Mathematical Modeling of Oven Drying kinetics and Study on Effective Moisture Diffusivity of *Spirulina platensis* Biomass

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Abstract*— Spirulina (*Arthrospira platensis*) is a cyanobacteria produced under hot and arid climates. Large scale Production of *Spirulina platensis* biomass has been extended due to considerable nutritional value for use as food supplements. It contains 60– 70% (wb) proteins, vitamins (A, B1, B2, B12), minerals (iron, calcium, potassium, phosphorus, manganese, copper, zinc, magnesium), High value phytonutrients and pigments, which have applications in healthy foods and therapeutics has been receiving more attention from researchers. After cultivation and harvesting, the biomass must be dried, to obtained fine powder which should be appropriate for use in food products. The aim of this study was to obtain and evaluate the experimental data of *Spirulina* biomass oven drying and modeling the drying process using empirical models. To this purpose, *Spirulina* biomass formed to filaments shape with 2 mm thickness and drying process was done at 50 and 60 °C. All experiments were performed in triplicate. To investigate the drying kinetics, Effective moisture diffusivity were used. The results showed that increase in temperature had significant effects on moisture diffusivity and as the temperature rise, moisture diffusivity increased. 12 different models were used for Modeling of drying kinetics. the models were compared based on the determination coefficient (R2), the sum of squared errors (SSE) and the root mean square error (RMSE) and the best models fitted to the data of drying process were Page model for 50°C and a tow term model for 60°C.

Keywords- *Spirulina*, Drying, Oven, Mathematical Modeling, kinetics

1- INTRODUCTION

Spirulina platensis is a photosynthetic prokaryotic microorganism which has been used as a dietary supplement. Amounts of protein (60 to 70% dry weight), low in fat, high in vitamins, especially vitamin B12, high levels of iron, a blue pigment Phycocyanin and essential fatty acids gamma-linolenic acid, made this microalge a potential source to consumed, against malnutrition(1). Several efficacy and health promoting benefits of *Spirulina* has been reported such as lowering the cholesterol level of blood, protect against some cancers, strengthen the immune system, increasing intestinal lactobacillus (2, 3, 4). The application of *Spirulina* as a food or be the ingredients in food formulations as the dietary supplements provide the color and increase the nutrional value of products (5). Phycocyanin (blue pigment) which has been receiving more attention from researchers has been used as a coloring agent in products such as chewing gum, soft drinks, candy and cosmetics (6) Dehydration is important procedure in downstream operation of *Spirulina* production since the fresh biomass cannot be preserved at ambient temperature. The basic objective in foodstuffs drying is the removal of water in the solids for to minimize the microbial growth and deterioration by chemical reactions (7) and leads the reduction in weight and volume of material, storage and transportation costs (8). The drying of *Spirulina platensis* constitutes approximately 30% of the total production cost. Generally, several drying processes are used for drying the fresh biomass after filtration: the spray drying (9) produces fine powder and the convective drying (10) produces fines broken dried cylinders. Also the other traditional methods used to process fresh biomass into dry *Spirulina* are freeze drying, solar drying, convective hot air drying and spouted bed. Modeling of drying process can be used for more precise control of drying operation of food products in terms of maintain quality and reducing the energy consumption. So by selecting the best model to describe the drying kinetics, change in food quality can be examined during drying process and properly design industrial driers according to food types (11). Many researchers investigated the drying kinetics of various agricultural products to find the best model to describe the drying procedure such as apples (12), date (13), sliced mango (14), fig (15) pieces of potato (16), sesame skin (17) and the Malaysian rice (18). Sharifi, 1386 conducted a study on drying modeling of thin orange slices. Finally, the data demonstrated that the Middle model fits the data well (19). Simal et al (2005) evaluated the accuracy of the mathematical model equations (Exponential), (Diffusional) and Page in order to model the drying kinetics of kiwi fruit. The results showed that the Page model was best fitted the experimental data (20).The aim of this study was to evaluate of *Spirulina* biomass drying kinetics and modeling of process with empirical models using oven drying at different temperatures.

