013	0.1381	0.3301	0.6152	0.7595
Adeq Precision				6.8588	8.4691	6.5802	5.7473	10.5441	11.2199

*: significant, **: not significant. $P < 0.05$. SDI: Spray Dryer Inlet Temperature, MD: Maltodextrin. Mean ± Standart Deviation. Analyses were performed in triplicate.

In our study, it was determined that microalgae species had a significant effect on EY. Among the possible reasons for this is that each microalgae species has different biochemical composition and cell structure. These biochemical and structural differences may be due not only to the substances deposited in the cell, but also to differences in the composition of the cell wall. Polysaccharides associated with algal cell walls include different polymeric substances such as cell wall polysaccharides and extracellular polymers. While some of these substances are lost during harvest, some of them are released into the culture medium, the soluble ones pass into the aqueous phase, and are included in the algal paste and dried algae mass (Bernaerts et al. 2018). Therefore, the concentrations of soluble polysaccharides are important for drying and encapsulation. Cell wall polymers are generally bound substances (Durmaz et al. 2020). Cell wall polymeric substances generally make up about 10% of the total biomass. Therefore, differences in cell wall properties affect the drying and encapsulation processes and the results of this process.

P. cruentum cells contain different carbohydrates; (i) cell storage polymers (starch derivatives), (ii) lipopolysaccharides, and (iii) extracellular polysaccharides (Durmaz et al. 2020; Yucel et al. 2021). Exo-polysaccharides can bind to the cell and are released into the culture medium. They contribute to the protection of cells from various environmental factors. However, the effects of polymeric substances, especially sulfated polysaccharides, released by cells into the culture medium, on the feed flow behavior and drying process should be considered (Rebolloso Fuentes et al. 2000). Sulphated polysaccharides have the ability to act as gelling agents in food structures. Polysaccharides in *P. cruentum* biomass have the ability to form viscous solutions and gel at low concentrations (Durmaz et al. 2020). The presence of these substances may cause algae-containing materials to stick to the relevant surfaces during flow, and this adhesive property may continue even in the dry form obtained. As observed in our study, the adherence of the feed to the surface of various system components (atomizer, chamber, cyclone etc) in the spray-dryer process caused low EY values for *P. cruentum*.

The concentrations of these substances vary depending on the culture conditions and strain. Previously, a soluble exo-polysaccharide concentration of 0.10–0.70 g L^{-1} for *Porphyridium* and 0.94 g L^{-1} for *D. salina* was determined (Balti et al. 2018). Therefore, it can be stated that the source of the difference between the species for the EY values in our study is due to the polysaccharide composition and concentration in the cell wall composition of the two species. In addition, the presence of salts and proteins can reduce the viscosity of solutions (Eteshola et al. 1998; Balti et al. 2018). In this case, the feed for *D. salina* can be expected to have a lower viscosity. As a result of this difference, higher EY rates were determined for *D. salina*.

3.2 Pigments and protein contents

Although proteins have lower economic value than some bioactive compounds, they are among the large fractions of microlagal biomass. The total protein content of microalgae biomass varies depending on the species (Gonzalez-Lopez et al. 2010). Despite this, microalgae are among the important vegetable protein sources. In addition, the increasing demand and expectation for vegetable proteins increase the importance of these organisms as sustainable resources.

In this study, crude protein concentrations of the samples prepared using different ratios of algal biomass and maltodextrin were 3.63-19.0 g 100 g^{-1} for *P. cruentum* and 6.99–29.9 g 100 g^{-1} for *D. salina* (Table 2). As expected, crude protein ratio increased in both species depending on the feed biomass ratio. In addition, it was determined that the effect of the spray dryer inlet temperature was negligible. Therefore, with the method and agent used, encapsulation and drying can be applied without significant crude protein losses in microalgae biomass. Significant models were determined for the effect of microalgae biomass:maltodextrin ratio and spray dryer inlet temperature on the amount of crude protein ($P < 0.05$). The R^2 values of these models for P. cruentum and D. salina were 0.9857 and 0.9832, respectively.

