

# Application of machine learning for development of a drying protocol for microalga *Chlorella minutissima* in a single rotary drum dryer for biodiesel production

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October 26, 2020

## Abstract

Drying of microalgal slurry is one of the important steps of downstream processing which faces several technical challenges for cost-effective biodiesel production. In this investigation, drying of *C. minutissima* was carried out by a single rotary drum dryer with varied drum surface temperature and rotational speed. Application of machine learning tool classified the range of residual moisture content to be <10% (wet biomass) for high lipid recovery with an accuracy of 97%. Based on the drying time, lipid recovery, and energy consumption, drum drying at 80 °C drum surface temperature with 0.3 rpm depicted 90% lipid recovery as compared to the bone-dried biomass. The energy consumption of 7.328 kWh for 1 kg of dried biomass was recorded with profoundly lower drying time, thus could be recommended for drying of the microalgal slurry at industrial scale.

## 1. INTRODUCTION

Microalgal biodiesel promises to be a zero CO<sub>2</sub>-emitting and renewable energy source. The biodiesel production from microalgae includes various steps beginning from cultivation of the desired strain followed by harvesting, drying of microalgal slurry, oil extraction from the biomass, and transesterification of lipid to biodiesel (O'Connell, Savelski, & Slater, 2013). However, the downstream processing of the harvested microalgal slurry faces several technical challenges for cost-effective biodiesel production. Drying of microalgal biomass is one of those important steps. Dewatering of the harvested microalgal slurry is essential to enhance the viability of biomass for lipid extraction, and also to reduce the costs of handling, transportation, packaging, and storage (Bennamoun, Arlabosse, & Léonard, 2013).

Many drying techniques are available nowadays which include advanced techniques like spray drying, tray drying, oven drying, freeze drying, vacuum-shelf drying, cross-flow air drying, etc, as well as the simple and natural solar drying. The suitability of a method depends on many factors such as the properties and types of the microalgal suspension, the downstream processes, the end product type and quality, and the overall cost of production (Chen, Chang, & Lee, 2015). The drying techniques such as freeze drying (Guldhe, Singh, Rawat, Ramluckan, & Bux, 2014), thin layer drying (Hosseinizand , Sokhansanj, & Lim, 2018), microwave drying (Villagrancia et al., 2016) etc. are mainly used at a laboratory-scale, whereas drum drying technique could be useful at industrial level for drying of large-scale microalgal slurry.

The major advantages of drying the microalgal slurry in a drum dryer are breaking the cell wall and sterilization of the dried biomass (Show, Lee, & Mujumdar, 2015). Mahadevaswamy & Venkataraman (1981) reported that drum drying of *Scenedesmus acutus* 273-3a biomass for a detention time of 8-10 sec reduced the microbial load during storage. An electrically-heated drum dryer was tested for drying of *Scenedesmus* sp. biomass containing 70% moisture for 10 sec at 120 °C and the energy consumption was calculated to be

52 kWh (Becker & Venkataraman, 1982). A steam-heated drum drying of *Spirulina* slurry was carried out at 120-128 °C for 16 sec for preparing the feed for aquaculture (Sethi & Naik, 2007). Recently, Wahlen et al. (2017), used a bench-scale rotary drum dryer for drying the *Scenedesmus* sp. at 50 °C. Thus, for faster drying, a drum dryer could be a suitable option for large-scale processing of microalgal slurry.

Machine learning, on the otherhand is a new edge technology used in every sector of research. It can be divided into two segments, i.e. supervised learning and unsupervised learning. Supervised learning is implemented when a structured data set is provided and we know what our output would look like. Whereas, unsupervised learning allows us to tackle the problem with little or no knowledge of what our results would be. It is further divided as shown in the Figure 1.

There are different algorithms to implement the mentioned modules (Figure 1). Regression can be done using linear regression algorithm and classification using logistic regression or simple vector machine. Algorithms like neural networks can be used for both. Unsupervised learning can be done through K-mean or principal component analysis.

