Jurnal Serambi Engineering JSE
Volume XI, No.1, Januari 2026 Hal 17088 - 17099
p-ISSN : 2528-3561
e-ISSN : 2541-1934

Optimization of Drying Conditions of *Chlorella vulgaris* Using Tray Dryer for Biodiesel Feedstock

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Received: December 23, 2025 Approved: January 12, 2026

Abstract
Microalgae are one of the primary feedstocks for biodiesel production due to their high lipid content, ranging from 4–77% of dry weight. *Chlorella vulgaris* is considered a superior species with a lipid content of 5–40% based on dry weight. Drying microalgae into powder form has been developed to improve handling, storage, and application, including in biodiesel production. However, drying remains a major challenge, as inappropriate methods may cause lipid degradation due to high-temperature exposure. This study aims to dry *Chlorella vulgaris* using a tray dryer and to optimize its operating conditions through analysis of variance based on Response Surface Methodology (RSM). Based on the literature, no previous studies have used a tray dryer for drying Chlorella vulgaris. Optimization was conducted by varying drying temperature (55–75°C) and air velocity (1.5–1.7 m/s) to achieve the highest drying efficiency. The highest efficiency was achieved at 79°C and 1.6 m/s, reaching 99.99% with energy consumption of 603.17 kWh/kg. Meanwhile, RSM analysis showed that the optimum condition was at 75°C and 1.7 m/s, resulting in 99.89% efficiency with energy consumption of 693.97 kWh/kg. Drying at both 75°C and 79°C proved to be efficient and safe in preserving lipid compounds in microalgae.
Keywords: *microalgae, chlorella vulgaris, tray dryer, drying, drying efficiency*

Abstrak
Mikroalga merupakan salah satu bahan baku utama untuk produksi biodiesel karena kandungan lipidnya yang tinggi, berkisar antara 4–77% dari berat kering. Salah satunya adalah *Chlorella vulgaris* dengan kandungan lipid 5–40% berat kering. Pengeringan mikroalga menjadi bentuk bubuk telah dikembangkan untuk meningkatkan penanganan, penyimpanan, dan aplikasi, termasuk dalam produksi biodiesel. Namun, pengeringan tetap menjadi tantangan utama, karena metode yang tidak tepat dapat menyebabkan degradasi lipid akibat paparan suhu tinggi. Studi ini bertujuan untuk mengeringkan *Chlorella vulgaris* menggunakan *tray dryer* dan mengoptimalkan kondisi operasinya melalui analisis varians berdasarkan *Response Surface Methodology* (RSM). Berdasarkan literatur, belum ada penelitian sebelumnya yang menggunakan *tray dryer* untuk mengeringkan *Chlorella vulgaris*. Optimasi dilakukan dengan memvariasikan suhu pengeringan (55–75°C) dan kecepatan udara (1,5–1,7 m/s) untuk mencapai efisiensi pengeringan tertinggi. Efisiensi tertinggi dicapai pada suhu 79°C dan kecepatan 1,6 m/s, mencapai 99,99% dengan konsumsi energi 603,17 kWh/kg. Sementara itu, analisis RSM menunjukkan bahwa kondisi optimum berada pada suhu 75°C dan kecepatan 1,7 m/s, menghasilkan efisiensi 99,89% dengan konsumsi energi 693,97 kWh/kg. Pengeringan pada suhu 75°C dan 79°C terbukti efisien dan aman dalam mengawetkan senyawa lipid pada mikroalga.
Kata Kunci: *microalgae, Chlorella vulgaris, tray dryer, drying, drying efficiency*

1. Introduction

Microalgae are photosynthetic organisms offering a wide range of benefits and potential applications in food, health, cosmetics, the environment, and energy. Due to their high lipid content, ranging from 4–77%, microalgae have been extensively developed in recent decades as a sustainable energy alternative to replace fossil fuels [1]. Additionally, microalgae absorb CO_2 from the atmosphere through photosynthesis, suggesting that producing biodiesel from microalgae could help reduce greenhouse gas emissions. Furthermore, microalgae grow quickly, making them highly productive without requiring fertile land. They do not compete with food crops, and they can reach maturity in a short time, which makes them popular for biodiesel production [2]. One type of microalgae capable of producing relatively high lipid levels is *Chlorella vulgaris*, which can reach 5–40% lipid content by dry weight under optimal growth conditions [3].