Table 2
Encapsulated *Dunaliella salina* and *Porphyridium cruentum* crude protein and pigment contents

Sample	SDI (°C)	Microalgae Biomass (%)	MD (%)	*Dunaliella salina*			*Porphyridium cruentum*		
				Moisture Content (g 100 g^{-1})	Water Activity (aw)	Crude Protein (g 100 g^{-1})	Moisture Content (g 100 g^{-1})	Water Activity (aw)	Crude Protein (g 100 g^{-1})
1	175	62.5	37.5	4.22±0.86	0.262±0.003	22.3±0.11	3.33±0.11	0.244±0.011	16.4±0.07
2	185	37.5	62.5	5.35±0.54	0.264±0.003	16.0±0.96	2.95±0.65	0.244±0.010	11.4±0.05
3	180	75.0	25.0	2.16±0.39	0.271±0.001	28.0±0.63	3.12±0.50	0.262±0.004	19.0±0.91
4	190	75.0	25.0	6.20±0.15	0.262±0.003	29.9±2.14	3.01±0.16	0.251±0.006	18.0±0.65
5	190	75.0	25.0	5.42±0.78	0.270±0.000	28.0±0.35	3.05±0.12	0.249±0.007	17.6±0.56
6	175	25.0	75.0	4.16±0.99	0.267±0.001	7.97±0.02	3.61±0.05	0.220±0.008	4.16±0.03
7	170	75.0	25.0	6.27±0.92	0.260±0.001	27.6±0.07	3.40±0.35	0.247±0.006	16.3±0.12
8	190	25.0	75.0	0.34±0.06	0.266±0.001	7.65±0.01	3.46±0.33	0.254±0.008	4.14±0.05
9	180	50.0	50.0	3.95±0.46	0.277±0.001	18.0±0.05	3.31±0.13	0.276±0.010	13.3±0.16
10	190	50.0	50.0	2.10±0.30	0.265±0.001	17.8±0.0.4	3.16±0.16	0.246±0.005	12.6±0.21
11	185	62.5	37.5	4.10±0.82	0.266±0.002	22.5±0.09	3.19±0.48	0.239±0.011	16.4±0.76
12	175	37.5	62.5	3.56±0.46	0.263±0.004	12.6±0.02	3.11±0.16	0.246±0.002	9.18±0.09
13	170	25.0	75.0	2.04±0.87	0.267±0.001	6.99±0.53	3.79±0.44	0.251±0.001	4.35±0.08
14	170	50.0	50.0	3.14±0.17	0.262±0.001	17.0±0.01	3.32±0.46	0.258±0.000	13.0±0.89
15	180	25.0	75.0	2.94±015	0.264±0.001	7.78±0.04	3.52±0.00	0.239±0.006	3.63±0.05
Model				Quadratic	Quadratic	Linear	Cubic	Quadratic	KCV
p value				0.0127*	0.2611**	< 0.0001*	0.0035*	0.7581**	< 0.0001*
Lack of fit F value				0.3794**	0.8107**	0.7679**	0.1966	nd	0.2442**
R^2				0.7575	0.2006	0.9832	0.9091	0.4418	0.9857
Adjusted- R^2				0.6228	0.0673	0.9819	0.8182	-0.3024	0.9777
Predicted- R^2				0.2867	-0.2380	0.9783	0.3250	-7.3479	0.9573
Adeq Precision				8.4728	2.8584	50.3909	9.7369	2.5628	27.3097

*: significant, **: not significant. P < 0.05. SDI: Spray Dryer Inlet Temperature, MD: Maltodextrin. Mean ± Standart Deviation. Analyses were performed in triplicate.

The amount of crude protein determined in this study was consistent with previous studies. The crude protein amounts for *P. cruentum* and *D. salina*, which did not contain any carriers or encapsulation agents, were determined as 13.0-28.2 g 100 g^{-1} (Bernaerts et al. 2018; Durmaz et al. 2020) and 19.1–38.3 g 100 g^{-1} (Colusse et al. 2020) g, respectively. In addition, the relationship between other components such as pigments and the amount of protein is remarkable. For example, Colusse et al. (2020) found a decrease in lutein and zeaxanthin levels but an increase in chlorophyll-a for D. salina grown in conditions with higher protein content. However, the different methods used in the analysis of the protein amount of microalgae biomass cause different results in various studies. In some studies, non-protein nitrogen is also calculated (Bernaerts et al. 2018). Nitrogen is also present in the structure of components such as DNA and chlorophyll, which are among the algal components. Inorganic nitrogens can also be encountered. Therefore, protein analysis results obtained in different studies may vary for the same algae (Gonzalez-Lopez et al. 2010).

The increasing interest and demand for natural pigments also leads to an increase in research on microalgae such as *D. salina* (Depra et al. 2020)d *cruentum* (Bernaerts et al. 2018; Durmaz et al. 2020). Among these pigments, carotenoids and chlorophyll stand out due to their widespread use (Mehariya et al. 2021). Based on its economic values, chlorophyll-a can be mentioned among the less important pigments (Colusse et al. 2020). However, its widespread use eliminates this disadvantage.

