Bioresource Technology 100 (2009) 1297–1303

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

# Characterization of thin layer drying of *Spirulina platensis* utilizing perpendicular air flow

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ARTICLE INFO

*Article history:*
Received 1 November 2006
Received in revised form 19 May 2008
Accepted 20 May 2008
Available online 14 October 2008

*Keywords:*
*Spirulina*
Solubility
Drying
Isotherms
Effective diffusivity

ABSTRACT

*Spirulina* is the most extensively used microalgae for animal and human nutrition mostly because of its high protein content, 60–65% on a dry weight basis. The drying is the most expensive operation. The aim of the study was to characterize drying of *Spirulina platensis* in thin layer. A Statistical model was applied to analyze the effects of independent variables (air temperature and loads of solids in the tray) on the response of solubility in acid medium. The analysis of phycocyanin content was determined at the best drying condition. The *Spirulina* isotherm data were adjusted through Guggenheim, Anderson and de Boer (GAB) and Brunauer, Emmett and Teller (BET) correlations. The nonlinear regression analysis of isotherms data showed that the GAB equation more effective adjusted the experimental data ($R^2 > 99\%$ and $E\% < 10\%$). Drying curves of *Spirulina* showed only a decreasing rate-drying period. The material load and the interaction between the air temperature and material load were significant effects ($P \leqslant 0.05$), and the best results of solubility in acid medium (≈79%) occurred at 60 °C and 4 kg/m$^2$. In under these conditions the phycocyanin content was determined to be 12.6% of dried *Spirulina*.



## 1. Introduction

Often, functional foods are considered traditional foods enriched with an ingredient capable of providing or promoting a specific beneficial action for human health. These are called functional ingredients. It is preferred that these ingredients have a natural origin, such as plants or perhaps algae and/or microalgae (Herrero et al., 2005). *Spirulina* one of the world's greater natural sources of vitamin $B_{12}$, possesses 62% amino acid content and contains a whole spectrum of natural mixed carotene and xanthophyll phytopigments. *Spirulina* has a soft cell wall made of complex sugars and protein (Estrada et al., 2001).

Recent studies have demonstrated that in the microalgae *Spirulina platensis* a blue protein called phycocyanin, belonging to the photosynthetic apparatus, has antioxidant and radical scavenging properties in both *in vivo* and *in vitro* models (Benedetti et al., 2006).

The drying of *S. platensis* constitutes approximately 30% of the total production cost (Richmond, 1994). The traditional methods used to process fresh into dry *Spirulina* are spray drying, freeze-drying, solar drying and convective hot air drying (Bonnin, 1993; Ding-Mei and Yu-Zao, 1997; Jiménez et al., 2003; Morist et al., 2001; Desmorieux and Hernandez, 2004; Desmorieux and Decaen, 2006). However, studies have been developed to drying this biomass with drums dryers. The product obtained was in flake form and with consistency that could be used commercially (Richmond, 1994).

The most commonly used method is the spray drying technique, in which the product is obtained in powder form. Usually, the spray dryer power does not satisfy all the criteria required for the use of this powder as a food product. Desmorieux and Hernandez, (2004) reported the influence of the drying process and they verified that the dried product obtained by spray drying at different temperatures did not have the same aspect and color. These authors reported the possibility of the microalgae *Spirulina* to be dried in convective dryers after filtration of the biomass as an alternative to spray drying, because of the low cost and operational ease, and they obtained a product with minimal loss of protein, about 10–20%.

The equilibrium moisture determines the moisture content that a material can have in relation to the relative humidity of the air. The sorption isotherms represent the relation between water activity and equilibrium moisture content of food, at a certain temperature. The isotherms can represent the loss (desorption) or the increase (adsorption) of moisture content as a function of the relative humidity of air or water activity (Pezzutti and Crapiste, 1997; Fennema, 1985). Various correlations for the equilibrium moisture content prevision of food, based on experimental curve results and presented a sigmoidal form have been reported (Mir and Nath, 1995). The two best known isotherm equations of food are Brunauer, Emmett and Teller (BET) (Eq. (1)) and Guggenheim, Anderson and de Boer (GAB) (Eq. (2)).

