Mathematical Modelling of Drying of Chlorella sp., Neochloris conjuncta and Botryococcus braunii at Different Drying Conditions

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Abstract

Drying is one of the most important process in the cultivation of microalgae. Performance of drying depends on appropriate drying methods. This study aimed (1) to determine the effect of different drying methods on the Chlorella sp., Neochloris conjuncta, and Botryococcus braunii strains and (2) to identify the most suitable model for drying methods.
Chlorella sp., Neochloris conjuncta and Botryococcus braunii cultures were grown in basal medium in raceways at the greenhouse condition in Isparta province. During experiment, air temperature and relative humidity, wind speed, solar irradiance, wet and dry mass and temperature of microalgae biomass were measured. Drying applications continued for approximately 3 days.
Microalgae were dried at solar tunnel, outdoor, and greenhouse conditions. Furthermore, the effect of drying methods such as open sun, solar tunnel, and greenhouse drying on drying time, and drying ratio of microalgae have been investigated. The drying data were applied to ten different mathematical models, namely, Newton, Page, Henderson and Pabis, Logarithmic, Midilli and Kucuk, Wang and Singh, Two Term, Two Term Exponential, Weibull and Logistic Equation Models. The performance of these models were compared according to the coefficient of determination, standard error of estimate and residual sum of squares, between the observed and predicted moisture ratios. Results showed that the Weibull equation gave the best prediction to the drying kinetics evidenced by coefficient of determination ranging from 0.9959 – 0.9992 for all drying methods. In addition, solar tunnel drying method has been determined to be the most suitable one among tested methods for drying of microalgae.

Key words: Chlorella sp., Neochloris conjuncta, Botryococcus braunii, drying, mathematical modelling, microalgae

1. Introduction

Drying of agricultural crops has always been of great importance to the conservation of food by human beings. Sun-drying is still the most common method used to preserve agricultural products in most tropical and subtropical countries. Sun drying is only possible in areas where, in an average year, the weather allows foods to be dried immediately after harvest. The main advantages of sun drying are low capital and operating costs and the fact that little expertise is required. Even though sun drying offers inexpensive way of drying operation, agricultural products are exposed to uncontrolled weather conditions and to the attack of insect, pests, microorganisms, and dust (Bala et al., 2003) and harmful effects of UV radiation (Stiling et al., 2012). The resulting loss of food quality in the dried products may have adverse economic effects on domestic and international markets (Imre, 1986; Tiriş et al., 1994). The introduction of

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solar dryers in developing countries can reduce crop losses and improve the quality of the dried product significantly when compared to the traditional methods of drying such as sun or shade drying. Additionally, solar tunnel dryer can be operated by a fan driven by photovoltaic module and this system removes moisture inside dryer. Solar tunnel dryer was utilized for drying of many agricultural products such as fruits, vegetables, cereals, grain, legumes, oil seeds, spices and even fish and meat (Bala et al., 2003). Due to the rich content of microalgae, they could be used in different sectors such as food, agriculture, cosmetics and biofuels. Microalgae biomass should be dried for many applications. Since conventional drying methods increases the cost of microalgae biomass, exploitation of solar as an alternative energy source is considered to be economic for the drying process. Therefore, in this study low-cost drying applications such as solar tunnel, open sun, and greenhouse drying methods were applied to dry microalgae biomass. This study aimed (1) to determine the effect of different drying methods on the *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* strains in Isparta province and (2) to determine the best describing mathematical model to experimental data.