2- Material and Methods

Spirulina platensis cultivated in open ponds with an area of about 10 m² and a depth of 40 cm in the food department of food science and technology in Ferdowsi university of Mashhad. Electromechanical pump was used for circulation providing suitable flow. Temperature was kept at defined range between 33-36 °C. In order to production of *Spirulina* biomass, Zarrouk formulation was used as the standard medium (21). Chemical composition of the Zarrouk synthetic medium included of NaHCO3, 16.8; NaNO3, 2.5; K2HPO4, 0.5; K2SO4, 1.0; NaCl, 1.0; MgSO4.7H2O, 0.2; CaCl2, 0.04; FeSO4 .7H2 O, 0.01; EDTA, 0.08 and micronutrients. Active culture of *Spirulina* was prepeared from microbial collection of Food Science and Technology of Mashhad. Monitoring the morphology of *Spirulina* to control the cultivation process and confirmation the viability of strains was done using light microscope (OLYMPUS EX41) equipped with an imaging system (Figure 1). Separation of biomass from the medium in 10th day of cultivation culture was done using a filter with specific mesh size (20 μm). Then the biomass was washed and rinsed using the sterile water to remove any chemical residue.

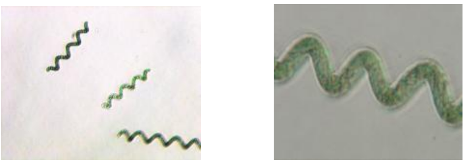

Figure 1. Morphological Features of *Spirulina platensis*

2-1-Initial moisture measurement

The template is used to format your paper and style the Measuring the moisture content of the sample according to AACC (1986) with oven drying at 105 ° C for 24 h (Memmert, 154 Beschickung-loading, Model 100-800) until reached to constant weight.

2-2-Drying tests

Plastic extruded die was used to form *Spirulina* biomass into filaments shape with a diameter of 7 cm and a thickness of 2 mm in order to preparing for drying process. Then filaments-formed biomass was placed in glass plate without any pre-treatment and finally put into an oven (Memmert, 154 Beschickung-loading, Model 100-800) at 50 and 60 ° C. Optimal drying conditions depend on several factors: on the biochemical aspect, The air temperature has to be lower than 65°C. *Spirulina* biomass was investigated by periodic weighing at defined time intervals using digital scale until to reach equilibrium moisture content of 2 to 4%, based on wet weight.

2-3-Calculation drying rate

Drying rate of *Spirulina* samples was calculated using following equation (22).

Where $M_{(t+\Delta t)}$ ' is moisture at ($t+\Delta t$), M_t is moisture content at each minute and Δt is the is the time difference describes as minute.

$$D.R = \frac{M_{(t+\Delta t)} - M_t}{\Delta t} \qquad (1)$$

2-4-Moisture ratio calculation

This parameter can show moisture content of samples at each times in compared to initial and final moisture and is obtained from the following equation (22):

$$MR = \frac{M_{(t)} - M_{(e)}}{M_0 - M_e} \qquad (2)$$

Where M_R is moisture ratio, M_0 is initial moisture content as dry basis ($\frac{kg_{water}}{Kg_{d.m}}$), $M_{(e)}$ is equilibrium moisture content, $M_{(t)}$ is moisture content at time t. Equilibrium moisture was the point which decreasing in weight have been stopped.

2-5- Mathematical modeling

The Most empirical models used for drying of agricultural products are including of 12 models (Table 1). In these models, the drying curves are obtained by plotting of moisture ratio according to drying time. The best model was selected based on the highest Correlation coefficient (R2) and the lowest value for the Sum of Squared Errors (SSE), Root Mean Square Error (RMSE).

$$R^2 = \frac{\sum_{i=1}^{n} (MR_i - MR_{pre,i}).\sum_{i=1}^{n} (MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i=1}^{n} (MR_i - MR_{pre,i})^2\right]}.\sqrt{\left[\sum_{i=1}^{n} (MR_i - MR_{\exp,i})^2\right]}} \qquad (3)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N} (MRP - MRE_3)^2\right]^{1/2} \qquad (4)$$

$$SSE = \sum\left(MR_{pre} - MR_{\exp}\right)^2 \qquad (5)$$

MR_P Is the predicted moisture ratio, MR_E is the experimental moisture ratio, N is the numbers of observations and Z is the number of constants in each model.