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0960-8524/$ - see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.biortech.2008.05.052

**Nomenclature**

| | | | |
|---|---|---|---|
| $A$ | Eq. (4) constant (dimensionless) | $t$ | time (s) |
| $C_B$ | adjustment parameter of Eq. (1) (dimensionless) | $X_1$ | Air temperature at codificated form (dimensionless) |
| $C_G$ | adjustment parameter of Eq. (2) (dimensionless) | $X_2$ | material load in codified form (kg/m$^2$) |
| DEF | effective diffusivity of moisture (m$^2$ s$^{-1}$) | $X_0$ | initial moisture content (dry basis) (kg kg$^{-1}$) |
| Fo | Fourrier number (dimensionless) | $\bar{X}$ | average moisture content (dry basis) (kg kg$^{-1}$) |
| $K$ | drying constant (min$^{-1}$) | $X_m$ | monolayer moisture content (dry basis) (kg kg$^{-1}$) |
| k | adjustment parameter of Eq. (2) (dimensionless) | $X_E$ | Equilibrium moisture content (dry basis) (kg kg$^{-1}$) |
| $R_0$ | radius initial (m) | $\beta_i$ | Eq. (7) constant (dimensionless) |
| $R_H$ | relative humidity (dimensionless) | $\Phi$ | sphericity (dimensionless) |
| $T$ | temperature (°C) | | |

According to Timmermann et al. (2001) the GAB equation is general and has more physical meaning than the BET equation, and may be calculated in terms of the three GAB parameters: which are $X_m$, $C_G$ and k,

$$X_E = \frac{X_m * C_B * RH}{(1 - RH)(1 - RH + C_B * RH)} \quad (1)$$

$$X_E = \frac{X_m * C_G * k * RH}{(1 - k * RH)(1 - k * RH + C_G * k * RH)} \quad (2)$$

where $X_E$ is equilibrium moisture content, $X_m$ is monolayer moisture content, RH is relative humidity and $C_G$, $C_B$ and k are adjustment parameters.

The study of food drying in thin layer has been implemented for the experimental determination of the parameters that characterize the operation, thus a more optimal process domain is obtained, as well as a better knowledge of the fundamental mechanisms involved. In thin layer drying, the temperature variation through the solids bed is reduced and it can be considered a process where the temperature varies only in time and not in position (Chirife, 1983).

An important correlation in food drying is the exponential law (Bala and Woods, 1992). This law establishes that the drying rate is proportional to the free water content of the foodstuff

$$\frac{dx}{dt} = -K(\bar{X} - X_E) \quad (3)$$

where the proportionality factor $K$ is the drying constant, $\bar{X}$ is the moisture content and $X_E$ is the equilibrium moisture content.

Eq. (3) is normally used in its integrated form, with two parameters, resulting in Eq. (4), the integration limits being: at zero time the material's moisture content is $X_0$ and at time $t$ the moisture content is $\bar{X}$

$$\left(\frac{\bar{X} - X_E}{X_0 - X_E}\right) = A\ \exp(-Kt) \quad (4)$$

The calculation of the effective diffusivity of moisture has been realized by many researchers according to an analogy between Eq. (4) and Fick's second law solution for the average moisture profile at long drying times (Fo > 0.2), considering the effective diffusivity of moisture and the thickness constants (Chirife, 1983). For spherical geometry this analogy is presented in the following equation:

$$D_{ef} = \frac{K \cdot R_0^2}{\pi^2} \quad (5)$$

where $D_{ef}$ is the effective diffusivity (m$^2$/s), $K$ is the drying constant and $R_0$ is the initial radius of the *Spirulina* (m).

The evaluation of the functional properties of food rich in protein is a relevant factor in the development of protein ingredients to be utilized in food formulation. The solubility of a protein is very important to the texture during foodstuff formulation (Krüger et al., 2002). The knowledge of the protein solubility characteristics is useful for the extraction of protein from natural sources. An optimal solubility level could increase the potential of protein application and this might be the most practical index for the determination of denaturation of a protein (Carvalho et al., 2005).

The aim of this paper was to characterize the thin layer drying of *S. platensis*, utilizing drying experimental curves and to determine the best condition of drying using a factorial-type experimental design for the protein solubility response. The phycocyanin content under the best drying condition determined by of factorial-type experimental was also evaluated.

