Optimization of dehumidified cold air drying process on antioxidant activity and physicochemical properties of marungga leaf powder (*Moringa oleifera*) using response surface methodology

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Abstract. Moringa leaves contain valuable antioxidant-rich bioactive compounds, yet these compounds are easily degraded by heat during drying. This study aimed to optimize a low-temperature drying method using dehumidified cold air to better preserve antioxidant stability while improving the physicochemical quality of moringa leaf powder. Optimization was performed using Response Surface Methodology with a Central Composite Design, involving two variables—drying temperature (35–45 °C) and time (4–6 hours). The responses evaluated included moisture content, yield, antioxidant activity, total flavonoids, protein content, solubility, and color. The model predicted optimal conditions at 37.75 °C for 4 hours, yielding moisture content of 10.418%, yield of 31.192%, antioxidant activity of 88.321%, total flavonoids of 44.281 mg GAE/g extract, protein content of 25.44%, solubility of 14.7%, and color value (a*) of 52.00 with SMER value of 0.73 kg/kWh. Both temperature and duration significantly affected most parameters ($p < 0.05$). The findings indicate that dehumidified cold air drying effectively maintains phytochemical stability and enhances the functional quality of moringa leaf powder, offering a promising approach for processing heat-sensitive plant materials.

1 Introduction

The Marungga plant (*Moringa oleifera*), widely known as the “miracle tree,” has gained global attention due to its high nutritional content and numerous health benefits. This plant is a rich source of essential nutrients such as proteins, vitamins, and minerals, and contains important secondary metabolites particularly polyphenols, flavonoids, carotenoids, tocopherols, and ascorbic acid that contribute to its biological activities [1][2]. Numerous studies have confirmed that Marungga leaves possess pharmacological activities, including antidiabetic [3], antiinflammatory [4], antioxidant [5], cardioprotective [6], hypocholesterolemic [7], hepatoprotective [8], antihypertensive [9], and antibacterial effects [10]. Scientific evidence from both *in vitro* and *in vivo* studies further highlights Marungga's potential as a natural source of bioactive compounds with broad health benefits, supporting its use as a raw material in functional food, nutraceutical, and pharmaceutical industries [11]. Nevertheless, a key challenge lies in maintaining the stability of these phytonutrients during postharvest processing, particularly during the drying stage.

The drying process serves to reduce moisture content, extend shelf life, and facilitate the handling and formulation of products such as marungga flour. However, improper drying conditions can lead to the degradation of thermolabile compounds, thereby reducing the quality of the final product [12]. The use of high temperatures (70–80 °C) has been shown to significantly reduce phenolic and flavonoid contents by 35–50% [13] and decrease vitamin C from 27.39 mg/100 g (shade drying) to 24.00 mg/100 g at 80 °C [14]. Antioxidant activity (DPPH scavenging) also declined from 77.79% to 60–65% within the same temperature range [15]. Visually, high temperatures cause the leaves to darken due to chlorophyll degradation, leading to reduced sensory quality and consumer acceptability [16]. Conversely, drying at low temperatures can preserve bioactive compounds and natural color but requires longer drying times and higher energy consumption, making it less practical and efficient [17].

As an alternative to conventional drying methods, dehumidified cold air drying technology offers a more efficient approach to preserving the stability of bioactive compounds while improving the physicochemical characteristics of the material. This system uses air that is first dehumidified to lower its absolute humidity, while maintaining the humidity gradient between the drying air and the material surface even at low temperatures [18]. Such conditions allow the drying process to proceed optimally without causing degradation of heat sensitive bioactive components such as β-carotene, flavonoids, phenolics, and vitamin C [19]. Preliminary tests have shown that this system can reduce absolute humidity to 1.6 g H_2O/kg dry air with a drying rate of 0.57 kg/h [20].

To achieve optimal drying results, it is necessary to optimize the drying temperature and duration in relation to the quality parameters of marungga leaf powder, particularly its antioxidant activity and physicochemical properties. Therefore, this study aimed to determine the optimal combination of temperature and drying time using the Response Surface Methodology (RSM) approach and to develop a predictive model capable of describing the relationship between process variables and key quality parameters, including moisture content, yield, antioxidant activity, flavonoids, protein, solubility, and color of marungga leaf powder.

2 Materials and Methods

2.1 Sample Preparation and Analysis of Raw Materials

Fresh marungga leaves were obtained from the Antirogo area in Jember, then sorted to separate the leaves from the stems and ensure uniform size. The leaves were washed under running water, dried to remove surface moisture, weighed to 750 g, and divided into three trays (250 g each). The raw materials undergo preliminary analysis of moisture content, antioxidant activity, flavonoid content, protein content, solubility, and color to determine the initial characteristics of the product.

2.2 Research Design

This study employed the Response Surface Methodology (RSM) with a Central Composite Design (CCD) using Design-Expert 13 software (Stat-Ease Inc., Minneapolis, USA). Two independent variables were defined: drying temperature (30–40 °C) and drying time (4–6 hours), while the response parameters observed included moisture content, yield, antioxidant activity, total flavonoid content, protein content, solubility, and the color of marungga leaf powder. The use of RSM offers advantages as it can evaluate the simultaneous effects of multiple process variables, identify factor interactions with a minimal number of experimental runs, and generate predictive mathematical models [21].

2.3 Drying Process and Analysis

The drying process was carried out using a fluidized-bed dryer with dehumidified cold air flow, which operates by reducing the absolute humidity of the air through dehumidification before it is directed into the drying chamber. An illustration of dehumidified cold air drying technology can be seen in Figure 1.

