Drying kinetics and statistical modeling of thin-layer drying of purple non-sulfur bacterial biomass

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Abstract. Thin-layer drying studies have been done for various materials, including vegetables, fruit, grains, wood, plants, biomass, and others. The present study is concerned with the investigation of the drying kinetics of harvested photosynthetic non-sulfur bacteria (PNSB) biomass. Four different drying models, i.e., Logarithmic, Newton, Page, and Henderson and Pabis were fitted to the experimental data obtained from drying a thin-layer of biomass in a laboratory oven at 60, 80, 100, and 120 °C. The results were assessed on statistical parameters such as the Akaike information criterion, and residual standard error. The results showed that Logarithmic model fitted the overall best for all the states of the thin layer at 60 °C and 80 °C, while Page model gave the best fit for 100 °C and 120 °C. The current research is aimed to study the drying behavior of the biomass and to aid in optimizing the drying procedure of the biomass.

Introduction

Aquaculture is a growing industry that requires a constant supply of protein for the cultivation of aquatic organisms. Recently single-cell protein (SCP) has emerged as an attractive option due to its high rate of productivity and lack of competition with arable land. Purple non-sulfur bacteria are one group of organisms that shows strong potential and can be integrated with photo-anaerobic wastewater treatment. The recovery of PNSB from such a system for SCP involves many steps, including preparation of media, fermentation, harvesting, and in the end, drying of the biomass [1]. After biomass harvesting, the dry solid content of the achieved product is still relatively low. Consequently, drying is carried out to remove/lower the moisture content. Generally, drying is defined as preserving a product by reducing the product's water content to limit microbiological or chemical deterioration [2]. A few of the most preferred biomass drying methods are convective, vacuum, solar, spray and freeze drying. Freeze-drying is recently a very popular method based on sublimation, preserving the product's actual characteristics and nutritional value. However, it is an expensive and time extensive method [3]. Thermal drying methods such as conventional oven drying, and solar drying are comparatively cheaper. Therefore, in the present study, the drying of PNSB biomass was done using a laboratory oven. The study focused on the impacts of temperature on drying and on understanding the multiple stages the biomass undergoes before it becomes dehydrated through fitting various mathematical drying models. It examines moisture movements occurring in the internal and external surfaces of the biomass based on a set of equations [4].

Materials and Methods

PNSB Cultivation. In this study, wastewater from a gas-to-liquids reforming process was used as a medium for the growth of photosynthetic non-sulfur bacteria. A 4 L anaerobic lab-scale bioreactor was utilized for cultivating the PNSB under a white LED light source.

PNSB Harvesting. PNSB biomass was harvested when the organic content of the wastewater was almost exhausted. The biomass from the wastewater was harvested by centrifuging at 8000 rpm for 10 minutes. For the thin layer drying experiment, approximately 13.7 to 13.8 grams of the harvested PNSB biomass was evenly spread over a circular aluminum petri dish.

PNSB Drying. The drying of harvested biomass was performed in a laboratory oven. The centrifuged biomass was placed in petri dishes was dried at 60, 80, 100, and 120 ℃, with each condition duplicated. The mass of PNSB paste in each petri dish was measured before drying using a digital weighing balance. Later, the instantaneous weight of the biomass was measured every 15 minutes until a constant weight was achieved. The mass balance-time data was converted to moisture ratio-time data for its use in equations of the drying models.

Modeling of Drying Curves

Four moisture ratio models have been employed in the study, enlisted in Table 1. These models are selected based on their successful application in previous literature.

Table 1: Drying models, their expressions, and successful application on various materials

Drying Model	**Analytical Expression**	**Parameters**
Henderson and Pabis	MR = a exp (-kt)	a k, t
Logarithmic	MR = a exp (-kt) + c	a, k, c, t
Newton	MR = exp (-kt)	k, t
Page	MR = exp ($-kt^y$)	k, y, t