For our defined problem, we have taken the supervised-classification module into consideration to label the outputs good or poor. Out of logistic regression and simple vector machine, logistic regression is employed based on the fact that we have a large number of features compared to training examples. Here, there was a chance for overfitting of the decision boundary for which regularization was also executed. Logistic regression is a predictive algorithm. The present investigation is thus, aimed at developing a microalgal drying protocol at different drum surface temperature with varying drum speed using the logistic regression with regularization to obtain maximum lipid from microalgal biomass for biodiesel purpose.

## 2. MATERIALS AND METHODS

### 2.1. Culture conditions for the experimental organism

*Chlorella minutissima*, a fast-growing green microalga, was selected for this study. Axenic cultures of the test microalga was maintained in Erlenmeyer flasks with N 11 medium as per Soeder & Bolze (1981). The temperature was maintained at  $25 \pm 2$  °C with photoperiod of 14 h and light intensity of  $75 \mu\text{mol photons m}^{-2}\text{s}^{-1}$  PAR.

For drying experiments, *C. minutissima* was cultivated in raceway ponds with volumetric capacity of 40,000 L each ( $14 \times 4 \times 0.75$  m). Before cultivation in raceway ponds, the selected microalga was scaled-up in the UZn medium (Koley, Mathimani, Bagchi, Sonkar, & Mallick, 2019), and was acclimatized to the outdoor condition as detailed in Sonkar, Deb, & Mallick (2020). The raceway ponds were operated at 30 cm of culture depth with a corresponding culture volume of 16000 L. Harvesting of the microalgal biomass was carried by pH-induced flocculation using NaOH at pH 12 for 12 h following Koley, Prasad, Bagchi, & Mallick (2017).

### 2.2. Drying experiments in a single rotary drum dryer

Drum drying is a continuous indirect heating process. A single rotary drum dryer consisting of a hollow cylinder made up of stainless steel was mounted horizontally on a supporting frame and rotated continuously. The speed of the drum could be regulated by a variable-speed drive. The diameter and length of the cylindrical drum were 48.5 and 45.2 cm, respectively. During the operation, thermal oil filled in the storage tank was heated up to  $100 \pm 2$  °C which was pumped into the hollow cylindrical drum for heating. The closed system of the drum did not allow the sample to be in contact with the oil, but provided uniform temperature distribution over the drum surface, which ensured consistent product quality.

The microalgal slurry was uniformly attached to the drum surface from the algal reservoir through continuous rotation. The heated drum slowly dried the wet microalgal slurry on the outside of the drum surface and was finally scrapped by the doctor blade (scraper device). The exposure of the microalgal slurry to a high temperature for a short period reduces the risk of damage to the dried-biomass. The residence time of the product on the drum surface depends upon the speed of the drum ranging from 0.1 revolution per minute (rpm) to several rpm. In the present investigation, the microalgal slurry was dried at varying drying

temperature from 70, 80, 90, and 100 °C at eight different rpm, i.e., 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 1.5, and 2.0 rpm.

### 2.3. Estimation of moisture content

The moisture content was determined by the following formula (Chakraverty, 1988):

$$MC = \frac{W_m \times 100}{(W_m + W_d)}$$

Where,

MC: Moisture content (%) in wet basis (wb)

$W_m$  : Weight of moisture in the biomass

$W_d$  : Weight of bone-dried biomass

(bone drying referred to oven drying of the biomass at  $103 \pm 2$  °C for 24 h, Chakraverty, 1988).

### 2.4. Extraction and estimation of lipids

The standard protocol of Bligh & Dyer (1959) was followed for lipid extraction from the drum dried microalgal biomass with chloroform, methanol and distilled water as solvents. The organic layer was evaporated in a water bath followed by drying at 104 °C for 30 min. The weight of the lipid was estimated in a high precision balance of Sartorius, Germany.

### 2.5. Application of machine learning

There were four factors in these experiments, namely, drum speed (rpm), drum surface temperature (°C), residual moisture content (% wb) and lipid yield (mg g<sup>-1</sup> of dry biomass). Residual moisture content and lipid yield of corresponding drum speed and drum temperature were mapped to get two features. The training data sets were labelled good (1) or poor (2) based on the lipid yield and residual moisture content (Table 1). Logistic regression with regularisation was used to do the classification of the data gathered through experiments (Dreiseitl & Ohno-Machado, 2002). The following steps mentioned in the Figure 2 were employed.