Carotenoids are pigments that are widely used in food and cosmetic technology. *D. salina* is a microalga in which approximately 8% of its total biomass is composed of β-carotene, which is one of the main carotenoids (Yucel et al. 2021). Carotenoids are compounds with low polarity (Hosseini et al. 2017). For microalgae with relatively weak cell walls, such as *D. salina*, in studies using carriers and drying applications, the losses in the amount of carotenoids can be associated with this polarity property. Therefore, the use of different carriers as well as the presence of emulsifiers may result in dried microalgae (*D. salina*)

with a higher total carotenoid content after spray-dryer. Rebolloso Fuentes et al. (2000), P. *cruentum* total carotenoid amount in dry matter is 1020 μg g^{-1}, Durmaz et al. (2020) determined it as 400 μg g^{-1}. In this study, the total carotenoid amounts for *D. salina* and *P. cruentum*, which were prepared using different amounts of maltodextrin, were 1322.7-9267.2 μg g^{-1} and 142.7-645.3 μg g^{-1}, respectively (Table 1). Significant models of the effects of independent variables on the total amount of carotenoids for both microalgae were determined with R^2 values of 0.6304 and 0.5527, respectively ($P < 0.05$). As shown in Figs. 1 and 2, temperature increase for *P. cruentum* had no significant effect on the total carotenoid amount, while for *D. salina*, depending on the microalgae concentration, high temperature application could provide an advantage for this parameter. *D. salina* is an important source for obtaining pigments for different application areas (Garcia-Gonzalez et al. 2005). However, not only drying and encapsulation, but also the effects of culture conditions on both productivity and composition should be considered. For example, an increase in salinity generally results in an increase in the amount of carotenoids (Garcia et al. 2007), while it causes a decrease in some components such as phytosterols (Francavilla et al. 2010). Therefore, for microalgae with different cultivation conditions, modifications may be required in drying and encapsulation processes due to variations in metabolite compositions.

The change in the amount of chlorophyll-a (2038.7-10474 μg g^{-1}) of *D. salina* samples (Table 1) was quite similar to the total amount of carotenoids, and a significant model ($R^2 = 0.6190$) was determined for this parameter ($P < 0.05$). Spray dryer inlet temperature application of 175°C and above resulted in higher chlorophyll-a content. However, the application of high microalgae concentration (> 62.5%) and temperature (> 185°C) caused a decrease in the amount of chlorophyll-a for *D. salina*. For *P. cruentum*, the interaction of temperature and microalgae concentration on chlorophyll-a content (423.8-1647.5 μg g^{-1}) and its model $R^2 = 0.8732$) were significant ($P < 0.05$). Chlorophyll-a contents for *P. cruentum* are consistent with previous studies (Durmaz et al. 2020). However, *D. salina* hlorophyll-a content was determined to be higher than previous studies (Pereira and Otero, 2019; Colusse et al. 2020). The source of this difference may be the cultivation conditions and/or strain of microalga. In addition, the carotenoid/chlorophyll ratio for *D. salina* is expected to be greater than 6 (Pereira and Otero, 2019). Our findings were contradictory to this.

3.3 Particle Sizes and Phycico-chemical Properties

The size and morphology of the particles are important parameters for the characterization of powders. These properties are used to determine usage possibilities for food applications. For example, the increase in particle size of algal components in spreads and chocolates negatively affects flow and sensory properties (Genc Polat et al. 2020 and 2022). The mean particle sizes for *P. cruentum* and *D. salina* were 80.1-143.7 μm and 112.7–143.0 μm, respectively (Table 3). The effects of process variables were significant for both microalgae ($P < 0.05$). As a result of the encapsulation of different biological materials with the spray-dryer, the average particle size was found to be > 50 μm (Desai & Park, 2005; Gharsallaoui et al. 2007; Nedovic et al. 2011). In addition, this value was 34.8–74.2 μm for another commonly used microalgae, *C. vulgaris* (Konar et al. 2022). The possible reason for the relatively larger particle sizes is the agglomeration of substances that make up the composition of the *D. salina* and *P. cruentum*'s cell and cell wall.