In Table 1, a, c, k, and y are model constants where t represents the time in minutes. The governing factor that forms the model equations is the dimensionless moisture ratio (MR), which is calculated as:

$$MR = \frac{Mt-Me}{Mi-Me} \tag{1}$$

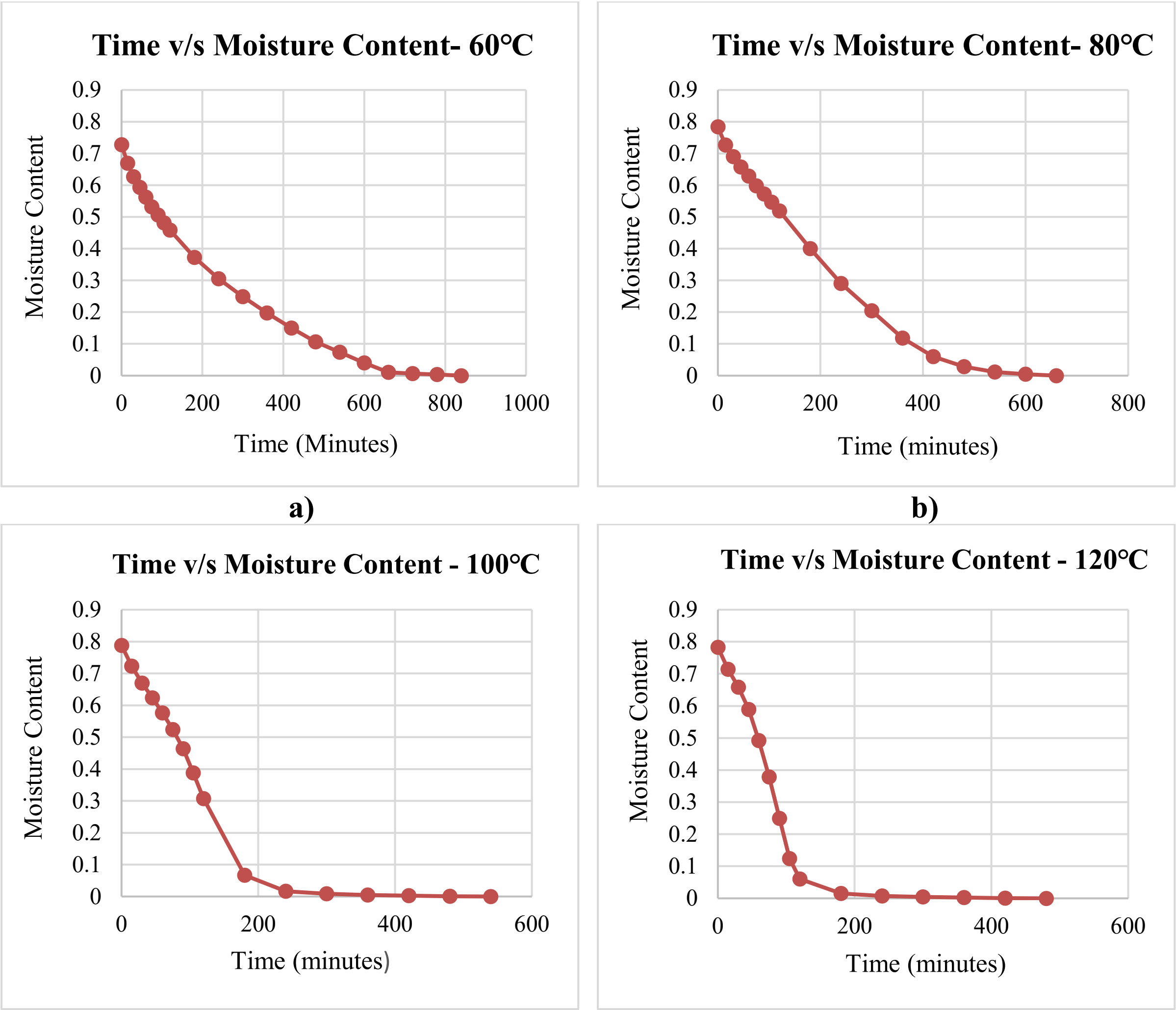
Where Mt is the moisture content at time t, Me is the equilibrium moisture content, and Mi is the initial moisture content. Me is relatively smaller than Mt and Mi. Therefore, Eq. 1 can be simplified as follows,

$$\mathrm{MR} = \frac{\mathrm{Mt}}{\mathrm{Mi}} \tag{2}$$

Statistical Analysis of Modeling Results. The experimental drying data were fitted to the four selected models using R software (R version 4.2.1). Statistical parameters such as residual standard error (RSE) and Akaike information criterion (AIC) were used for the goodness of fit of the chosen models to the experimental data. The lower the AIC and RSE values, the better the model will fit [5].