However, harvested microalgal biomass typically contains a very high moisture content, ranging from 85–99%. This necessitates a drying stage before further extraction [4]. The drying process aims to reduce the moisture content to below 10% (wet basis) and plays a crucial role in the efficiency of lipid extraction, especially in solvent-based methods. A series of interrelated stages occurs during the drying process. First, heat is transferred from high-temperature air to the material's surface, causing its temperature to rise. Subsequently, the absorbed heat propagates into the interior of the material, triggering an increase in its internal temperature. The increased temperature causes the vapor pressure of water within the material to exceed the vapor pressure of the surrounding air. This pressure difference drives water vapor to move to the surface of the material through diffusion. The final stage of this process involves transferring water vapor from the material's surface to the surrounding air. This continues until equilibrium is reached between the material's water content and the air's humidity [5].

Several factors influence the drying rate of microalgae biomass, including drying temperature, air velocity, surface area, drying time, and relative humidity [6], [7]. Among these, drying temperature and air velocity play the most significant roles. Higher temperatures can increase the evaporation rate by enhancing vapor pressure gradients and opening material pores, thereby accelerating moisture removal [8]. Meanwhile, increased air velocity improves heat and mass transfer rates but may cause case hardening if excessive [9]. These two parameters are therefore critical and were selected for optimization in this study. High water content can hinder solvent diffusion and decrease lipid yield. Therefore, drying is an essential step to maximize contact between the solvent and lipids. Drying also enhances storage stability and ease of handling. However, improper drying methods can cause lipid degradation. Selecting an appropriate drying method is therefore essential for maintaining biomass quality and improving process efficiency.

In this study, a tray dryer was used to dry the microalgae *Chlorella vulgaris*. This dryer was chosen because it is simple to operate, has relatively low energy consumption compared to a spray dryer, has a shorter drying time than a freeze dryer, and offers more consistent operating conditions than a solar dryer, which depends on sunlight intensity [10]. Drying *Spirulina platensis* using a tray dryer resulted in minimal changes to its fatty acid composition, with oleic acid increasing from 3.10% to 3.20% and stearic acid from 2.89% to 2.90% [11].

This study focuses on optimizing the operating conditions of the tray dryer — namely, temperature and air velocity — to achieve maximum drying efficiency without compromising microalgae quality. Dewatering efficiency quantitatively describes how effectively the drying process reduces the moisture content of microalgae biomass. It is a key indicator for evaluating dryer performance, as it directly reflects the process's ability to remove water content from the biomass.

Drying *Scenedesmus quadricauda* with a tray dryer at 48°C and an air velocity of 4 m/s for six hours resulted in a moisture content of up to 7.17% [12]. Meanwhile, drying *Tetradesmus obliquus* using a tray dryer at 80°C for six hours produced a final moisture content of 10% [4]. In addition, the optimal temperature for drying *Chlorella vulgaris* has been identified in the range of 75–80°C, which balances drying efficiency and the preservation of bioactive compounds, as demonstrated through differential scanning calorimetry (DSC) and thermogravimetry (TGA) analyses [13].

However, studies specifically examining tray drying of *C. vulgaris* are still lacking, leaving its optimal operating conditions unknown. Therefore, this study aims to optimize the drying process of *C. vulgaris* using a tray dryer with temperature variations ranging from 55 to 75°C and air speeds ranging from 1.5 to 1.7 m/s. These ranges were selected based on equipment limitations and operational feasibility to achieve high drying efficiency while maintaining lipid quality.

2. Material and Methods

This research consists of several stages, including pre-treatment (centrifugation and flocculation), initial moisture content determination, and drying. The best pre-treatment result will be used for the next stage, which is drying using a tray dryer. The equipment, materials, and methods used are explained below

Tools And Materials

The main equipment used for microalgae drying is the Tray Dryer Aparatus 230 Vac 50 Hz single-phase – 3.1 kVA (dimensions: 1830 × 800 × 1700 mm) as shown as **Fig.1**. A thermo-hygrometer and an anemometer were used to measure temperature and air velocity. The materials used were Chlorella vulgaris microalgae and liquid NaOH with a concentration of 50% (w/v).

Figure 1: Tray dryer aparatus

Experimental Design Using Response Surface Methodology (RSM)

Drying of microalgae using a tray dryer was carried out after the pre-treatment and initial moisture content determination stages. The drying process of *Chlorella vulgaris* microalgae was conducted using a tray dryer with temperature variations ranging from 55 to 75°C and air velocity variations ranging from 1.5 to 1.7 m/s. The experimental design in this study was developed using Response Surface Methodology (RSM) based on a Central Composite Design (CCD) to evaluate and optimize the effects of temperature and air velocity as independent variables on drying efficiency (moisture content percentage) as the response function. The experimental design generated using RSM in Design Expert V13 is presented in **Table 1**.