2-6- Effective moisture diffusivity

Effective moisture diffusivity was calculated using Fick's second law (12)

$$\frac{\partial_X}{\partial_t} = D_{eff}\frac{\partial^2 X}{\partial x^2} \qquad (6)$$

X is the moisture content compared to the reference point in dry basis. t is time, x is Spatial coordinate and D_{eff} is effective diffusion coefficient (m^2/S.) Fick's second law is often used to describe the phenomenon of moisture diffusion (12). Fick equation for an infinite slab shown in below

$$MR = \frac{(x_t - x_e)}{(x_0 - x_e)} = \frac{8}{\pi_2}\exp(\frac{1\pi^2.D_{eff}.t}{L_1}) \qquad (7)$$

Where Deff is effective diffusion coefficient, L is the half of thickness(meter) and t is the time of drying(minute).

2-7- Statistical Analysis

Comparison of mean was calculated using the SPSS 16 program at a confidence level of a 0.01. All experiments were repeated at 3 times. Mathematical modeling was used to fit the experimental data by MATLAB software (version of 2007).

3- Results and Discussions:

Initial moisture measurement:

The means of initial moisture content of Spirulina biomass was calculated about 78% in wet basis and 354/5 % in dry basis.

3-1 Moisture ratio

Figure 1 exhibits the variation of moisture ratio as a function of time. The moisture ratio of the samples decreased continually with drying time. The gradient reduction of moisture ratio is more in primitive times than the end of the drying time that is due to the phenomenon of reduction of saturated moisture. Since at the beginning of drying process, the moisture transfer rate is high and caused the quick reduction in moisture content which is shown as a sharp decline in figure 2. But over the time, moisture transfer rate from depth to surfaces decreased due to the reduction in water content of product resulted in lower drying rate. As expected, increase in the temperature of drying reduces the time required to reach any given level of moisture ratio since the heat transfer Increases which exhibited a sharper decline in moisture rate (23,18).

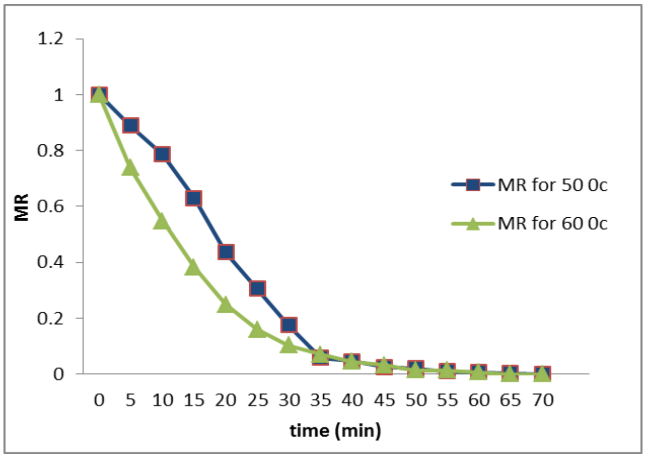

Figure 2. Experimental moisture ratio versus drying time in two temperatures

3-2- Mathematical Modeling

Data of drying process converted to the relative humidity (MR) and plus data obtained from the drying times were fitted using of 12 model presented in Table 1. In order to select the best model fitted to the observed data, formulas 3, 4 and 5 used and R2, RMSE and SSE values were calculated and compared. The Page model gives a good estimation for the drying of *Spirulina* biomass at 50 °C and Tow term model was the best models fitted to the data of drying process at 60°C. Values of the R2 and RMSE and SSE for 12 are listed in Table 3. Values of the drying constant and coefficients of the best model are also shown in Table 4. These results are in agreement with other findings reported that the two term model was the best model fitted to the drying data of pistachio.