Table 3
Encapsulated *Dunaliella salina* and *Porphyridium cruentum* crude protein and pigment contents

Sample	SDI (°C)	Microalgae Biomass (%)	MD (%)	*Dunaliella salina*			*Porphyridium cruentum*		
				Wettability (sec)	Hygroscopity (g 100 g^{-1})	Particule Size (µm)	Wettability (sec)	Hygroscopity (g 100 g^{-1})	Particule Size (µm)
1	175	62.5	37.5	1262.5±19.5	8.90±0.23	129.3±5.13	1681.5±19.1	5.07±0.83	143.7±4.16
2	185	37.5	62.5	1428.5±9.50	9.37±0.78	134.3±2.51	1447.5±91.2	3.80±0.93	116.8±10.4
3	180	75.0	25.0	705.0±17.0	9.91±1.05	137.0±1.73	1608.5±34.7	20.5±1.53	80.1±12.1
4	190	75.0	25.0	900.0±4.00	5.84±0.82	140.7±3.21	1908.5±12.9	8.44±1.64	85.7±8.62
5	190	75.0	25.0	956.5±14.5	6.02±0.41	142.3±2.51	1807.5±17.8	8.24±1.42	81.5±8.11
6	175	25.0	75.0	986.5±11.5	6.49±0.99	129.3±11.2	1219.5±6.36	13.42±2.00	143.7±8.14
7	170	75.0	25.0	833.6±19.5	5.74±0.65	134.0±2.65	1699.5±38.9	22.44±3.15	103.3±12.9
8	190	25.0	75.0	999.0±4.00	8.12±0.27	143.0±6.55	1311.0±36.8	11.76±2.70	133.3±25.7
9	180	50.0	50.0	1090.0±42.0	8.34±0.09	121.3±9.81	1549.0±26.9	11.15±1.64	103.3±4.73
10	190	50.0	50.0	1112.4±14.5	5.70±0.58	112.7±3.55	1516.5±36.1	15.49±0.62	105.3±19.9
11	185	62.5	37.5	1361.5±12.5	7.77±0.49	131.7±9.24	1686.0±67.9	8.59±1.17	140.0±4.58
12	175	37.5	62.5	1470.0±82.0	10.7±0.62	128.7±3.17	1449.0±33.9	6.26±2.72	119.3±10.4
13	170	25.0	75.0	978.5±3.50	11.2±0.53	125.3±3.79	1252.5±50.2	9.96±1.08	134.3±6.51
14	170	50.0	50.0	1206.5±13.5	7.12±0.30	125.1±5.00	1518.5±58.7	15.73±0.07	127.0±14.1
15	180	25.0	75.0	829.0±7.00	5.65±0.14	131.7±1.15	1208.5±7.78	14.33±2.44	123.7±4.62
Model				Quadratic	Quadratic	Quadratic	Quadratic	Quadratic	Cubic
p value				0.0030*	0.0461*	0.0047*	< 0.0001*	0.2323**	0.0011*
Lack of fit F value				0.1931**	0.0674**	0.1842**	nd	nd	0.1782**
R^2				0.6195	0.6661	0.8087	0.9932	0.7128	0.7552
Adjusted- R^2				0.5561	0.4807	0.7024	0.9841	0.3299	0.6884
Predicted- R^2				0.4355	0.2939	0.4239	0.8770	-6.1126	0.5468
Adeq Precision				6.5155	5.9030	8.5308	31.6580	5.0824	7.2720

*: significant, **: not significant. P < 0.05. SDI: Spray Dryer Inlet Temperature, MD: Maltodextrin. Mean ± Standart Deviation. Analyses were performed in triplicate.

Another important factor is the moisture content. In this study, samples with lower moisture content were obtained for *P. cruentum* samples (2.95–3.79 g 100 g^{-1}) by using low microalgae concentration at high temperature (P < 0.05). In *D. salina* samples (0.34–6.20 g 100 g^{-1}), it can be stated that microalgae concentration is a more effective variable than temperature on the moisture content of samples (Table 3). For edible powder products, an ideal moisture value of less than 4.00 g 100 g^{-1}can be defined as ideal (Lei & Langrish, 2021). Also, Bernaerts et al. (2018) determined the moisture content as 1.50–8.20 g 100 $g^{-1}$for various microalgae, including lyophilized *P. cruentum*. In addition, moisture content may adversely affect the stability of dried and encapsulated microalgae biomass, and agglomeration may occur, especially during storage (Shivakumar et al. 2012; Castejon et al. 2021). The moisture content of the samples obtained as a result of this study was generally suitable for storage stability.

In addition, models of the effect of independent variables on moisture content of *P. cruentum* (R^2 = 0.9091) and *D. salina* (R^2 = 07575) samples were significant. However, models for water activity were not significant (P < 0.05), however they were under limit (0.600) for microbial stability. The water activity values of all samples were between 0.239 and 0.277 (Table 3). These results were in agreement with previous studies in which spray-dried *Spirulina sp.* (De Olivera et al. 2021) and *C. vulgaris* (Konar et al. 2022) were investigated.