Table 1. Experimental design

Run	Drying Temperature (°C)	Air Velocity (m/s)
1	65	1.6
2	65	1.6
3	65	1.6
4	55	1.7
5	75	1.5
6	75	1.7
7	65	1.6
8	65	1.6
9	79	1.6
10	65	1.75
11	65	1.45
12	55	1.5
13	51	1.6

Pre-Treatment

The pre-treatment process was carried out to convert liquid Chlorella vulgaris into a slurry in order to improve the efficiency of the drying process. Two methods were used for pre-treatment: centrifugation and flocculation using NaOH solution. The most suitable method was selected based on technical considerations and energy requirements during the pre-treatment process.

Centrifuge

Centrifugation pre-treatment was carried out on 500 mL of Chlorella vulgaris suspension. The centrifugation process was conducted at 4000 rpm for 20 minutes to separate the biomass from the liquid medium. After the process was completed, the supernatant at the top of the tube was carefully removed by decantation. The microalgal biomass that had settled at the bottom was collected in the form of slurry using a spatula.

Flocculation

Flocculation pre-treatment was performed on 1000 mL of Chlorella vulgaris suspension. A 50% NaOH solution was gradually added to the suspension until the pH reached approximately 12. After the addition of the flocculant, the mixture was stirred using a magnetic stirrer for 15 minutes to ensure uniform distribution of NaOH throughout the system. The suspension was then left undisturbed for 3 hours to allow the formation of flocs and the separation of microalgal biomass from the supernatant. The supernatant was carefully removed by decantation. The remaining biomass was filtered using a Buchner funnel under vacuum to further separate residual water.

Initial Moisture Content Determination

Determination of dry weight was carried out to obtain the initial moisture content of Chlorella vulgaris microalgae following the flocculation pre-treatment, prior to the drying process using a tray dryer. This moisture content data was used to assess the amount of water remaining after the flocculation process and served as a baseline for comparison with the post-drying condition.

The analysis was performed using the gravimetric method. In this process, the microalgae slurry was evenly distributed in a petri dish (80 mm diameter × 15 mm height), then dried in an oven at 103°C until a constant weight was reached. During drying, the sample was periodically removed from the oven every 30 minutes, cooled in a desiccator, and weighed to monitor the gradual decrease in mass. Once the weight began to stabilize, the weighing interval was shortened to every 20 to 10 minutes. The process continued until the sample reached a constant weight, indicating that all moisture had evaporated. The initial moisture content (MC) of the microalgae slurry was then calculated using the following equation.

$$\text{Initial MC } (X_1) = \frac{W_0 - W_1}{W_0} \text{ x } 100\% \ldots (1)$$

W_0 = initial wet weight of microalgae slurry (g), W_1= dry weight of microalgae after drying (g).

Drying Process Using Tray Dryer

Drying of Chlorella vulgaris microalgae was carried out using a tray dryer with temperature and air velocity variations determined through the Response Surface Methodology (RSM). Prior to drying, the microalgae slurry sample was weighed using an analytical balance to determine its initial mass. The sample was then evenly spread in a petri dish with an inner diameter of 80 mm and a height of 15 mm, forming a uniform layer with a thickness of 5 mm.

The drying process was conducted at an ambient relative humidity (RH) range of 55–65%. The tray dryer used had three levels (**Figure 2**), and the sample was placed on the second (middle) tray. The petri dish was supported on an aluminum tray with dimensions of 39.9 cm × 29.3 cm × 0.7 cm.

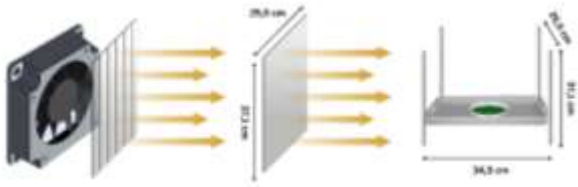

Figure 2. Illustration of microalgae drying using a tray dryer

During drying, sample weighing was carried out outside the equipment using an analytical balance. Weighing was initially performed every 30 minutes, then reduced to 20 minutes and 10 minutes as the drying rate slowed. The drying process was considered complete when the sample mass remained constant for three consecutive measurements. After the drying process was completed, the moisture reduction was calculated using Equation (2) below.

$$\text{Moisture Reduction during Tray Drying } (X_2) = \frac{W_{0-td} - W_{1-td}}{W_{0-td}} \text{ x } 100\% \ldots (2)$$