## 2. Methods

### 2.1. Culture conditions of *S. platensis*

*S. platensis* strain LEB-52 (Costa et al., 2004) was cultivated in a 450 L open outdoor photo-bioreactors, under uncontrolled conditions, in the south of Brazil. During these cultivations, water was supplemented with 20% Zarrouk synthetic medium (Zarrouk, 1966), containing (g/L): $NaHCO_3$, 16.8; $NaNO_3$, 2.5; $K_2HPO_4$, 0.5; $K_2SO_4$, 1.0; NaCl, 1.0; $MgSO_4.7H_2O$, 0.2; $CaCl_2$, 0.04; $FeSO_4$ 7H2O, 0.01; EDTA, 0.08 and micronutrients. An initial biomass concentration was 0.15 g/L. Samples were taken every 24 h to determine the biomass concentration by optical density measurements at 670 nm using a spectrophotometer Quimis model Q108 (São Paulo, Brazil). At the end of cultivation, the biomass was recovered by filtration and pressed to recover the biomass with a moisture content of 76% (wet basis).

### 2.2. Drying equipment

The *Spirulina* drying experiments were conducted using the apparatus presented in Fig. 1. The wet *Spirulina* was placed on one stainless steel perforated tray, with whole openings of 2 mm and dimensions 0.25 m length and 0.195 m width. Dry bulb temperatures were measured above and below the tray, and the wet bulb temperature at the dryer exit was measured by thermocouples (copper–constantan), using a millivoltimeter Tecnolog model Novus N1400 (Rio Grande do Sul, Brazil) with a precision of 2 °C. The air drying conditions were: temperatures of 50 and 60 °C, relative humidity between 7 and 10% and air velocity of 1.5 m/s. For the load of 4 kg/m$^2$, 190 g of fresh *Spirulina* was used and for the load of 6 kg/m$^2$ this value was 285 g.

### 2.3. Experimental procedure of drying

*Spirulina* drying was conducted with samples in cylindrical pellet form with a diameter of 3 mm and sphericity ($\Phi$) of 0.6. The mass of the samples was measured on an electronic balance Marte model AS2000C (São Paulo, Brazil), with a precision of 0.01 g. The material load and drying temperatures were determined by an

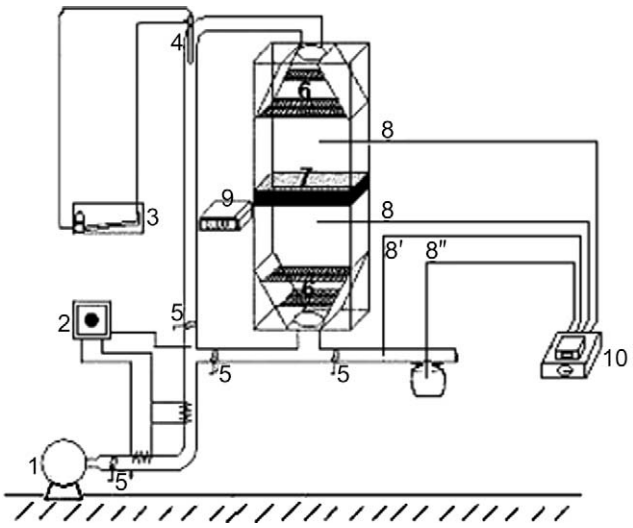


**Fig. 1.** Tray dryer with perpendicular air flow: 1- Centrifugal fan; 2- Temperature controller; 3-Manometer; 4- Pitot tube; 5- Air-deviation valve; 6- Air distributor; 7- Perforated tray; 8- Thermocouples, (′) dry bulb, (″) wet bulb; 9- Electronic scale; 10- Milivoltimeter.

experimental design matrix. Measures of the mass values and temperature were done every five minutes during the drying experiments. The values of production capacity were determined by dividing of the material load in the tray by the total drying time to reach the moisture content below 10% (w.b.) in each experiment of the design matrix. The final product obtained by thin layer was crushed in a knife mill model Wiley (PA, USA). The powder was retained on the 80 mesh sieve.

Equilibrium moisture contents of samples were determined using isotherms, obtained at 50 and 60 °C. The static gravimetric method was used and the relative air humidity was fixed by a sulfuric acid solution (0.20–0.70 w/w) that was placed under the sample. The experimental apparatus consisted of eleven glass bottles, with 7 cm of height and 6 cm of diameter. Every bottle was filled three quarters with eleven concentrations of sulfuric acid solutions (20–70% w/w) and these solutions gave the corresponding values of relative air humidity of 5–89% inside the bottles (Perry and Chilton, 1985). The samples, placed on a support in each bottle were not in contact with the acid solution. For each experiment, 3 g of wet *Spirulina* was measured on electronic balance Kern model 430-21 (Haubstadt, Germany), with a precision of 0.001 g, placed into each bottle with controlled temperature. Each experiment was performed in triplicate. The equilibrium moisture was reached when the weight was constant. The final moisture content was analyzed in order to determine the equilibrium moisture content.