### 2.6. Estimation of energy consumption

The energy consumption in the single rotary drum dryer was calculated by a digital clamp multimeter (Model: Metravi-107, Metravi Instruments Pvt. Ltd., West Bengal, India). It records the AC/DC voltage in the range of 0.0-599.9 V with a resolution of 0.1 V and current in the range of 0.0-399.0 A with a resolution of 0.1 A. The accuracy was  $\pm 5\%$  for both, AC/DC voltage and current.

### 2.7. Statistical analysis

One-way and two-way ANOVA (Analysis of Variance) with Duncan's new multiple range test were used for revealing the significance of the data with the help of IBM SPSS version 22 statistical software (Chicago, Illinois, USA). The experiments were conducted in triplicate and repeated thrice for validation of the study.

## 3. RESULTS AND DISCUSSION

### 3.1. Bone drying of *C. minutissima* slurry

The microalgal slurry was taken in glass vials and kept for drying in a laboratory-scale oven at  $103 \pm 2$  °C for 24 h. This was referred to be bone drying materials. The moisture content of the microalgal slurry was found to be ~90% of the wet biomass (wb). The lipid yield of the bone-dried samples was recorded to be  $142.1 \pm 4.1$  mg g<sup>-1</sup> of dry biomass, whereas for the biomass slurry dried at  $60 \pm 2$  °C till to reach constant weight following Rai, Mallick, Singh, & Kumar (1991) in the same laboratory-scale oven was  $146.3 \pm 3.2$  mg g<sup>-1</sup> of dry biomass (Table 2). These observations revealed that there was insignificant variation in lipid yield

between the bone-dried and the biomass obtained by drying at 60 °C, although the biomass yield varied significantly under both the conditions.

### 3.2. Drum drying at different temperature with variable speed

Drum speed and surface temperature of the drum are the two major variables that affect the residual moisture content of the dried algal biomass. The residual moisture content of the microalgal slurry was found to be reduced maximum up to  $41.4 \pm 2.7\%$  (wb) under the drum speed of 0.1 rpm at drum surface temperature of 70 °C (Figure 3A). By increasing the drum surface temperature to 80 °C, the residual moisture content of the microalgal slurry was reduced to  $< 10\%$  (wb) under the drum speed of 0.1, 0.2, and 0.3 rpm (Figure 4A). Likewise, at 90 °C of drum surface temperature, the residual moisture content was reduced up to  $4.6 \pm 1.1$ ,  $5.3 \pm 1.3$ ,  $6.1 \pm 1.5$ , and  $7.3 \pm 2.6\%$  (wb) at 0.1, 0.2, 0.3, and 0.4 rpm, respectively (Figure 5A). Further, at 100 °C of drum surface temperature, the residual moisture content was  $3.5 \pm 1.7$ ,  $3.9 \pm 1.5$ ,  $4.4 \pm 2.3$ ,  $6.3 \pm 1.6$ , and  $7.1 \pm 2.1\%$  (wb), respectively, for the drum speed of 0.1, 0.2, 0.3, 0.4, and 0.5 rpm (Figure 6A). From Duncan's new multiple range test analysis, it can be concluded that there was no significant variation in the residual moisture content of the drum-dried biomass at 80 °C with drum speed of 0.1-0.3 rpm, 90 °C with drum speed of 0.1-0.4 rpm, and 100 °C with drum speed of 0.1-0.5 rpm (Table 3).