2. Materials and Methods
Experimental materials

Chlorella sp., *Neochloris conjuncta* and *Botryococcus braunii* cultures were grown in basal medium with raceways in the greenhouse condition at the Department of Agricultural Machinery and Technologies Engineering at Suleyman Demirel University in Isparta province. *Chlorella sp.* (SAG 241.80), *Botryococcus braunii* (SAG 807-1) and *Neochloris conjuncta* (SAG 78.80) were cultivated in erlenmeyers (500 ml – 2 L) and reactors (10 L –50 L) in laboratory conditions. Basal medium was selected as the nutrient medium. The final pH of this medium was 7.0 after being autoclaved. The algal cells were grown at a temperature of $25\pm1°C$ and PAR (Photosynthetically Active Radiation) of 125 µmol m^{-2} s^{-1} measured by Delta Ohm PAR meter. Cultures were transferred to the raceway when the desired density was reached. 50 liters of culture in the laboratory were transferred to 250 liters reactors in the greenhouse (6 x 5 m). Afterwards, cultures were transferred to three-1.5 ton capacity-raceways separately. Seven days later, the microalgae biomasses were obtained and harvested. The gravimetric moisture content of microalgae cultures were determined as 79.6, 70.9 and 82.4% w.b. for *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii*, respectively using standard method at 105°C for 24 hours.

Drying methods

A solar tunnel dryer constructed at Department of Agricultural Machinery and Technologies Engineering at Suleyman Demirel University was used in this study (Figure 1). It comprised of a flat plate solar collector, a drying tunnel, a solar cell module, and a small axial fan. All units are mounted on metal frame. The bottom of solar collector has hexagonal channels and is directly connected to drying tunnel. The bottom of solar tunnel dryer is painted black to absorb radiation. The collector is coated with a

transparent polycarbonate material. The dryer is equipped with a 150 W solar cell module. A fan delivers air to the drying tunnel. Solar energy absorption area of the collector is 2 m length and 1.9 m width. The drying tunnel area is twice the area of collector. The dryer is oriented in east-west direction and its drying tunnel is not shaded by trees or buildings between 9:00 am and 5:00 pm.

Figure 1. The experimental solar tunnel dryer

A greenhouse constructed at Department of Agricultural Machinery and Technologies Engineering at Suleyman Demirel University was used for greenhouse drying in this study. The dimensions of greenhouse is 6 x 5 meter (30 m²). Three raceways were located at the same greenhouse. Additionally, the cultures were dried under open sun drying during all day (32-39°C).

Drying procedure

During experiment, air temperature and relative humidity, wind speed, solar irradiance, wet and dry mass and temperature of microalgae biomass were measured. The drying was carried out with three replications for each drying methods. Drying application continued for approximately 3 days. Drying experiment started after the completion of the loading at 9:00 am and was paused at 5:00 pm for each day. Weight loss of the microalgae in the solar tunnel dryer was measured during the drying period at four hour intervals with a digital balance. In the afternoon after 5:00 pm, the cultures of microalgae in the solar tunnel dryer were kept in the dryer in the environmental conditions. Then, cultures were exposed to the same weather conditions. The drying process was terminated until no mass change was detected. Experiments were carried out on September 9-11, 2015. Solar irradiance were measured hourly (09:00 am- 17:00 pm) on a horizontal surface by pyranometer. Relative humidity and temperature of drying air were measured using K type thermocouples and DT-3 hygrometer at the drying tunnel of dryer. Air velocity at the outlet of drying tunnel was measured by a hotwire anemometer. *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* microalgae cultures were distributed uniformly in a thin layer in plates, and then exposed to open sun, solar

tunnel, and greenhouse drying conditions. The moisture content for each sample was measured at interval of 4 hours each, until equilibrium is maintained.

Mathematical modelling of the drying curves

Drying curves were fitted with 10 thin layer drying models, namely, Newton, Page, Henderson and Pabis, Logarithmic, Midilli and Kucuk, Wang and Singh, Two Term, Two Term Exponential, Weibull and Logistic Equation Models (Table 1).

The moisture ratio (MR) of microalgae cultures was calculated based on moisture content as a function of time (t) (M(t)), initial moisture content of cultures (M_0), and equilibrium moisture content of cultures (M_e).

$$MR = \frac{M(t) - M_e}{M_0 - M_e} \tag{1}$$

All moisture contents were reported as wet basis (wb.%). Simplification of MR in Eq. (1) as M/M_o was suggested by Diamente and Munro, 1993; Elicin and Sacılık, 2005 due to the continuous fluctuation of relative humidity of drying air under solar tunnel dryer conditions. Therefore, the drying rate as g_{water}/h (DR) of the microalgae cultures were determined by Eq. (2):

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

Where M_{t+dt} is the moisture content at $t+dt$ ($g_{water}/g_{dry\ matter}$). A non-linear regression analysis (Sigma Plot 12.00) was applied to experimentally obtained MR as a function of time using drying models given in Table 1. The constants (a, n, b, c, m, k, and g) of models tested in Table 1 were determined based on the non-linear regression analysis. The performance of models was evaluated by coefficient of determination (R^2), the standard error of estimate (SEE), and residual sum of square (RSS).