The drying operation periods were analyzed by drying curves of dimensionless moisture content ($\bar{X}/X_0$) as a function of drying time and drying rate as a function of material moisture content on a dry base. The drying constant ($K$) was obtained from the curves of dimensionless free moisture content as a function of drying time, using Eq. (4), adjusted at two parameters. A nonlinear regression of data was made using the Quasi–Newton method of Statistica for Windows software by Microsoft (Ver. 5.0, StatSoft Inc., Tulsa, Okla, USA). From the calculated values of $K$, the effective diffusivity of moisture (Eq. (5)) was obtained for the different experiments.

### 2.4. Analytical methodology

*Spirulina* composition was determined through analytical methods of Nitrogen-total, moisture content, ash and lipids, according to methods of AOAC (1995). The carbohydrate composition was done by difference of the other constituents. Each experiment was performed in duplicate.

The solubility in acid medium, at pH 2, was realized by the proposed method of Morr et al. (1985) at the final dehydrated product, with some modifications: around 2.5 g of *Spirulina* were added in 50 mL of chloridric acid 0.1 N. It was subsequently put in a magnetic stirrer for 15 min and then centrifuged in a Centrifuge Fanem model Baby I 206BL (São Paulo, Brazil) at 4000×g for15 min. After the centrifugation, the tubes content were filtered and the supernatant protein was determined by Micro Kjeldahl (AOAC, 1995), with conversion factor of 6.25. Protein solubility was calculated as the percentage of soluble protein in the supernatant relative to the total protein content in the sample. Each experiment was conducted in duplicate.

Quantitative analysis of phycocyanin was done by spectrometrically, according to Boussiba and Richmond (1979), on fresh and dried biomass. Initially the dried masses of samples were determined, and 2 g of the sample added to the pan and dried in the oven for 6 h. The percent of dried mass was calculated by subtracting the total dried mass of the pan weight and dividing the result to derive the wet sample mass. To determine the phycocyanin, 40 mg of *Spirulina* was weighed, 10 mL of phosphate buffer 100 mM added and stirred until complete dissolution. The samples were stored in refrigerator at 4 °C overnight. The samples were subsequently mixed and centrifuged in a Centrifuge Fanem model Baby I 206BL (São Paulo, Brazil) at 10 °C, 4000×g for 5 min. The absorbance was read in a spectrophotometer (Químis Q-108DRM) at 615 nm using phosphate buffer as blank. Phycocyanin was calculated according to the following equation:

$$\%\ \text{Phycocyanin} = \frac{A_{615} \cdot n_d \cdot 100}{3.36 \cdot (\text{mg sample}) \cdot (\%\ \text{dry weight})} \quad (6)$$

where % phycocyanin is the percentage of the value of phycocyanin, $A_{615}$ is the absorbance at 615 nm, $n_d$ is the dilution number, 100 is the representative of 100%, and 3.36 is the extinction of coefficient for phycocyanin at 615 nm. Each experiment was conducted in duplicate.

### 2.5. Statistical methodology

The drying experiments were developed according to the factorial-type experimental design with two factors and two variation levels (Box et al., 1978), for the protein solubility response at acid pH. The experiments were determined according to the experimental design matrix presented in Table 1 in replicate ($n = 2$), for the air temperature and material load factors. Temperatures of 50 and 60 °C were chosen because, according to previous reports, temperatures above 60 °C may cause degradation of existing proteins and pigments in the *S. platensis* (Desmorieux and Decaen, 2006). The loads of 4 and 6 kg/m$^2$ were set to guarantee the thin layer condition.

For statistical analysis of the protein solubility response in acid medium, an analysis of the variance (ANOVA) was performed, with Statistica 5.0 for Windows. The factors were air temperature and material load in codified form. Eq. (7) represents the statistical

**Table 1**
Experimental design matrix of the drying experiments for *Spirulina* in codified and non-codified forms

| Experiment (No.) | $X_1(T_{cod})$ | $X_2(ML_{cod})$ | Air temperature (°C) | Material load (kg/m$^2$) |
|---|---|---|---|---|
| 1 | −1 | −1 | 50 | 4 |
| 2 | +1 | −1 | 60 | 4 |
| 3 | −1 | +1 | 50 | 6 |
| 4 | +1 | +1 | 60 | 6 |

theoretical model in codified form for the protein solubility response in acid pH,

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 \quad (7)$$

where $\beta_0$, $\beta_1$, $\beta_2$ and $\beta_3$ are constants, $X_1$ is the air temperature in codified form and $X_2$ is the material load in codified form.