3.4 Wettability and Hygroscopicity

The wettability is expressed in terms of the time (second) needed for a given quantity of powder to penetrate the free surface of water at rest (Foo et al. 2020). The wettability behavior of powder and encapsulated materials can provide information about their tendency to become hydrated in water (De Oliveira et al. 2020). The relationship between this behavior and the homogeneous distribution and dissolution ability of the samples in different food applications is important. In addition, some undesirable features and problems such as agglomeration cause an increase in wettability (Montes et al. 2011). Wettability values for *D. salina* samples prepared using maltodextrin increased up to approximately 50% algal biomass usage ratio (Table 3). The use of higher ratios of microalgae biomass in feed solution resulted in a decrease. This is thought to be due to the fact that maltodextrin exceeded the encapsulation capacity of *D.*

salina biomass and was exposed to water penetration more easily. For *P. cruentum*, on the other hand, it can be stated that with the increase in biomass ratio and spray dryer inlet temperature, the polysaccharides from *P. cruentum* have an effect on gelation and viscosity, resulting in a structure where water is more difficult to penetrate. Significant models were determined for both microalgae with the effect of independent variables on wettability ($P < 0.05$).

Hygroscopic powders adsorb more water from air humidity, increasing their cohesion and decreasing their flowability (Kapoor and Feng, 2022). Hygroscopity values of *D. salina* samples were 5.65–11.2 g 100 g^{-1} (Table 3). The interaction of the biomass ratio used for this microalgae and the temperature level of the spray dryer inlet had a significant effect on hygroscopity ($P < 0.05$). In addition, samples with relatively low hygroscopity values were obtained. Therefore, stable powders can be obtained in *D. salina* biomass with the spray-dryer method. Because the absorption level of water molecules in a humid environment of these powders were generally low (Caparino et al. 2012). Also, hygroscopity values can be improved with the use of with low dextrose equivalent (DE) maltodextrin. Because low DE maltodextrin contains fewer hydrophilic groups and adsorbs less moisture from the air (Tonon et al. 2011). A significant model could not be determined for the hygroscopity of the samples prepared with *P. cruentum* biomass ($P > 0.05$). In addition, the hygroscopity values of the powders containing these microalgae were higher (3.80-22.44 g 100 g^{-1}). Among the possible factors affecting these findings are the particle sizes of the powders. It was determined that samples with larger particle size had lower hygroscopity value for both microalgae species. Large particle size causes less contact surface, which results in low water absorption (Kuck and Norena, 2016).

3.5 Color Characterization

The colorimetric (L*, a*, b*, C* and hº) properties of the samples containing *P. cruentum* and *D. salina* biomass were determined (Table 4). Significant models were determined for the effects of independent variables on L*, b* and C* values for *D. salina*, and L*, a* and C* values for *P. cruetum* ($P < 0.05$). It can be stated that microalgae samples have visual properties that can be associated with pigment profiles. In microalgae drying and extraction studies, changes in colorimetric properties are associated with pigment concentrations and degradation. Mouahid et al. (2016) emphasized the relationship between the transition from red tones to yellow tones and the degradation of carotenoids for *D. salina* after drying. These researchers suggested shortening the drying time. It was also emphasized that this modification would provide an advantage in process costs. In this study, higher b* values (17.7–28.7) were determined at lower microalgae biomass concentrations for for D. salina, but this parameter was affected by the spray dryer inlet temperature. In addition, the increase in b* value with the decrease in maltodextrin ratio was a remarkable result. The L* (35.5–59.9) values of *D. salina* samples were particularly affected by the feed solution composition. L* values decreased with the increase in maltodextrin ratio. L* values (45.4–73.0) of *P. cruentum* samples were similarly affected. However, they had higher L* values than *D. salina* samples. Phycobiliproteins in the composition of *P. cruentum* are brightly colored pigments (Lauceri et al. 2019). Therefore, they can be associated with L* values. The results obtained in this study indicated that spray dryer conditions and feed composition affect the visual properties of encapsulated and dried microalgae biomass.