The summary of lipid yield ( $\text{mg g}^{-1}$  of dry biomass) and lipid recovery (%) at different drum surface temperature under varying drum speed is presented in Table 4. The maximum lipid yield was found to be  $72.1 \pm 5.2 \text{ mg g}^{-1}$  of dry biomass with the corresponding lipid recovery of 50.7% only as compared to the bone-dried samples under the drum speed of 0.1 rpm at 70 °C of drum surface temperature (Figure 3B, C). This is well in agreement with the report of Balasubramanian, Doan, & Obbard (2013), where a significant reduction in lipid extraction efficiency was evident from the biomass of *Nannochloropsis* sp. with higher moisture content. The possible reason could be that the hydrophilic outer layer of the microalgal cell wall was surrounded by water molecules that resist the non-polar solvent penetrating inside the cell and hinders the extraction of lipids (Balasubramanian et al., 2013). At the drum surface temperature of 80 °C, the lipid yield was estimated to be ranged between 130.6-131.3  $\text{mg g}^{-1}$  of dry biomass at the drum speed of 0.1-0.3 rpm, and the maximum lipid yield of  $131.3 \pm 3.1 \text{ mg g}^{-1}$  of dry biomass with lipid recovery of 92.4% was obtained at 0.3 rpm (Figure 4B, C). Similarly, the lipid yield was found to be in the range of 130.2-132.2  $\text{mg g}^{-1}$  of dry biomass with 0.1-0.3 rpm at the drum surface temperature of 90 °C. The maximum lipid yield of  $132.2 \pm 3.4 \text{ mg g}^{-1}$  dry biomass was obtained under the drum speed of 0.4 rpm at 90 °C with the corresponding lipid recovery of 93% as compared to the bone-dried samples (Figure 5B, C). Likewise, at 100 °C of drum surface temperature, the maximum lipid yield was found to be in the range of 127.5-133.3  $\text{mg g}^{-1}$  of dry biomass between 0.1-0.5 rpm; the maximum lipid yield was estimated to be  $133.3 \pm 5.4 \text{ mg g}^{-1}$  of dry biomass under 0.5 rpm with the corresponding lipid recovery of 93.8% at drum surface temperature of 100 °C (Figure 6B, C). From Duncan's new multiple range test analysis, no significant variation was observed in the lipid yield of the drum-dried biomass at 80 °C from 0.1-0.3 rpm, 90 °C from 0.1-0.4 rpm, and 100 °C from 0.1-0.5 rpm (Table 4). From this observation, drum surface temperature of 80, 90, and 100 °C with the drum speed of 0.1-0.3, 0.1-0.4, and 0.1-0.5 rpm, respectively, could be selected for maximum lipid recovery from the algal biomass. Zepka, Jacob-Lopes, Goldbeck, & Queiroz (2008) reported that the constituents of biomass such as lipid, carbohydrate, and protein contents could alter significantly based on the drying temperature. A study revealed that *Chlorella vulgaris* biomass dried at 60 °C in an oven resulted in a slight reduction of lipid content, whereas at 80 °C or much higher temperature, the lipid content was considerably decreased (Widjaja, Chien, & Ju, 2009). The study cited the possible explanation for the low triacylglycerol yield as oxidation of fatty acid upon exposure to the higher temperature. Contrary to this, the present study showed that drying the microalgal slurry from 80-100 °C in a drum dryer has insignificant impact on lipid recovery. The probable explanation could be the short duration of exposure of the wet microalgal slurry to a high temperature that reduces the risk of damage to the dried-biomass and its constituents.

### 3.3. Identification of decision boundary by machine learning

Figure 7 shows the distribution of raw data set and identification of the decision boundary respectively for which the above data sets are desirable. This method can be further used to predict whether the testing

data set should be termed good or poor (Bera, Saha, & Bhattacharjee, 2020). Logistic regression with regularisation gave the best output in classifying our experimental results (Shi, Li, Ding, & Gao, 2020). A lot of trials were done to set the values of regularisation constant as 1 and degree of feature mapping as 12. A decision boundary curve was plotted which divided the X-Y plane into two parts, one being the good yield region and the other poor (Figure. 7B). The data points represented as “X” were termed as good yield and “O” as poor yield. It is evident from the graph that as the moisture content increases the lipid yield reduces. There is an increase in lipid yield when residual moisture content is reduced, drum temperature is increased and drum speed is reduced. This classification helps us in determining the range of the above mentioned factors in which one can get high lipid yield. The plot has an accuracy of 97.037% and corroborates our observation that a moisture content of <10% (wb) would result lipid recovery > 90% of the bone-dried biomass (Figure 7B).