Table 1. Mathematical models tested for the moisture ratio values of the microalgae cultures

No	Model name	Model Equation	References
1	Newton	$MR = \exp(-kt)$	Toğrul and Pehlivan 2002
2	Page	$MR = \exp(-kt^n)$	Akpinar 2008
3	Henderson and pabis	$MR = a \exp(-k\ t)$	Doymaz, 2014
4	Logarithmic	$MR = a \exp(-k\ t) + c$	Akpinar 2008
5	Midilli *et al.*	$MR = a \exp(-kt^m) + b\ t$	Midilli *et al.* 2002
6	Wang and Singh	$MR = 1 + at + bt^2$	Babalis *et al.* 2006
7	Two term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	Yaldiz *et al.* 2001
8	Two term exponential	$MR = a \exp(-kt) + (1-a)*\exp(-m*k*x)$	Sharaf-Elden *et al.* 1980
9	Weibull distribution	$MR = a - b \exp[-(kt^n)]$	Babalis *et al.* 2006
10	Logistic	$MR = a_0/(1 + a \exp(k\ t))$	Soysal 2005

3. Results and discussion

Solar drying of microalgae cultures was conducted on September in 2015. Throughout the experiment, the weather was sunny and no rain was recorded. The experiment lasted for approximately 3 days. Figure 2 shows the change of solar irradiance during the experiment. The influence of different drying conditions of microalgae cultures on moisture ratio, drying rate values were also investigated.
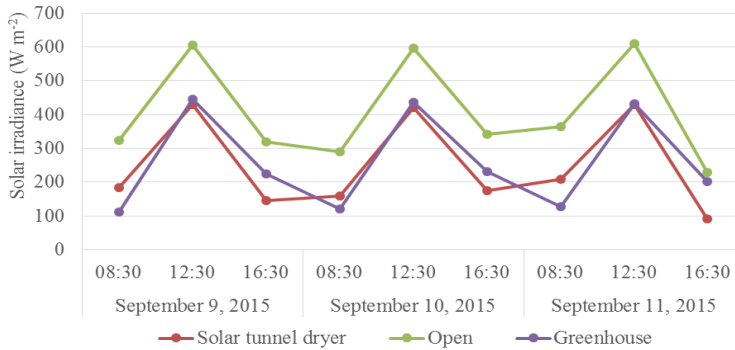

Figure 2. Solar irradiance level

The drying curves of microalgae cultures using different drying conditions are shown in Figure 3, 4, and 5. In all figures, C, N, and B stands for *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* microalgae cultures, respectively. When the moisture content decreased, the moisture ratio continuously decreased. The drying time necessary for reduction of initial moisture content from (79.66 %) to the desired final moisture content up to (19.47, 20.55 and 20.70%) for *Chlorella sp.* microalgae cultures at solar tunnel drying, open sun drying and greenhouse drying was found to be 56 hours. The times taken for drying of *Neochloris conjuncta* microalgae cultures from the initial moisture content of 70.9% to final moisture content of around 20.88, 20.59 and 21.65% were 56 hours while drying time for *Botryococcus braunii* microalgae cultures from the initial moisture content of 82.42% to final moisture content of 13.54, 13.54 and 15.90% were 56 hours in solar tunnel drying, open sun drying and green house drying, respectively. Experimental and predicted moisture ratio values with drying time obtained from the Weibull Model are shown in Figure 3, 4, and 5.