With W_{0-td} = initial wet weight of microalgae slurry (g), W_{1-td} = weight after the tray drying process (g). Then, the final moisture content of the microalgae after drying was determined using Equation (3) below.

$$\text{Final Moisture Content after Tray Drying } (X_3) = X_1 - X_2 \ldots (3)$$

With X1= initial moisture content before drying (%) and X2 = moisture loss during tray drying (%). After that, the drying efficiency was calculated using Equation (4) below.

$$\text{Drying Efficiency}(\%) = \frac{X_1 - X_3}{X_1} \text{ x } 100\% \ldots .(4)$$

With X1= Initial moisture content before drying (%) and X3 = Final moisture content after tray drying (%).

Calculation Of Energy Consumption In Pre-Treatment And Drying

Energy consumption was calculated for both the pretreatment and drying stages to support the evaluation of overall process efficiency. In the pretreatment stage, energy consumption was determined to compare the energy requirements between flocculation and centrifugation methods. The energy consumption for each pretreatment method was calculated using Equation (5) below.

$$\text{Energy Consumption (E)} = \text{P} \times \text{t} \ldots (5)$$

With t = operating time (hours) and P = power of equipment used (kW).

In the drying stage, energy consumption was calculated based on the electrical power used by the heater and blower in the tray dryer, as well as the total drying time. The energy required to dry one kilogram of microalgae was calculated using Equation (6) below.

$$\text{Energy Consumption}(\text{E}_{\text{total}}) = \frac{(\text{P}_{\text{blower}} + P_{heater}) \times \text{t}}{\text{m}} \ldots (6)$$

With E_{total} = energy consumption of the blower and heater during drying (kWh/kg), t = drying operation time (hours), P_{blower} = power of the blower during the process (kW), P_{heater} = power of the heater during the process (kW), and m = initial mass of microalgae slurry (kg).

3. Results and Discussion

This section presents the results of each experimental stage, including the evaluation of pre-treatment methods (centrifugation and flocculation), initial moisture content determination, and drying of *Chlorella vulgaris* using a tray dryer. The effects of drying temperature and air velocity on drying efficiency are analyzed, followed by statistical optimization using Response Surface Methodology (RSM) to determine the optimum conditions.

Pre-Treatment Analysis Of Chlorella Vulgaris Slurry Preparation

Two pre-treatment methods were evaluated to convert liquid *Chlorella vulgaris* into slurry prior to drying: centrifugation and flocculation using NaOH. Centrifugation was performed at 4000 rpm for 20 minutes, resulting in a dense microalgal slurry settled at the bottom of the tube. Although this method effectively separated biomass from the liquid medium, it consumed relatively high energy (0.4 kWh per 500 mL) and posed operational difficulties due to slurry adhesion on the inner wall of the centrifuge tube, making recovery laborious and inefficient.

In contrast, flocculation was carried out by raising the culture medium's pH to 12 using NaOH, followed by gentle stirring and gravitational sedimentation for 2–3 hours. The supernatant was partially removed, and the remaining suspension was filtered using a Buchner funnel to obtain a concentrated green slurry with a moisture content ranging from 82% to 89%, depending on filtration time. This method required only 0.255 kWh per 1000 mL and allowed for supernatant reuse after pH neutralization, improving the sustainability of the process.

Compared to centrifugation, NaOH-based flocculation demonstrated better operational practicality, lower energy consumption, and easier scalability. Post-flocculation drying required only 140–280 minutes, which is considerably faster than the 360 minutes reported by Anyanwu et al. [12] for drying *Scenedesmus quadricauda* without any pre-treatment. Moreover, drying efficiencies ranged from 97.99% to 99.99%. Literature has also confirmed that NaOH flocculation does not significantly affect lipid content in microalgae [14], further supporting its use as a gentle and effective pre-treatment. Therefore, NaOH flocculation was selected for this study as the preferred strategy for preparing *C. vulgaris* slurry before tray drying.

Moisture Content and Drying Performance

The initial moisture content of the Chlorella vulgaris slurry was determined prior to the drying process using a tray dryer. This measurement served as the baseline to evaluate the effectiveness of the drying process by quantifying the remaining moisture after pre-treatment with NaOH-induced flocculation. The analysis was conducted using a gravimetric method based on weight difference before and after drying in a hot air oven.

A known mass of slurry was evenly spread in an 80 mm × 15 mm Petri dish and dried in an oven at 103 °C until a constant weight was achieved. The drying temperature followed the standard bone-drying principle to ensure complete removal of moisture from the biomass, as described by Bagchi et al. [4]. During the drying process, the sample was periodically removed every 30 minutes for cooling in a desiccator and reweighing. As the weight approached stability, the measurement interval was reduced to every 20 and then 10 minutes to detect the final drying point with higher accuracy.