## 3. Results and discussion

### 3.1. Chemical composition

The results of the composition of fresh *Spirulina* (wet basis) are shown in Table 2. All the results are referred to the fresh *Spirulina* moisture content. The fresh *Spirulina* had a protein content of 74% in dry basis.

### 3.2. Equilibrium moisture and drying characterization

The results of the equilibrium moisture content determinations of the samples as a function of the relative humidity are shown in Fig. 2 by the desorption curves at 50 and 60 °C. In Fig. 2, the typical sigmoid shaped curve that could be considered as characteristic of food isotherms was observed (Das and Das, 2002; Walker et al., 1973; Pezzutti and Crapiste, 1997; McMinn et al., 2005). The equilibrium moisture content decreased with increasing temperature at constant relative humidity. The extent of the increase depends on the nature or constitution of the food (Rizvi, 1995). It is apparent from Fig. 2, that in the case of *Spirulina*, this behavior was pronounced at 50 and 60 °C, may be due to physical and/or chemical damages occurred during the drying process of *Spirulina*. Desmorieux and Decaen (2006) studied the drying of *Spirulina* and reported that desorption isotherm is not influenced by the air temperature in range 25–40 °C.

The results of the estimation by the minimum square method, with the respective values of $R^2$, medium error relative and the parameters determined by the equations being analyzed are presented in Table 3. Based in Table 3, it is apparent that the three parameters of GAB model presented a better correlation (above 99%) and % error (below 10%) than the two parameters of BET model. The GAB model presents a number of parameters that describes adequately the experimental data in a relative humidity from 10 to 90%, which could be interest for food (Timmermann et al., 2001). However, the BET model has theoretical limitations to describe the monolayer behavior of food in relative humidity values above 40% (Kaymak-Ertekin and Sultanaglu, 2001; Tomczak, 2004). The value of the monolayer moisture content ($X_m$) is of particular interest, since it indicates the amount of water that is strongly adsorbed to specific sites and is considered as the optimum value at which a food is more stable. In Table 3, it was observed that $X_m$ values decreased for the two models as temperature increased. According to Desmorieux and Decaen (2006) the equilibrium moisture content at 100% of relative humidity is near 3 $kg_w/kg_{dm}$ at 25 °C for *Spirulina*. The equilibrium moisture content (d.b.) in each drying experiment was calculated using Eq. (2), with the parameters in Table 3 and the relative humidity values of drying air. The values of equilibrium moisture content are 0.06 at temperature of 60 °C and 0.09 at 50 °C.

The curves that describe the behavior of *Spirulina* drying at different temperatures for loads of 4 and 6 kg/m$^2$ are shown in Figs. 3–5. Analyzing the dimensionless moisture content curves (d.b.) as a function of drying time (Fig. 3) and drying rate as a function of moisture content. (Fig. 4), a constant rate-drying period was not observed. This is characteristic of food with high protein content (Chirife, 1983). This observation is in agreement with previous results in thin layer drying of biological products (Diamante and

**Table 2**
Composition of *Spirulina* fresh pressed in a wet basis

| Specification | Composition[a] (%) (w.b.) |
|---|---|
| Moisture | 76.7 ± 0.6 |
| Ash | 1.7 ± 0.1 |
| Protein | 17.2 ± 1.1 |
| Lipids | 2.0 ± 0.1 |
| Carbohydrate[b] | 2.4 ± 0.2 |

[a] The values are means ± standard deviation, in replicate ($n$ = 2).
[b] By difference.