The drying rate defined as the quantity of water removed with time is shown in Figure 6, 7, and 8 for different microalgae at solar tunnel, open sun and greenhouse drying. The total drying rates to reach the final moisture content were 2.51, 2.49, and 3.01 g water/h at *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* microalgae cultures for solar tunnel drying, respectively (Figure 6). The drying rate is shown in Figure 7 for *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* microalgae cultures during open sun drying. The results were 1.77, 1.86, and 2.68 g_{water}/hour for *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* microalgae cultures at open sun drying, respectively. The drying rate sharply increased within four and eight hours and then decreased. As can be seen in Figure 8, the drying rates of *Chlorella sp.*, *Neochloris conjuncta* and *Botryococcus braunii* microalgae cultures for greenhouse drying took 1.63, 1.76, and 1.77 g_{water}/h, respectively. This behavior was periodic and gradually diminishing in magnitude on each day of

drying. It can be said that the drying rate of all dried microalgae cultures at solar tunnel drying was higher than that of all dried microalgae in open sun and greenhouse dryer.
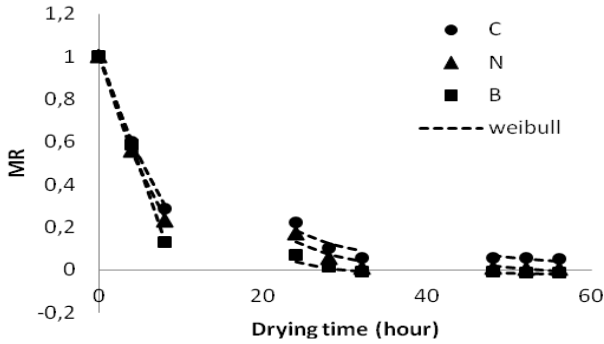

Figure 3. Variation of experimental and predicted moisture ratios with drying time for solar tunnel drying of microalgae (Weibull Model)
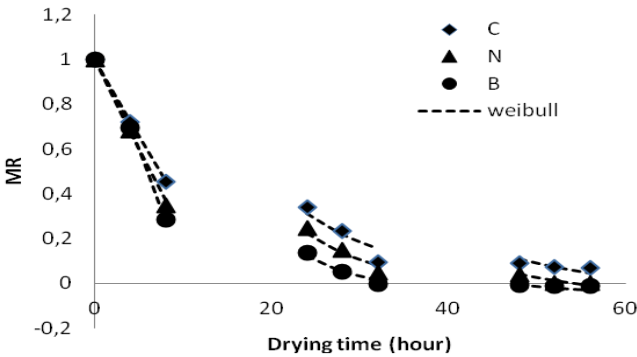

Figure 4. Variation of experimental and predicted moisture ratios with drying time for open sun drying of microalgae (Weibull Model)
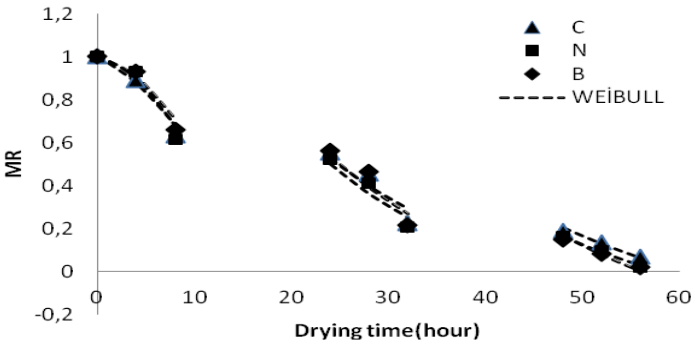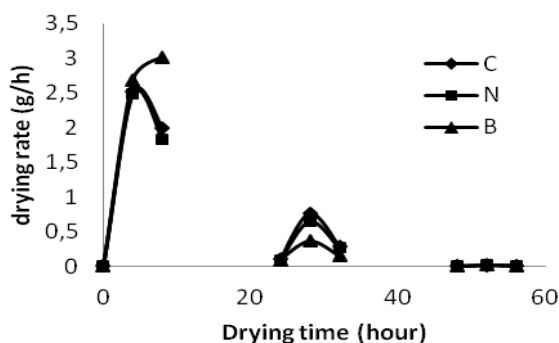