### 3.4. Energy consumption for drum drying

In this investigation, a comparative evaluation of energy consumption for drum-dried biomass at 80, 90, and 100 °C of drum surface temperature with varying drum speed was thoroughly conducted. The energy consumption of the drum dryer used in this study for drying 1 kg of biomass at 80 °C for 0.3 rpm was 7.328 kWh. By decreasing the rotational speed of the drum, the time required for obtaining 1 kg of dried biomass increased, which resulted in greater energy consumption. At 90 °C, the energy consumption was 8.4 kWh/ kg dry biomass for 0.4 rpm, whereas it was 9.511 kWh/ kg dry biomass at 100 °C for 0.5 rpm. Thus, considering the lipid recovery above 90% of the bone-dried materials, the minimum energy consumption to get 1 kg of dried biomass was at 80 °C for 0.3 rpm followed by 90 °C for 0.4 rpm and 100 °C for 0.5 rpm amongst all the other conditions (Table 5). Moreover, the difference in the time consumption for drying 1 kg of biomass at 80 °C for 0.3 rpm as compared to 90 °C for 0.4 rpm and 100 °C for 0.5 rpm was found to be marginal. Thus, considering the lipid recovery, energy consumption, and time required to obtain 1 kg of dried biomass, drum surface temperature of 80 °C with drum speed of 0.3 rpm can be concluded to be the best fit for large-scale drying of the harvested algal biomass in a single rotary drum dryer.

A study conducted by Bagchi, Rao, & Mallick (2015) revealed that *Scenedesmus* sp. biomass dried at 80 °C in a laboratory-scale hot air oven recorded an energy consumption of 5.231 kWh/ kg of dry biomass, whereas it was 11.227 kWh/ kg of dry biomass at 80 °C in a tray dryer with lipid recovery of >90% as compared to the bone-dried biomass (Bagchi, 2017). A significant reduction in drying time was observed in drum drying as compared to oven drying and tray drying (Table 6). The lipid recovery with the drum-dried biomass was at par with oven- and tray-dried biomass. The energy consumption was found to be 40% higher in drum drying as compared to oven drying. However, as compared to tray drying, energy consumption was reduced by 35% for 1 kg of dried biomass. Moreover, a profound reduction in drying time was evident with drum drying. Therefore, considering the drying time, lipid recovery, and energy consumption, the drum dryer carries immense potential and could be recommended for drying microalgal slurry at an industrial scale.

## 4. CONCLUSION

Machine learning algorithms provide an ease for identifying patterns. If used with precision, this tool can give incredible outputs. The plot demonstrates an inverse relationship between lipid yield and residual moisture content for corresponding drum temperature and speed. This classification determines the range of residual moisture content to be <10% (wb) for high lipid recovery with an accuracy of 97%. Further predictions of any new data set can be done based on this algorithm. In future, linear regression method can also be implemented to get lipid yield value based on moisture content or may be using drum temperature and speed.

## ACKNOWLEDGEMENTS

Dr. Sashi Sonkar gratefully acknowledges UGC-RGNF Scheme, New Delhi, India for fellowship. The authors are thankful to NASF, Indian Council of Agricultural Research, New Delhi, India, for financial support. The authors also acknowledge Prof. S. P. Adhikary, Vice-Chancellor, Fakir Mohan University, Odisha, India for the identification of the test microalga.

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**Table 1** Variables used

Variables	Description	Type
X <sub>1</sub>	Residual moisture content	Input
X <sub>2</sub>	Lipid yield	Input
Y	Poor or Good result = 0 or 1	Output

**Table 2** Biomass and lipid yield of *C. minutissima* dried at 60 °C and bone-dried samples

Parameter	60 °C till to reach a constant weight (Rai et al., 1991)	Bone drying (103 °C for 24 h)
Biomass yield (g)	2.51 ± 0.06 <sup>b</sup>	2.29 ± 0.08 <sup>a</sup>
Lipid yield (mg g <sup>-1</sup> dry biomass)	146.3 ± 3.2 <sup>a</sup>	142.1 ± 4.1 <sup>a</sup>

Note: Data presented are means  $\pm$  SD ( $n = 3$ ).

Analysis was conducted row-wise and superscripted by different alphabets to denote significant differences ( $P < 0.05$ , Duncan's new multiple range tests).