**Table 3**
Adjustment of GAB and BET models for *Spirulina* isotherms at 50 and 60 °C

| Model/temperature (°C) | $X_m$ (d.b.) | $C_G$ | $C_B$ | k | $R^2$ (%) | % Error |
|---|---|---|---|---|---|---|
| GAB – 50 | 0.11 | 37.41 | – | 0.945 | 99.45 | 5.19 |
| BET – 50 | 0.10 | – | 44.78 | – | 92.81 | 6.98 |
| GAB – 60 | 0.07 | 36.14 | – | 0.942 | 99.01 | 8.64 |
| BET – 60 | 0.06 | – | 44.85 | – | 95.16 | 10.96 |

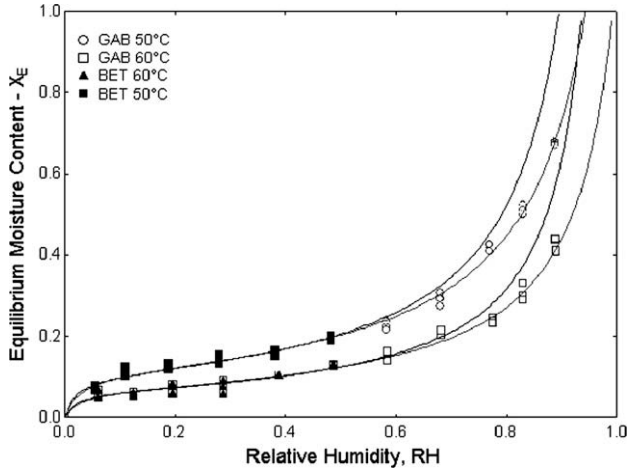


**Fig. 2.** Desorption isotherms for *Spirulina* at temperatures of 50 and 60 °C.

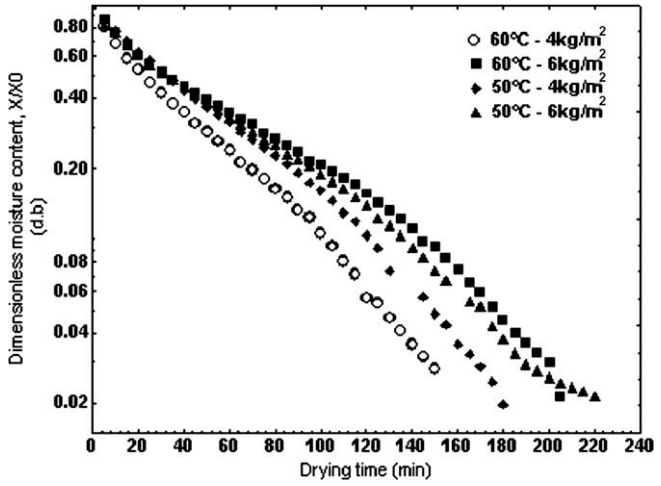


**Fig. 3.** Drying curve of *Spirulina platensis* at temperatures of 50 and 60 °C, in loads of 4 and 6 kg/m2, in semi-log scale.

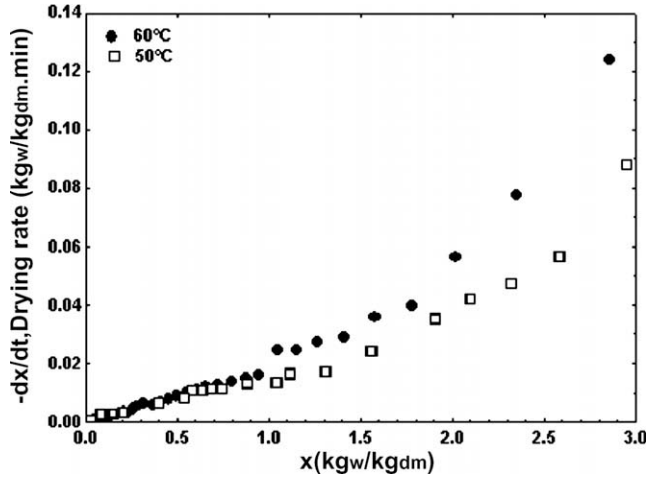


**Fig. 4.** Drying rate curve in function of moisture content of *Spirulina platensis*, at 50 and 60 °C, 4 kg/m$^2$.

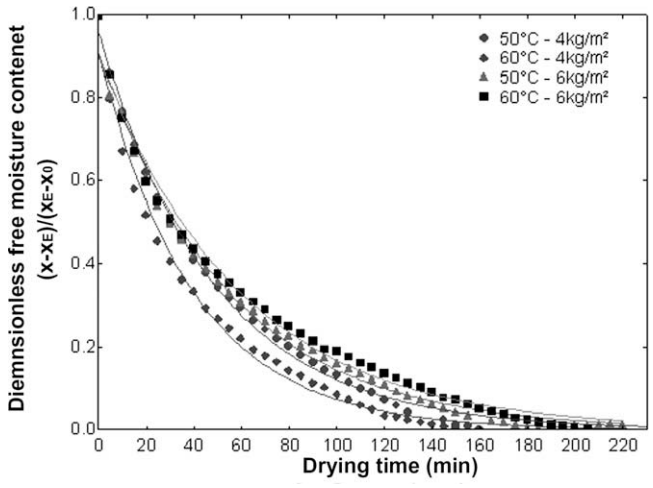


**Fig. 5.** Dimensionless free moisture content in function of time for all temperatures and material loads.

Munro, 1991; Doymaz and Pala, 2003; Desmorieux and Decaen, 2006). In Figs. 3 and 4 it was observed that practically all of the drying occurred in the first phase of the falling rate period.