The final constant weight was recorded as the dry weight, and the initial moisture content was calculated based on the difference between wet and dry mass. The results are summarized in Table 2, showing the initial moisture content values of the microalgal slurry obtained after flocculation pre-treatment. These values serve as a reference point for analyzing the drying efficiency in subsequent experiments using the tray dryer.

The prepared slurry of Chlorella vulgaris microalgae for tray drying is shown in **Figure 3**, exhibiting a thick texture and a deep green coloration. Following the drying process, as detailed in **Figure 4**, distinct physical changes were observed on the surface of the biomass—specifically, the appearance of cracks on the dried Chlorella vulgaris microalgae. These surface cracks are attributed to the release of bound water during the drying process Bound water is a type of water present in a material, where its vapor pressure is lower than that of pure water at the same temperature. This water is held within the material through physical and chemical bonds [15].

Table 2. Initial moisture content of Chlorella vulgaris slurry after oven drying

Run	Temp. (°C)	Drying Time (menit)	Initial Moisture Content (%wb)
1	103	110	86.47
2	103	120	88.65
3	103	80	83.77
4	103	80	87.14
5	103	80	85.93
6	103	70	85.85
7	103	110	86.75
8	103	80	82.92
9	103	120	85.93
10	103	120	86.01
11	103	110	85.64
12	103	80	87.25
13	103	110	89.65

Figure 3. Chlorella vulgaris microalgae before tray drying

Upon cracking and complete drying, the microalgal biomass typically exhibits a brittle texture, which facilitates the subsequent step of mechanical disruption or grinding into microalgal powder. The dried microalgae are then suitable for lipid extraction. The cracked and optimally dried cell structure promotes lipid release during extraction by increasing surface area and weakening the mechanically resistant cell walls. Furthermore, drying provides advantages in terms of storage stability, as dried biomass is more stable and has a longer shelf life. This is particularly beneficial when immediate lipid extraction is not feasible

following biomass production. In addition to the formation of cracks, visual observation also indicated that no significant color change occurred during the drying process. The dominant green hue of the initial slurry remained consistent across all runs in the final dried products.

Figure 4. Chlorella vulgaris microalgae after tray drying

Table 3 presents the moisture content of Chlorella vulgaris microalgae prior to and following the drying process conducted using a tray dryer.

Table 3. Drying efficiency data using tray dryer for each run

Run	Drying Temp. (°C)	Air Velocity (m/s)	X1 (%wb)	X3 (%wb)	Drying Efficiency (%)
1	65	1.60	86.47	0.43	99.50
2	65	1.60	88.65	0.44	99.50
3	65	1.60	83.77	0.41	99.51
4	55	1.70	87,14	1.09	98.75
5	75	1.50	85.93	0.12	99.86
6	75	1.70	85.85	0.08	99.91
7	65	1.60	86.75	0.42	99.52
8	65	1.60	82.92	0.37	99.55
9	79	1.6	85.93	0.01	99.99
10	65	1.75	86.01	0.30	99.65
11	65	1.45	85.64	0.59	99.31
12	55	1.50	87.25	1.27	98.54
13	51	1.60	89.65	1.80	97.99

Based on the data presented in **Table 3**, the drying process of Chlorella vulgaris microalgae using a tray dryer demonstrated highly effective results, with final moisture contents ranging from 0.08% to 1.80%, reduced from initial moisture levels of 82.92% to 89.65%. The drying efficiency across all runs was remarkably high, ranging between 97.99% and 99.99%. The highest efficiency was observed in run 9, reaching 99.99%, under operating conditions of 79°C and an air velocity of 1.6 m/s. These results indicate that all combinations of operating parameters successfully achieved efficient drying, and the tray dryer performed consistently in reducing the moisture content of the microalgae.

The extremely low final moisture contents suggest that the drying processes conducted fall within the category of complete drying. Although several studies, such as those by Bagchi et al. [16] and Karmakar et al. [13], recommend a moisture content of approximately 10% (wet basis) as an energy-efficient threshold for lipid extraction, achieving lower moisture levels still offers specific advantages. In particular, low moisture contents contribute to extended storage stability by inhibiting microbial growth and slowing lipid degradation. Moreover, thoroughly dried biomass is easier to handle, weigh, and store, with minimal requirements for humidity control.