Results and Discussion

Drying Kinetics. In the study, the initial moisture content of the selected samples of harvested PNSB biomass varied between 70% and 80%. There are three generic phases in the drying of biomass. The first is the warm-up phase, in which the temperature of the biomass increases until the bulk temperature reaches the oven environment's temperature. The next phase is the phase of maximum drying rate. This phase is isenthalpic. Water evaporation occurs on the biomass's surface, covered by a layer of free non-bonded water molecules. In the last reduced drying phase, water molecules entrapped within the biomass, i.e., with intercellular connections, tend to evaporate until the mass of the biomass becomes constant [6].



a) b)

c) d)

Figure 1: Graphs illustrating the variation of mass of the samples with time for different temperatures (a represents for 60ºC, b for 80 ºC, c for 100 ºC, and d for 120 ºC)

The drying kinetics show that drying of thin-film of the PNSB biomass is the slowest for the lowest temperature (60 °C). The drying process took the longest time (approx. 840 minutes) for the moisture content to be removed completely from the samples at 60 °C. In comparison, drying of thin film took the least time at 120 °C, i.e., 480 minutes. At 100 °C, the drying rate was only slightly slower, in comparison to 80 °C, which took twice as long to dry completely. The analysis indicates that the drying time decrease as the temperature increase, which portrays an inverse relationship between the two parameters. At higher temperatures, the heat and mass transfer rate increases, resulting in quicker moisture evaporation from inside the film to the outside.

In Figure 1, the drying curve is initially more upwards concave at 60 °C, with a steeper, more linear initial response as the temperature increases. There was a slower decrease in drying rate at lower temperatures (60 °C and 80 °C). However, at the higher temperatures of 100 °C and 120 °C, the drying rate was much quicker with a short or unnoticeable warming up period, resulting in only maximum and reduced drying phases being observed.

Statistical Analysis of Drying Models. Modeling was done to analyze the model that best predicts the experimental data. The two best-fitted models of the selected ones (in ascending order) are given in Table 2:

Table 2: Statistical model fitting to the acquired drying data

Temperature [°C]	Model	Checks	
		AIC	RSE
60	Logarithmic	-208.5684	0.01906
	Newton	-170.0247	0.03085
80	Logarithmic	-127.7947	0.03833
	Page	-125.2065	0.04025
100	Page	-110.5012	0.04048
	Logarithmic	-73.57193	0.07106
120	Page	-110.7946	0.03576
	Logarithmic	-55.67538	0.08826

The lower the values of the statistical parameters, the better the model fit is. It can be concluded from Table 2 that the Logarithmic model performed the best at lower temperatures such as 60 °C and 80 °C. After which, the Page model displayed the best fit at 100 °C and 120 °C.

As seen in Figure 1, the drying curves at 60 °C and 80 °C display a more logarithmic fit than at 100 °C and 120 °C, which justifies the best fit of the Logarithmic model. The slope of the curve is more time-dependent at lower temperatures. On the contrary, heat plays a major role at higher temperatures along with time, showing a much quicker decrease in the mass. Page model has its dependency on other external factors besides time. Therefore, this explains the best fitting of the Page model at 100 °C and 120 °C. The results are found to be concurrent with previous studies on microwave drying of microalgae (*Chlorella vulgaris*) [7], air drying of some food materials such as tomatoes [8] and banana slices [9], and thyme leaves [10].

Summary

This study has investigated the drying kinetics of PNSB biomass cultivated in gas-to-liquid process wastewater. The three phases in a drying process are warming, maximum drying, and reduced drying. All the phases were perceivable at 60 °C and 80 °C, while only the latter two mentioned phases were apparent at 100 °C and 120 °C. Four widely studied models were applied to the experimental data, and statistical analysis was done. Based on the acquired results for the examined models, the Logarithmic model was the best to define the drying behavior of the considered biomass film at 60 °C and 80 °C. Likewise, Page model predicted the best results for 100 °C and 120 °C.

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