The experimental curves of dimensionless free moisture content (d.b.) as a function of drying time were used to calculate the constant drying ($K$) values, using Eq. (4). In Fig. 5 the fitting of model. (Eq. (4)) for all the experiments is presented.

The results of factorial design matrix $2^2$ are presented in Table 4 with the values of total drying time, drying constant, effective diffusivity, production and protein solubility of the final dehydrated product with the moisture content fixed at 9–10% on wet basis, which corresponds to the commercial moisture content.

**Table 4**
Drying characterization of *Spirulina* in thin layer

| Run | Total time (min) | K ($s^{-1}$) | Def ($m^2$/s) × $10^{-11}$ | Production* (kg $m^{-2}$/s) × $10^{-4}$ | Protein solubility** (%) |
|---|---|---|---|---|---|
| 1 | 180 | $3.5 \times 10^{-4}$ | 2.86 | 3.69[a] | 42.6 ± 0.6 |
| 2 | 150 | $4.2 \times 10^{-4}$ | 3.42 | 4.44[b] | 79.2 ± 1.8 |
| 3 | 220 | $2.8 \times 10^{-4}$ | 2.33 | 4.53[b] | 42.6 ± 1.6 |
| 4 | 205 | $3.0 \times 10^{-4}$ | 2.46 | 4.86[b] | 31.7 ± 1.2 |

* Tukey test: different letters indicate significant differences ($P < 0.05$).
** The values are means ± standard deviation, in replicate ($n = 2$).

The Tukey test was performed using the production response values from Table 4. A significant difference was noted at a level of 95% ($P < 0.05$) for drying experiment no. 1, with the lower load and air temperature. The higher constant drying value was reached in the second experiment (higher air temperature and lower material load), which represented the shortest time of operation, resulting in smaller alteration of the final product. Using the constant drying values and Eq. (5), the effective diffusivity of moisture of the experiments was calculated according to the data presented in Table 4. Since *Spirulina* drying was in cylindrical form, an equivalent radius was used to calculate the effective diffusivity of moisture, multiplying the radius by sphericity.

In Table 4 it was verified that the load of material in the tray influenced the effective diffusivity of moisture, because the effective diffusivity values were higher in 4 kg/m$^2$ (experiments 1 and 2), independent of air temperature utilized. This may be explained due to the highest drying time of the material in load at 6 kg/m$^2$ (experiments 3 and 4) that caused high alteration of the material.

Utilizing the effective diffusivity of moisture values and the drying times in Table 4 for the different conditions evaluated, the Fourrier number values were obtained ($Fo = Def \cdot t/(\Phi.R)^2$) in a range of 0.35−0.40, verifying that the relation $Fo > 0.2$ was established, for long drying times. The study of the air temperature and material load effects on the protein solubility in acid medium (Table 4) was performed through the variance analysis, utilizing the ANOVA and the square response (Fig. 6).

The factors were analyzed to a significance level of 95% ($P < 0.05$). It was observed that the effect of the material load and the interaction between air temperature and material load had a statistical significance on the solubility in acid medium. The air temperature had a positive effect on the solubility. The material load presented a negative effect because it increased the exposure time of these proteins, thus causing denaturation.