Table 4
Encapsulated *Dunaliella salina* and *Porphyridium cruentum* crude protein and pigment contents

Sample	SDI (°C)	Microalgae Biomass (%)	MD (%)	*Dunaliella salina*					*Porphyridium cruentum*			
				L*	a*	b*	C*	h°	L*	a*	b*	C*
1	175	62.5	37.5	40.4±0.43	-9.64±0.14	24.0±0.27	25.9±0.30	111.9±0.12	47.2±0.80	15.2±0.82	3.05±0.25	15.5±
2	185	37.5	62.5	51.0±1.28	-8.69±0.29	28.1±0.96	29.4±0.99	107.2±0.04	49.2±0.51	17.7±0.50	5.65±0.06	18.5±
3	180	75.0	25.0	35.5±0.16	-3.45±0.08	18.6±0.43	18.9±0.44	100.5±0.03	54.3±0.59	18.3±0.42	9.75±0.13	20.7±
4	190	75.0	25.0	36.6±0.24	-5.38±0.08	23.1±0.29	23.8±0.30	103.1±0.04	54.0±0.63	17.5±0.86	9.92±0.44	20.1±
5	190	75.0	25.0	36.0±1.16	-5.38±0.15	22.2±0.65	22.8±0.67	103.7±0.05	52.0±0.61	17.5±0.75	9.92±021	20.1±
6	175	25.0	75.0	58.2±0.88	-8.37±0.05	28.2±0.09	29.4±0.09	106.4±0.29	71.3±0.90	12.9±0.34	12.7±0.38	18.1±
7	170	75.0	25.0	40.1±0.37	-6.24±0.04	23.2±0.22	24.0±0.21	105.1±0.15	58.6±0.39	15.7±0.55	8.54±0.42	17.9±
8	190	25.0	75.0	59.9±0.48	-8.33±0.11	27.3±0.32	28,5±0.34	107.0±0.04	72.7±0.16	13.6±0.33	13.2±0.58	18.7±
9	180	50.0	50.0	46.1±0.46	-5.04±0.08	23.7±0.20	24.2±0.20	102.0±0.11	61.9±0.62	14.5±0.40	12.8±0.47	18.8±
10	190	50.0	50.0	45.0±0.43	-5.14±0.04	24.4±0.22	24.9±0.21	101.9±0.16	61.0±0.47	14.1±0.30	12.0±0.40	18.5±
11	185	62.5	37.5	39.5±1.22	-8.28±0.26	24.0±0.63	25.4±0.68	109.0±0.12	45.4±0.14	16.5±0.07	2.63±0.07	16.7±
12	175	37.5	62.5	51.1±1.54	-8.64±0.25	28.7±0.61	30.0±0.66	106.8±0.12	53.2±0.80	19.0±0.39	4.45±0.18	19.5±
13	170	25.0	75.0	59.2±0.15	-7.58±0.09	26.8±0.21	27.9±0.23	105.8±0.06	69.0±0.46	14.5±0.24	14.6±0.29	20.6±
14	170	50.0	50.0	47.3±0.49	-3.80±0.10	17.7±0.28	17.8±0.28	102.2±0.20	60.4±0.87	15.9±0.79	10.4±0.50	19.0±
15	180	25.0	75.0	59.9±0.05	-8.29±0.03	27.5±0.04	28.7±0.05	106.8±0.05	73.0±0.29	14.1±0.14	12.9±0.08	19.1±
Model				Quadratic	Quadratic	Quadratic	Linear	Cubic	Quadratic	Cubic	Quadratic	Cubic
p value				< 0.0001*	0.6470**	0.0406*	0.0039*	0.3157**	0.0021*	0.0105*	0.0942**	0.043
Lack of fit F value				0.2368**	nd	0.2268**	0.1904**	0.1057*	nd	nd	nd	nd
R^2				0.9818	0.5049	0.8585	0.5190	0.2655	0.6428	0.6526	0.3254	0.508
Adjusted- R^2				0.9788	-0.1552	0.6699	0.3879	0.0652	0.5832	0.5234	0.2130	0.374
Predicted- R^2				0.9703	-7.2866	-0.5632	0.0810	-0.4905	0.4840	0.2675	0.0288	0.060
Adeq Precision				37.6494	2.2384	6.2550	5.7023	2.3203	6.8502	5.2019	3.5905	5.054

*: significant, **: not significant. P < 0.05. SDI: Spray Dryer Inlet Temperature, MD: Maltodextrin. Mean ± Standart Deviation. L*: brightness, a*: ± red-green, and blue, C: chroma, h°: hue angle. Five replicates of the colour experiments were performed.