Table 4 presents the air conditions inside the tray dryer as well as the specific energy consumption recorded in each run throughout the drying process. Each drying run had a different duration, depending on the operating conditions applied. Based on the observations in this study, an increase in temperature and air velocity tended to accelerate the attainment of equilibrium conditions, indicated by the point at which the weight of the microalgae no longer changed. This equilibrium state occurs when the moisture content within the microalgae becomes balanced with the humidity of the surrounding drying air, resulting in no

further evaporation of water. This indicates that temperature and air velocity play a crucial role in accelerating the water evaporation process until equilibrium is reached.

Table 4. Air conditions, time, and energy consumption data during drying using tray dryer for each run

Run	Tray Dryer Air RH (%)	Drying Time (min.)	Drying Efficiency (%)	Energy (kWh/kg)
1	13.2-15.6	180	99.50	400.91
2	13.1-15.2	190	99.50	400.50
3	12.9-15.5	190	99.51	481.59
4	17.6-21.3	240	98.75	338.91
5	8.8-9.9	170	99.86	694.38
6	8.8-9.9	160	99.91	693.97
7	13-15.5	180	99.52	404.52
8	13.1-16.3	180	99.55	453.38
9	8.1-9	140	99.99	603.17
10	9.9-11	190	99.65	665.53
11	12.3-15.7	210	99.31	391.89
12	12.8-16.1	280	98.54	277.55
13	19.3-23	280	97.99	310.58

The energy consumption during the drying of Chlorella vulgaris microalgae showed a wide range of values, from 277.55 to 694.38 kWh/kg. This variation was influenced by the operating conditions namely, temperature and air velocity—as well as the actual drying time required for the sample weight to reach a constant value. In addition, the sample mass used during drying also affected the amount of energy consumed.

The highest energy consumption was recorded in run 5 at 694.38 kWh/kg, which employed a high temperature of 75°C, an air velocity of 1.6 m/s, and a drying efficiency of 99.86%. Although the drying time was relatively short compared to other runs (170 minutes), the combination of high temperature and air velocity significantly increased the energy consumption. In contrast, the lowest energy consumption was observed in run 12 at 277.55 kWh/kg, which used the lowest temperature of 55°C, an air velocity of 1.5 m/s, and a drying efficiency of 98.54%, with a relatively long drying time of 280 minutes. These results indicate that achieving high drying efficiency often requires greater energy consumption, particularly when high temperature and air velocity are involved.

Evaluation of the Effect of Temperature and Air Velocity on Drying Using RSM

The analysis obtained from the Analysis of Variance (ANOVA) was conducted to evaluate the significance of the influence of operating conditions, namely temperature and air velocity, on the drying efficiency of Chlorella vulgaris microalgae using a tray dryer. The results of this analysis are presented in **Table 5**, which shows the effect of each variable on the drying efficiency of Chlorella vulgaris microalgae.

Table 5. ANOVA results of the cubic model for drying efficiency

Analysis of Variance (ANOVA)					
Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-Value**
Model	4.08	7	0.5823	720.15	< 0.0001
A-Temp.	2.00	1	2.00	2473.55	< 0.0001
B-Air Vel.	0.0578	1	0.0578	71.49	0.0004
AB	0.0064	1	0.0064	7.92	0.0374
A2	0.4514	1	0.4514	558.23	< 0.0001
B2	0.0007	1	0.0007	0.9152	0.3827
A2B	0.0049	1	0.0049	6.12	0.0563
AB2	0.0176	1	0.0176	21.77	0.0055
Residual	0.0040	5	0.0008		
Lack of Fit	0.0023	1	0.0023	5.40	0.0808
Pure Error	0.0017	4	0.0004		
Cor **Total**	4.08	12			

The ANOVA model is considered statistically significant when the p-value is less than the significance level ($\alpha < 0.05$). The p-value is related to the magnitude of the F-value; the larger the F-value, the smaller the p-value. This indicates that the model can adequately explain the variation in the experimental data. Based on the ANOVA results for the reduced cubic model, the model demonstrates high statistical significance with an F-value of 720.15 and a p-value of < 0.0001, indicating that it validly represents the relationship between the independent variables and drying efficiency. The factors of temperature (A) and air velocity (B) were found to have significant effects on drying efficiency, with p-values of < 0.0001 and 0.0004, respectively. The AB interaction and the quadratic interaction term AB^2 also showed significant effects, while A^2 exhibited a strong nonlinear relationship with the response. On the other hand, the quadratic effect of B^2 and the interaction term A^2B were not significant within the tested operating conditions.