**Table 3** Summary of the residual moisture content (% wb) at a different temperature under varying drum speed

Drum speed (rpm)	Drum surface temperature	Drum surface temperature	Drum surface temperature
	<b>70 <math>\pm</math> 2 °C</b>	<b>80 <math>\pm</math> 2 °C</b>	<b>90 <math>\pm</math> 2 °C</b>
0.1	41.4 $\pm$ 2.7 <sup>Ba</sup>	5.2 $\pm$ 1.6 <sup>Aa</sup>	4.6 $\pm$ 1.1 <sup>Aa</sup>
0.2	52.8 $\pm$ 1.9 <sup>Bb</sup>	5.6 $\pm$ 1.5 <sup>Aa</sup>	5.3 $\pm$ 1.3 <sup>Aa</sup>
0.3	63.7 $\pm$ 2.6 <sup>Bc</sup>	8.9 $\pm$ 2.8 <sup>Aa</sup>	6.1 $\pm$ 1.5 <sup>Aa</sup>
0.4	70.1 $\pm$ 3.1 <sup>Cd</sup>	13.2 $\pm$ 2.3 <sup>Bb</sup>	7.3 $\pm$ 1.4 <sup>Aa</sup>
0.5	78.5 $\pm$ 2.8 <sup>Ce</sup>	20.7 $\pm$ 3.4 <sup>Bc</sup>	11.5 $\pm$ 1.5 <sup>Ab</sup>
1.0	85.2 $\pm$ 2.5 <sup>Df</sup>	73.8 $\pm$ 4.2 <sup>Cd</sup>	48.2 $\pm$ 3.7 <sup>Bc</sup>
1.5	89.2 $\pm$ 2.3 <sup>Cfg</sup>	85.5 $\pm$ 4.6 <sup>Ce</sup>	74.1 $\pm$ 3.9 <sup>Bd</sup>
2.0	92.7 $\pm$ 1.8 <sup>Cg</sup>	91.1 $\pm$ 2.2 <sup>Cf</sup>	86.4 $\pm$ 1.5 <sup>Be</sup>

Note: Data presented are means  $\pm$  SD ( $n = 3$ ).

Analysis was conducted row-wise (A-D) as well as column-wise (a-g) and superscripted by different alphabets to denote significant differences ( $P < 0.05$ , Duncan's new multiple range tests).

**Table 4** Summary of lipid yield (mg g<sup>-1</sup> of dry biomass) at different temperature with varying drum speed

Drum speed (rpm)	Drum surface temperature	Drum surface temperature	Drum surface temperature	Drum surface temperature
	<b>70 <math>\pm</math> 2 °C</b>	<b>80 <math>\pm</math> 2 °C</b>	<b>90 <math>\pm</math> 2 °C</b>	<b>100 <math>\pm</math> 2 °C</b>
0.1	72.1 $\pm$ 3.2 <sup>Ag</sup> (50.7)	130.6 $\pm$ 4.8 <sup>Be</sup> (91.9)	130.2 $\pm$ 1.5 <sup>Be</sup> (91.6)	128.5 $\pm$ 5.8 <sup>Be</sup> (90.4)
0.2	67.3 $\pm$ 1.8 <sup>Af</sup> (47.4)	130.9 $\pm$ 4.5 <sup>Be</sup> (92.1)	130.7 $\pm$ 4.5 <sup>Be</sup> (92.0)	128.3 $\pm$ 4.4 <sup>Be</sup> (90.3)
0.3	59.2 $\pm$ 2.6 <sup>Ae</sup> (41.7)	131.3 $\pm$ 3.1 <sup>Be</sup> (92.4)	131.0 $\pm$ 6.2 <sup>Be</sup> (92.2)	129.1 $\pm$ 6.3 <sup>Be</sup> (90.9)
0.4	54.1 $\pm$ 4.2 <sup>Ad</sup> (38.1)	123.1 $\pm$ 1.4 <sup>Bd</sup> (86.6)	132.2 $\pm$ 3.4 <sup>Be</sup> (93.0)	130.1 $\pm$ 4.8 <sup>Be</sup> (91.6)
0.5	51.4 $\pm$ 3.1 <sup>AcD</sup> (36.2)	94.2 $\pm$ 5.2 <sup>Bc</sup> (66.3)	124.1 $\pm$ 2.1 <sup>Cd</sup> (87.3)	133.3 $\pm$ 5.4 <sup>Be</sup> (93.8)
1.0	47.1 $\pm$ 2.4 <sup>Abc</sup> (33.1)	53.3 $\pm$ 2.5 <sup>Ab</sup> (37.5)	68.2 $\pm$ 2.2 <sup>Bc</sup> (48.0)	73.2 $\pm$ 6.6 <sup>Bb</sup> (51.5)
1.5	44.2 $\pm$ 1.9 <sup>Aab</sup> (31.1)	46.1 $\pm$ 2.1 <sup>Aa</sup> (32.4)	52.4 $\pm$ 2.9 <sup>Bb</sup> (36.9)	55.4 $\pm$ 5.7 <sup>Ba</sup> (39.0)
2.0	39.4 $\pm$ 2.1 <sup>Aa</sup> (27.7)	42.1 $\pm$ 2.8 <sup>ABa</sup> (29.6)	45.3 $\pm$ 1.1 <sup>BCa</sup> (31.9)	48.2 $\pm$ 3.3 <sup>Ca</sup> (33.9)