Conclusion

In this study, significant models of the effects of feed solution composition and spray dryer inlet temperature on various pigment concentrations, protein content, physico-chemical and visual properties were determined in the encapsulation and drying of *P. cruentum* and *D. salina*. The increase in interest and demand for microalgae requires the development of post-harvest methods that will increase their use in different applications. Common uses include being a source of vegetable protein and pigment. The spray-dryer technique can be used for drying and encapsulation of various microalgae due to its technological and economic advantages. However, the results obtained as a result of this study revealed that different processes should be developed for each microalga. In addition, the end-use and biochemical composition of the dried and encapsulated biomass should be considered in the process and method design. Microalgae powders with low moisture content, water activity and hygroscopicity can be obtained by using the spray-dryer method and microalgae at different ratios. The particle size properties of these powders are generally advantageous for their use in various foods. However, exo-polymers, cell wall properties and cell storage polysaccharides are important for high efficiency encapsulation and drying. As a result of the presence and levels of these components, as well as the possible effects of substances such as sulfated polysaccharides, low efficiency spray-drying may result. Considering the encapsulation yield values, it is recommended to use alternative methods to spray-dryer for *P. cruentum*. In addition, further studies should be performed to determine the effects of encapsulation and process conditions on microalgae bioactive components, and their bioavailability properties.

Declarations

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Data Availability Statement

Authors are share or make available any data and materials supporting the results or analyses presented in this paper.

Declaration of author's contributions

We hereby declare that all authors worked together in this work and participated in data analyses, discussion of results, writing and revising the manuscript. All authors have agreed to the authorship and submission of the manuscript to the Journal of Applied Phycology journal for peer review.

Statement of informed consent, human/animal rights

No conflicts, informed consent, human or animal rights applicable.

Conflict of interest

The authors declare no conflict of interest.