Table 3. Statistical results obtained from the selected models

A) 50 °C

Model name	**R^2**	**SSE**	**RMSE**
Newton	0.9381	0.114	0.09024
Page	0.9975	0.004674	0.01896
Modified page	0.6761	0.5751	0.2623
Henderson and Pabis	0.9518	0.08872	0.08261
Logarithmic	0.9696	0.05603	0.06833
Tow term	0.9741	0.04758	0.06575
Two term exponential	0.9661	0.06242	0.07533
Modified Henderson and Pabis	0.5764	0.7796	0.2943
Aproximation of diffusion	0.9110	0.1638	0.1168
Midli	0.3085	1.273	0.3401

B) 60 °C

Model name	**R^2**	**SSE**	**RMSE**
Newton	0.9952	0.006262	0.02195
Page	0.9994	0.0007407	0.007885
Modified page	0.9489	0.0007270	0.019837
Henderson and Pabis	0.9994	0.0007976	0.009985
Logarithmic	0.9973	0.00292	0.01629
Tow term	0.9996	0.0005418	0.007361
Two term exponential	0.9914	0.01111	0.03333
Modified Henderson and Pabis	0.9994	0.0007976	0.009985
Aproximation of diffusion	0.9891	0.01414	0.03585
Midli	0.1026	1.16	0.3406

Table 4. Values of the drying constant and coefficients of the best models.

Tempreture (°C)	Best model	Values of the drying constant and coefficients				
		a	b	k	n	c
50 °C	Page	–	0.003426	–	1.834	–
60 °C	Two term	10.68	0.1045	0.1102	–	-9.682

3-3- Effective diffusion coefficients

Effective diffusion coefficients were calculated at different temperatures using Fick's law and equation 7 which is the extended form of equation 6 that was for infinite slab and the results reported in Table 5. Effective diffusion coefficients increased with increase in drying temperature. The lowest diffusion coefficients was 4.16×10^{-9} and at 50 ° C and the highest value was 5.77×10^{-9} at 60 ° C. Dissa et al, 2010 studied the drying process of *Spirulina* biomass and reported that by increasing in thickness of biomass from 3 to 6 mm, effective diffusion coefficients increased from 1.06×10^{-10} to 1.67×10^{-10} (24). Similar results have been reported about the effect of thickness and drying temperatures on effective diffusion coefficients (25).

Table5- Effective moisture diffusivity at different temperatures.

Temperature	**D_{eff} (m^2/s)**
Oven 50°C	$4.16\times 10^{-9\ A}$
Oven 60°C	$5.77\times 10^{-9\ B}$

Means comparison of these parameters was done by Duncan test (α=0.01) showed significant difference between the temperatures of 60 and 50 ° C. Average drying rate in temperatures of 50 and 60 to reach the equilibrium moisture content of 5%, were respectively, 3.259 and 3.640 ($\frac{kg_{water}}{Kg_{d.m}}$) per hour. Table 6 shows the average rate of drying process in different temperatures which indicates a direct relationship between these two parameters.

Table 6- Average rate of drying process of *Spirulina* biomass.

	Oven 50°C	**Oven 60°C**
Average drying rate ($Kg_w.kg_{d.m}^{-1}.h^{-1}$)	$3.259^A\pm0.007$	$3.259^A\pm0.007$

4- Conclusions

The results of the analysis of experimental data showed that the after drying process of *Spirulina* biomass and modeling the drying data using 12 models, based on the determination coefficient (R^2), the sum of squared errors (SSE) and the root mean square error (RMSE) Page models was the best model for temperature of 50 °C and the Two term model was the best for the temperature of 60°C. Effective diffusion coefficient of moisture significantly increased with increasing temperature.

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