This indicates that within the applied operating range, the nonlinear effect of air velocity and its interaction with A^2 did not have a significant influence on the drying efficiency. The non-significant lack of fit ($p = 0.0808$) and the low pure error value indicate that the obtained model has a good fit to the experimental data and is capable of accurately modeling the drying process of Chlorella vulgaris. From the analysis, the mathematical model used is a reduced cubic model. "Reduced cubic" refers to a cubic model (containing third-order and interaction terms) that only includes variables found to be statistically significant based on ANOVA results. The actual equation obtained is presented below.

$$\text{Drying efficiency (\%)} = 265.08811 - (2.94610 \times \text{temperature}) - (209.79208 \times \text{air velocity}) + (3.60548 \times \text{temperature} \times \text{air velocity}) + (0.005137 \times \text{temperature}^2) + (60.34518 \times \text{air velocity}^2) - (0.004833 \times \text{temperature}^2 \times \text{air velocity}) - (0.942857 \times \text{temperature} \times \text{air velocity}^2) \ldots (7)$$

The R^2 value of 0.9990 indicates that the model explains 99.90% of the variation in drying efficiency. The adjusted R^2 of 0.9976 suggests that the model remains accurate even after accounting for the number of variables. The predicted R^2 of 0.9624, with a difference of 0.0352 from the adjusted R^2, falls within an acceptable range (<0.2), indicating strong predictive capability without overfitting. An adequate precision value of 89.6606 greatly exceeds the minimum required value of 4, demonstrating an excellent signal-to-noise ratio. The standard deviation of 0.0284 and the coefficient of variation (CV) of 0.0286% reflect an extremely low data dispersion, with an average value of 99.35%. The CV being well below 10% indicates that the experimental data are highly precise and reliable.

ANOVA was used to analyze the significance of each variable and their interactions in influencing the drying efficiency. The interaction between temperature and air velocity on the drying efficiency is illustrated in **Figures 5** and **6** below.

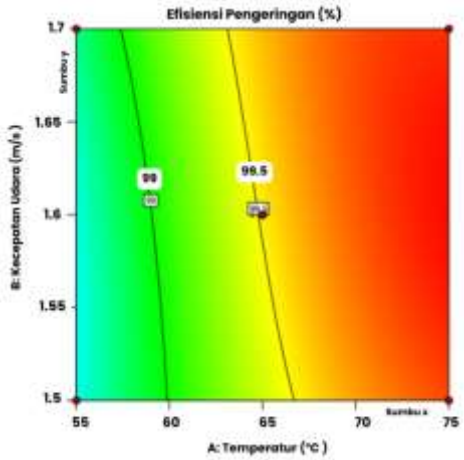

Figure 5. Contour plot of temperature and air velocity on drying efficiency

From the experimental results visualized through contour and surface plots, it can be concluded that temperature and air velocity parameters significantly affect drying efficiency. The red areas represent higher drying efficiency values, while the blue areas represent lower ones. In Figures 5 and 6, as the temperature increases (towards the right), the drying efficiency also increases, with the highest temperature

being 75°C. It can be observed that the higher the temperature, the contour colors shift from blue to red, indicating improved drying efficiency.

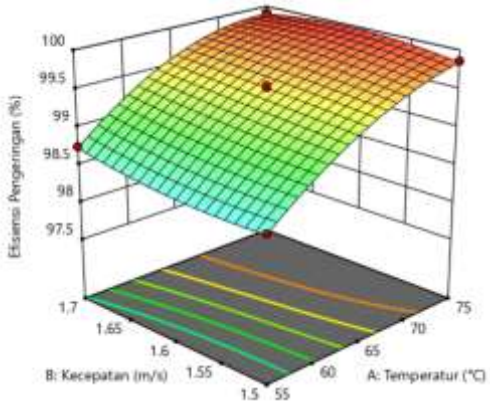

Figure 6. Surface plot of temperature and air velocity on drying efficiency

Similarly, increasing the air velocity (upwards) also leads to an increase in drying efficiency, with the highest air velocity being 1.7 m/s. Although the color change along the air velocity axis is less prominent, it still indicates a trend of increasing efficiency with higher air velocity.

The results show that temperature has a more dominant effect on drying efficiency compared to air velocity. This is evidenced by the predominantly vertical contour plot, which indicates that efficiency is more sensitive to changes in temperature. The transition of colors from blue to red with increasing temperature supports this finding. Meanwhile, the relatively narrow color change along the air velocity axis suggests a smaller effect. This finding is in line with the study by Anyanwu et al. [12], which states that temperature is the primary factor in microalgae drying.