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Figures

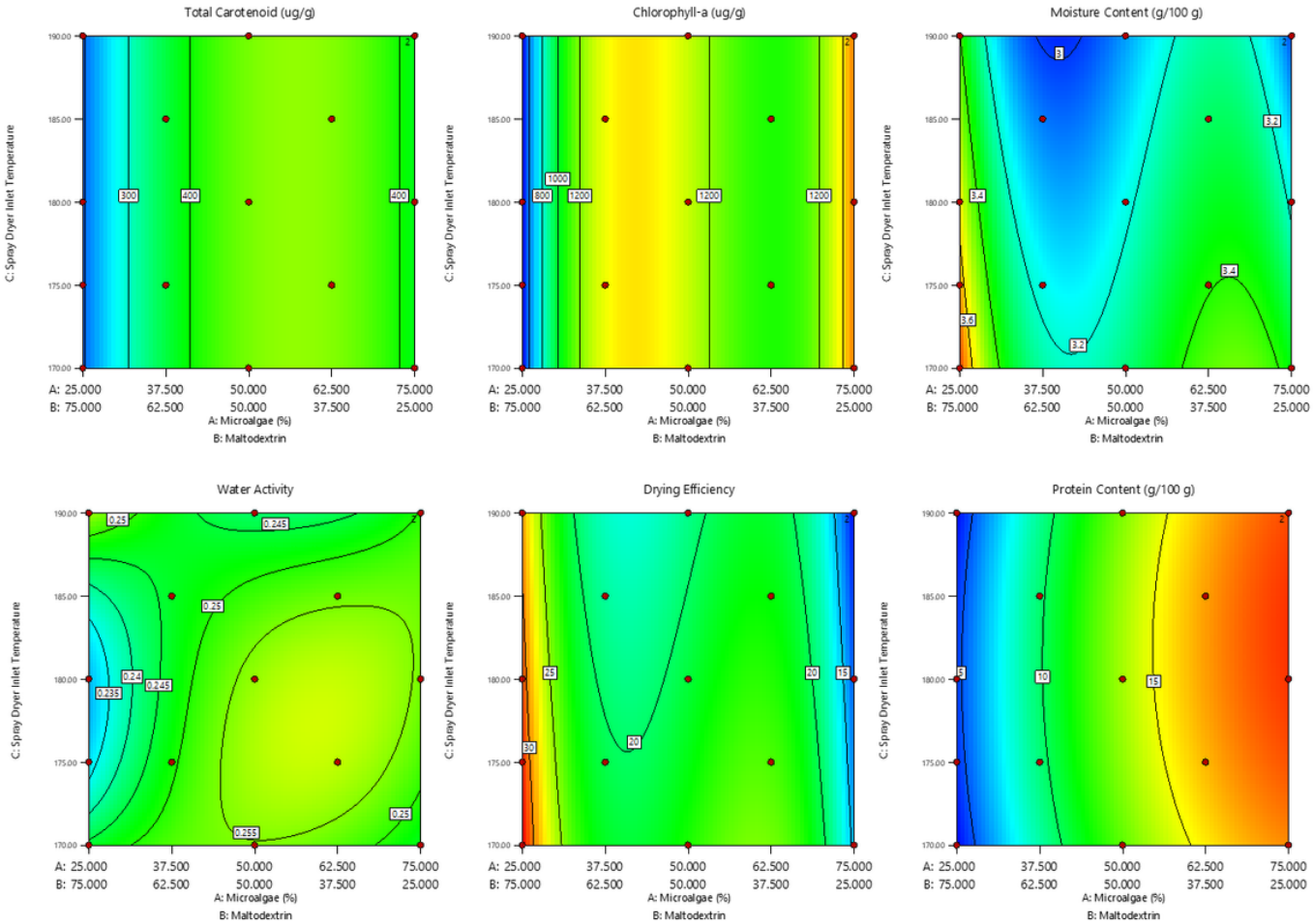


Figure 1

Contour plots of *Porphyridium cruentum* Spray Drying Optimization

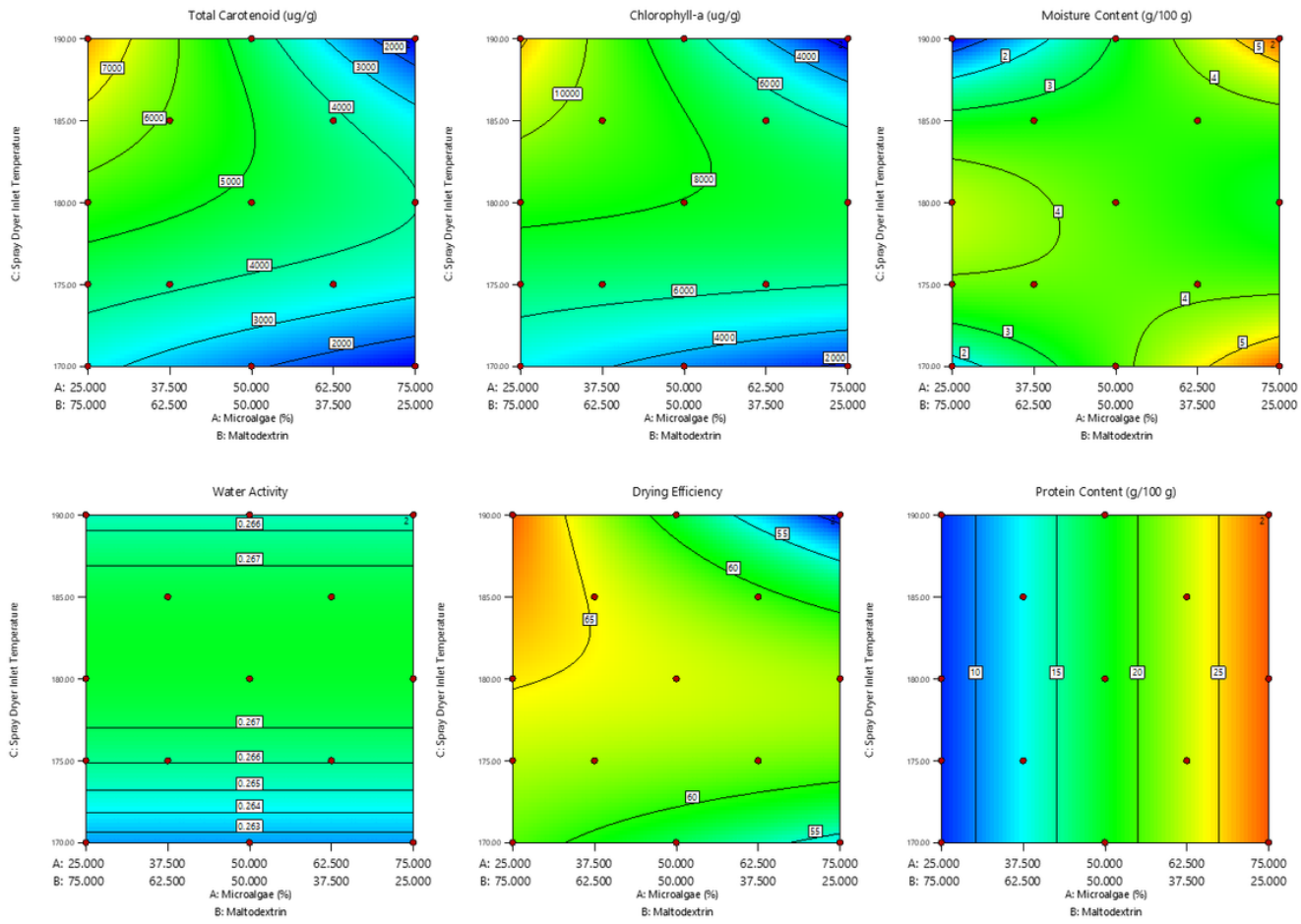


Figure 2

Contour plots of *Dunaliella salina* Spray Drying Optimization

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