Note: Data presented are means  $\pm$  SD ( $n = 3$ ).

Analysis was conducted row-wise (A-C) as well as column-wise (a-g) and superscripted by different alphabets to denote significant differences ( $P < 0.05$ , Duncan's new multiple range tests).

Data in the parentheses present the % lipid recovery considering the lipid recovery from the bone-dried biomass as control, i.e., 100%.

**Table 5** Energy consumption at different temperature under various drum speed



Drum surface temperature	Drum speed (rpm)	Drying time/ kg dry biomass (h)	<sup>+</sup> Lipid recovery (%)
80 ± 2 °C	0.1	3.10	91.9
	0.2	1.93	92.1
	0.3	1.49	92.4
	0.4	1.31	86.6
	0.5	1.17	66.3
90 ± 2 °C	0.1	3.27	91.6
	0.2	2.10	92.0
	0.3	1.71	92.2
	0.4	1.52	93.0
	0.5	1.37	87.3
100 ± 2 °C	0.1	3.43	89.7
	0.2	2.27	90.3
	0.3	1.88	90.9
	0.4	1.68	91.6
	0.5	1.57	93.8

<sup>+</sup>Lipid recovery of bone-dried biomass was considered as 100%.

**Table 6** Comparative assessment of drying time, lipid recovery, and energy consumption of oven-dried and tray-dried with drum-dried biomass at 80 °C

Drying method	Drying time/ kg dry biomass (h)	Lipid recovery (%)	Energy consumption (kWh/ kg dry biomass)
Oven drying <sup>+</sup>	8.00	93.0	5.231
Tray drying <sup>++</sup>	6.00	93.0	11.227
Drum drying	1.49	92.4	7.328

<sup>+</sup>Bagchi et al. (2015), <sup>++</sup>Bagchi (2017)

## FIGURE LEGENDS

**FIGURE 1** Components of machine learning

**FIGURE 2** Steps employed for machine learning

**FIGURE 3** (A) Residual moisture content, (B) lipid yield, and (C) lipid recovery from *C. minutissimabiomass* at 70 °C in a single rotary drum dryer with variable speed.

Bone-dried biomass: Control

**FIGURE 4** (A) Residual moisture content, (B)lipid yield, and (C) lipid recovery from *C. minutissimabiomass* at 80 °C in a single rotary drum dryer with variable speed.

Bone-dried biomass: Control

**FIGURE 5** (A) Residual moisture content, (B)lipid yield, and (C) lipid recovery from *C. minutissimabiomass* at 90 °C in a single rotary drum dryer with variable speed.

Bone-dried biomass: Control

**FIGURE 6** (A) Residual moisture content, (B)lipid yield, and (C) lipid recovery from *C. minutissimabiomass* at 100 °C in a single rotary drum dryer with variable speed.

Bone-dried biomass: Control

**FIGURE 7 (A)** Distribution of raw data, **(B)** Division of data set using a decision boundary.

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Figure.pdf available at <https://authorea.com/users/369837/articles/488655-application-of-machine-learning-for-development-of-a-drying-protocol-for-microalga-chlorella-minutissima-in-a-single-rotary-drum-dryer-for-biodiesel-production>