Figure 5. Variation of experimental and predicted moisture ratios with drying time for greenhouse drying of microalgae (Weibull Model)

Figure 6. Variation of drying rate as a function of drying time for solar tunnel drying of microalgae
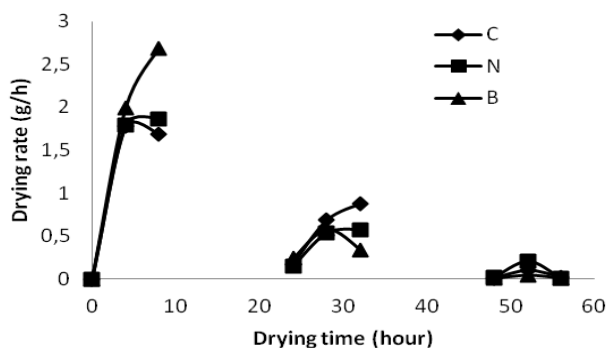
Figure 7. Variation of drying rate as a function of drying time for open sun drying of microalgae
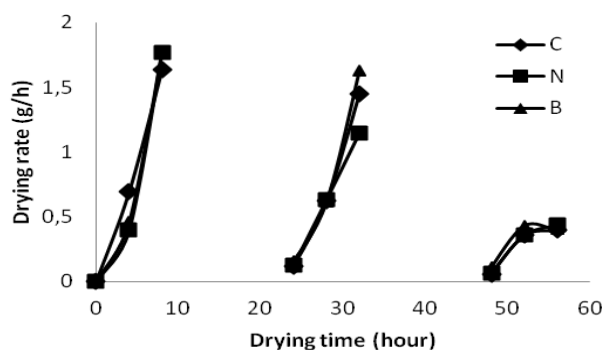
Figure 8. Variation of drying rate as a function of drying time for greenhouse drying of microalgae

Non-linear regression analysis was performed using the sigma plot computer program. R^2 was one of the important criteria for selecting the best model to define the drying curves of microalgae cultures. Besides R^2, the various statistical parameters such as SEE and RSS are used to evaluate the goodness of fit of the models. Therefore, the lower the SEE and RSS values and the higher R^2 values were used to determine the quality of the

fit. The statistical analyses results applied to these models at drying process at solar tunnel, open sun and greenhouses drying are given in Tables 2, 3 and 4 for microalgae cultures. The results of the statistical computations undertaken to assess the consistency of 10 drying models are presented in Tables 2, 3 and 4 for the Weibull Distribution model. The Weibull Distribution model yielded the highest values of R^2 and the lowest values of SEE and RSS. To take into account the effect of the drying variables on the Weibull Distribution model constants a, b, k and n were regressed against those of drying air temperatures using multiple regression analysis. Based on the multiple regression analysis, the accepted model was as follows:

$$MR(a,b,k,n) = \frac{M - M_e}{M_0 - M_e} = a - b \exp[-(kt^n)]$$

(5)

Table 2. Non-linear regression analysis results for solar tunnel drying of microalgae cultures.

	C			N			B		
	R²	SEE	RSS	R²	SEE	RSS	R²	SEE	RSS
Newton	0.9911	0.0308	0.0076	0.9948	0.0246	0.0048	0.9720	0.0602	0.0290
Page	0.9915	0.0321	0.0072	0.9957	0.0237	0.0039	0.9963	0.0233	0.0038
Henderson and pabis	0.9911	0.0330	0.0076	0.9949	0.0260	0.0047	0.9731	0.0631	0.0279
Logarithmic	0.9944	0.0283	0.0048	0.9951	0.0275	0.0045	0.9793	0.0599	0.0215
Midilli -Kucuk	0.9955	0.0276	0.0038	0.9958	0.0279	0.0039	0.9967	0.0260	0.0034
Wang And Singh	0.9537	0.0750	0.0393	0.9404	0.0887	0.0550	0.9171	0.1108	0.0860
Two term	0.9951	0.0289	0.0042	0.9949	0.0308	0.0047	0.9731	0.0747	0.0279
Two term exponential	0.9951	0.0265	0.0042	0.9948	0.0284	0.0048	0.9720	0.0695	0.0290
Weibull distribution	**0.9959**	**0.0265**	**0.0035**	**0.9964**	**0.0256**	**0.0033**	**0.9991**	**0.0133**	**0.0009**
Logistic	0.9911	0.0356	0.0076	0.9957	0.0258	0.0040	0.9968	0.0234	0.0033

Table 3. Non-linear regression analysis results for open sun drying of microalgae cultures.