Model Validation Using Experimental Verification Point

To assess the reliability of the developed model, experimental verification was performed by testing a new operational condition that was not included in the model fitting process. This validation step ensures that the model not only meets statistical criteria but also accurately represents real system behavior. A trial run was conducted at a randomly selected point within the experimental range, specifically at a drying temperature of 70°C and air velocity of 1.5 m/s. The predicted drying efficiency at this point was calculated using the actual polynomial model (Equation 7), and the result was then compared to the drying efficiency obtained through direct experiment. The comparison is presented in **Table 6**.

Table 6. Model validation using experimental verification point

Temp. (°C)	Air Velocity (m/s)	Predicted Drying Efficiency (%)	Experimental Drying Efficiency (%)	Error (%)
70	1.5	99.67	99.75	0.08

The result shows that the prediction error was only 0.08%, which falls well below the acceptable threshold of 5%. This indicates that the model has a high degree of accuracy and is reliable for predicting drying efficiency within the tested range of conditions. Thus, the polynomial model can be considered robust for representing the tray drying process of Chlorella vulgaris.

Optimal Operating Conditions for Tray Drying Chlorella Vulgaris

The optimum drying condition for Chlorella vulgaris slurry was determined based on the response surface model developed using Central Composite Design (CCD). The analysis considered the effects of two independent variables—drying temperature and air velocity—on drying efficiency. The RSM model identified 75 °C and 1.7 m/s as the optimal drying condition within the experimental design range, yielding a predicted drying efficiency of 99.89% with a desirability value of 1.000. The recommended condition is shown in **Table 7**.

Table 7. Recommended operating condition for tray-drying Chlorella vulgaris

Temp. (°C)	Air Velocity (m/s)	Drying Efficiency (%)	Desirability	Specific Energy (kWh/kg)
75	1.7	99.89	1.000	693.97

However, experimental results showed that a drying temperature of 79 °C and air velocity of 1.6 m/s—slightly outside the RSM design range—produced an even higher drying efficiency of 99.99%. This suggests that while the RSM provides a statistically optimized condition within the experimental bounds, the actual best performance may occur slightly beyond that range. Thus, 79 °C and 1.6 m/s may be considered the best experimental condition, even though the model formally recommends 75 °C and 1.7 m/s.

The specific energy required at the RSM-predicted optimum was relatively high, at 693.97 kWh/kg. In contrast, the best experimental condition required only 603.17 kWh/kg. This highlights the trade-off between drying efficiency and energy consumption: achieving higher efficiency typically demands greater energy input. Therefore, practical optimization must also consider energy economy in addition to statistical desirability.

Sample geometry also played a role in drying performance. In this study, slurry was dried in thin layers of 5 mm thickness, placed in an 80 mm Petri dish (25.1 cm^3), which contributed to uniform heating and high drying efficiency. In contrast, Anyanwu et al. dried 800 cm^3 of Scenedesmus quadricauda on four trays and achieved only 92.83% efficiency at 48 °C and 4 m/s. Although their energy consumption was lower (0.34 kWh/kg), the initial moisture content (99.35%) and sample volume were much higher than in the present study.

Thermal analysis by Karmakar et al. [13] showed that C. vulgaris lost moisture most efficiently at 75–80 °C, aligning with the recommended range. Bagchi et al. [4] further found that lipid degradation occurred when drying Tetradesmus obliquus at 100 °C, whereas drying at 80 °C preserved lipid content. These findings confirm that operating in the 75–80 °C range is both efficient and safe for bioactive compound retention.

4. Conclusion

This study investigated the optimization of *Chlorella vulgaris* drying using a tray dryer, with temperature and air velocity as the main operating parameters. A pre-treatment method using NaOH-based flocculation successfully reduced the initial moisture content to 82.92–89.65%, producing a slurry with better handling characteristics and requiring lower energy input (0.255 kW).

Experimental results showed that both drying temperature and air velocity significantly influenced the drying efficiency. The highest drying efficiency, 99.99%, was achieved at 79°C and 1.6 m/s, indicating that higher values of these parameters improve water removal while preserving microalgal quality. Response Surface Methodology (RSM) analysis revealed that temperature had a more dominant effect on drying efficiency compared to air velocity.

The optimal drying condition determined through RSM was found at 75°C and 1.7 m/s, achieving a drying efficiency of 99.89%. These conditions offer a balance between effective moisture reduction and the preservation of key microalgal compounds such as lipids and bioactives, making them suitable for downstream applications like biodiesel production.

5. References

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