Eq. (8) represents the statistical model in its codified form, obtained from the regression analysis for the percentage of protein solubility response in acid medium with a correlation of 90.6%.

$$Y = 49.87 + 11.08X_1 - 22.04X_2 - 25.39X_1 \cdot X_2 \quad (8)$$

The square response (Fig. 6) allows the evaluation of the best region of actively for the protein solubility response. The factors of the study are represented by the lines (edges). The theoretical values of the percentage of protein solubility in acid medium, determined by the statistical theoretical model (Eq. (8)), are located at the corner of the graph. In Fig. 6 it may be observed that

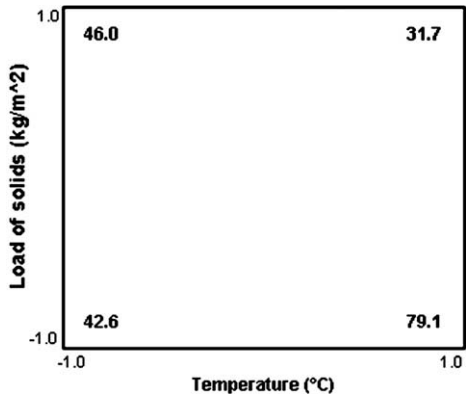


**Fig. 6.** Square of protein solubility response in acid of the experimental design.

**Table 5**
Comparison of dried *Spirulina* obtained in the best condition drying condition (wet basis)

| Specification | Composition[a] (%) (w.b.) |
|---|---|
| Moisture | 9.7 ± 0.8 |
| Ash | 7.3 ± 0.2 |
| Protein | 64.1 ± 1.3 |
| Lipids | 8.6 ± 0.3 |
| Carbohydrate[b] | 10.3 ± 0.5 |
| Phycocyanin | 12.6 ± 0.7 |

[a] The values are means ± standard deviation, in replicate ($n = 2$).
[b] By difference.

the higher solubility value was reached at the lower material load and the higher air temperature. Thus, for *Spirulina* drying in thin layer utilizing perpendicular air flow, air temperature of 60 °C and material load of 4 kg/m$^2$ are recommended to obtain the higher value of solubility in acid medium (79.1%), and highest production capacity in the drying experiments (Table 4).

It was observed that loss of 17% in protein content occurred in the best drying condition. Desmorieux and Hernandez, (2004) reported that the protein loss was proportional to the increase in temperature with losses of 10% at 40 °C and 20% at 70 °C. All the results are based on fresh *Spirulina* protein content while in spray drying losses were approximately 10–15% (Desmorieux and Hernandez, (2004)).

Table 5 presents the composition of dry *Spirulina* in the best drying condition (experiment 2). The moisture content was below approximately 10% to guarantee microbiological stability (Tiburcio et al., 2007). The protein content of the samples was 64% and it was similar to values reported in the literature for other algal food products (Morist et al., 2001; Jiménez et al., 2003; Langdon and Önal, 1999).

The phycocyanin content at the best drying condition is presented in Table 5 being the value of phycocyanin in the fresh *Spirulina* of 16%. This value is considered high when compared with other authors that utilized different drying methods. Morist et al (2001) obtained approximately 4% of phycocyanin content when *Spirulina* was dried by freeze-drying. Campanella et al (1999) analyzed a commercial *Spirulina* product and obtained appromately 8.4% of *Spirulina* product.

Drying methods for the processing of *Spirulina* resulted in approximately 50% of losses of phycocyanin. The quality of phycocyanin required would influence the selection of suitable drying method before extraction for purification of this product. Extraction and purification represent important costs components of the overall process. So an adequate drying operation let to obtain phycocyanin of high quality with reducing the cost of extraction and steps in the purification.

## 4. Conclusion

Drying of *S. platensis* in thin layer utilizing perpendicular air flow occurred during the decreasing rate period. The factors used in this study were the air temperature (50 and 60 °C) and the material load in tray (4 and 6 kg/m$^2$) and resulted in total drying times in the range 150–220 min. The GAB equation was the best for the correlation of the experimental equilibrium isotherms; with $R^2 > 99\%$ and medium error relative lower than 10%. The values of protein solubility in acid medium were in a range of 42.6–79.1%. The material load and the interaction between air temperature and material load were significant at level of 95% ($P < 0.05$). The best working region was at 60 °C and 4 kg/m$^2$. At this condition, the dried product had a protein content of 64%. The phycocyanin content was 12.6% in relation to dried *Spirulina*. *Spirulina* is commercialized dried in the form of pills or tablets is recommended by suppliers mainly as a health food, a protein source, vitamin supplement, diet pill and as a treatment for anemia in humans. Phycocyanin is the major phycobiliprotein in *S. platensis* and it is mainly used as fluorescent markers in biomedical research, nutrient ingredient, natural dye for food and cosmetics and also as a potential therapeutic agent in oxidative stress-induced diseases.

## Acknowledgement

The authors are grateful to CAPES (Brazilian Agency for Improvement of Graduate Personnel), Brazil, for the financial support that made this work possible.

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