	C			N			B		
	R²	SEE	RSS	R²	SEE	RSS	R²	SEE	RSS
Newton	0.9933	0.0270	0.0058	0.9932	0.0307	0.0124	0.9718	0.0619	0.0307
Page	0.9942	0.0269	0.0051	0.9956	0.0246	0.0042	0.9972	0.0208	0.0030
Henderson and pabis	0.9935	0.0283	0.0056	0.9919	0.0335	0.0079	0.9742	0.0633	0.0281
Logarithmic	0.9935	0.0305	0.0056	0.9947	0.0293	0.0052	0.9837	0.0544	0.0178
Midilli-Kucuk	0.9952	0.0289	0.0042	0.9958	0.0284	0.0040	0.9978	0.0220	0.0024
Wang And Singh	0.9921	0.0313	0.0069	0.9798	0.0528	0.0195	0.9728	0.0650	0.0296
Two term	0.9935	0.0335	0.0056	0.9919	0.0396	0.0079	0.9742	0.0749	0.0281
Two term exponential	0.9933	0.0312	0.0058	0.9912	0.0377	0.0085	0.9718	0.0715	0.0307
Weibull distribution	**0.9934**	**0.0338**	**0.0057**	**0.9974**	**0.0223**	**0.0025**	**0.9992**	**0.0133**	**0.0009**
Logistic	0.9941	0.0292	0.0051	0.9953	0.0276	0.0046	0.9970	0.0234	0.0033

Table 4. Non-linear regression analysis results for greenhouse drying of microalgae cultures.

	C			N			B		
	R²	SEE	RSS	R²	SEE	RSS	R²	SEE	RSS
Newton	0.9594	0.0673	0.0362	0.9462	0.0826	0.0546	0.9278	0.0979	0.0768
Page	0.9862	0.0420	0.0123	0.9861	0.0449	0.0141	0.9848	0.0480	0.0162
Henderson and pabis	0.9669	0.0650	0.0295	0.9580	0.0780	0.0426	0.9423	0.0936	0.0614
Logarithmic	0.9842	0.0484	0.0141	0.9829	0.0537	0.0173	0.9825	0.0557	0.0186
Midilli-Kucuk	0.9867	0.0487	0.0119	0.9873	0.0508	0.0129	0.9874	0.0519	0.0134
Wang And Singh	0.9846	0.0443	0.0137	0.9810	0.0512	0.0184	0.9810	0.0537	0.0202
Two term	0.9669	0.0769	0.0295	0.9580	0.0923	0.0426	0.9423	0.1108	0.0614
Two term exponential	0.9594	0.0777	0.0362	0.9462	0.0954	0.0546	0.9278	0.1131	0.0768
Weibull distribution	**0.9868**	**0.0485**	**0.0118**	**0.9898**	**0.0454**	**0.0103**	**0.9876**	**0.0514**	**0.0132**
Logistic	0.9863	0.0451	0.0122	0.9850	0.0504	0.0152	0.9848	0.0519	0.0161

Conclusions

Chlorella sp., Neochloris conjuncta and Botryococcus braunii microalgae cultures were dried using a solar tunnel dryer, open sun and greenhouse methods. During the experiment, relative humidity and temperature of drying air, solar irradiation, moisture reduction from Chlorella sp., Neochloris conjuncta and Botryococcus braunii microalgae cultures were measured. All microalgae cultures were dried in the same drying time. The drying rate of all dried microalgae cultures at solar tunnel drying was higher than that of all dried microalgae cultures in open sun and greenhouse dryer. Among the all model tested, Weibull Model was the best descriptive model for solar tunnel drying, open sun drying and greenhouse drying of all of the microalgae cultures.

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