Fig. 1. Dehumidified cold air drying technology for drying marungga leaves

The dehumidified cold-air dryer used in this study was designed to provide low-temperature airflow with controlled humidity to ensure stable drying conditions. The technical specifications of the main components of the dryer are presented in Table 1.

Table 1. Specifications of the Dehumidifier Drying Machine

Component	Specification		
Drying Chamber Cylinder	Material	:	Stainless steel
	Diameter	:	600 mm
	Height	:	1000 mm
	Thickness	:	5 mm
Compressor	Power	:	1 HP
	Voltage	:	220 V
	Refrigerant	:	R22
Condenser	Type	:	TCM 100
	Power	:	1 HP
	Length	:	458 mm
	Width	:	121 mm
	Height	:	330 mm
Coils before Condenser	Length	:	4000 mm
	Diameter	:	0.5 inch
	Material	:	Copper
Condenser Fan	Speed	:	1300/1500 RPM
	Power	:	12–53 Watt

Component	**Specification**		
	Voltage	:	230 V
	Current	:	0.34 A
	Frequency	:	50/60 Hz
Evaporator	1 HP, 2-row custom		
Suction Blower	Airflow Capacity	:	1140 m^3/h
	Speed	:	2800 RPM
	Pressure	:	1980 Pa
	Power	:	550 Watt / 0.55 kW
	Voltage	:	220 V, 1 phase
	Frequency	:	50 Hz

After drying according to the treatment conditions, the dried leaves were cooled, ground using a hammer mill, and sieved through a 60-mesh screen to obtain fine powder. The powder was then stored in airtight containers prior to analysis. Flour quality analysis is conducted based on key parameters. Moisture content is determined using the oven method at a temperature of 105°C until a constant weight is achieved [7]. The value is calculated using the following formula:

$$Water\ content\ \% = \frac{W_1-W_2}{W_1-W_0}\ x\ 100\% \dots\dots\dots\dots (1)$$

Where W_0 = weight of the empty dish (g), W_1 = weight of the dish + sample before drying (g), and W_2 = weight of the dish + sample after drying (g).

Antioxidant activity was measured using the DPPH method at a wavelength of 517 nm [9]. The percentage of inhibition was calculated as:

$$\%\ inhibisi = \frac{A_0-A_s}{A_0}\ x\ 100\% \dots\dots\dots\dots (2)$$

where A_0= control absorbance and A_s = sample absorbance.

Total flavonoid content was determined colorimetrically using the $AlCl_3$ method [22] and expressed as mg quercetin equivalent (QE)/g sample based on a quercetin standard curve.

Protein content was analyzed using the Kjeldahl method [7], which includes digestion, distillation, and titration. The nitrogen content was calculated as:

$$\%\ N = \frac{(V_s-V_b)\ x\ N\ x\ 14{,}007}{W_s}\ x\ 10 \dots\dots\dots\dots (3)$$

and total protein content is calculated using the formula:

$$\%\ protein = \%N\ xF_k \dots\dots\dots\dots (4)$$

where V_s = titration volume of the sample (mL), V_b = titration volume of the blank (mL), N = normality of HCl, W_s = weight of the sample (mg), and F_k = 6.25 as the protein conversion factor.

Yield was calculated based on the ratio of the dry powder weight to the fresh leaf weight [22] using the formula:

$$Yield\ (\%) = \frac{W_t}{Ws}\ x\ 100\% \dots\dots\dots\dots (5)$$

where W_t = weight of the dry powder (g) and W_s = weight of the fresh leaves (g).

The experimental data were analyzed using ANOVA to evaluate the effects of temperature, time, and their interaction on each response.

As an additional evaluation of the drying performance, the optimum conditions obtained from the RSM optimization were further used to calculate the energy efficiency of the drying system. The energi experiment was conducted with 5.0 kg marungga leaf. This calculation employed the Specific Moisture Extraction Rate (SMER), which represents the amount of water evaporated per unit of electrical energy consumed. The SMER value was determined based on the mass of water removed during drying under the optimal conditions and the total electrical energy consumed by the dehumidified cold-air drying system. Although this analysis was not included as a variable in the RSM design, it was incorporated as a supplementary assessment to evaluate the energy performance of the process at the model's optimal operating conditions [23].

The SMER value represents the amount of water mass evaporated per unit of energy consumed. It can be calculated using Equation :

$$SMER_{total} = \frac{W_{air}}{E_{total}} \dots\dots\dots\dots\dots\dots (6)$$

where SMER$_{\text{total}}$ = specific moisture extraction rate (kg/kWh), w_{air}= total mass of evaporated water (kg), E_{total}= total energy consumed (kWh).

$$W_{air} = \frac{MC_1 - MC_2}{100 - MC_2}\ x\ W_d \dots\dots\dots\dots\dots\dots (7)$$

where W_{air}= water vapor load (kg), w_d= initial mass of material (kg), MC_1= initial moisture content (%), MC_2= final moisture content (%).

3 Results and Discussion

3.1 Characteristics of Marungga

Preliminary analysis of the raw material characteristics of marungga leaves showed that the fresh leaves had a high moisture content (72.0%), antioxidant activity of 67.4%, total flavonoid content of 4.77 mg GAE/g extract, protein content of 5.17%, solubility of 14.6%, and a color value (a*) of –11.92, indicating a dominant green hue. The high moisture content makes marungga leaves highly susceptible to postharvest deterioration such as spoilage, nutrient loss, and microbial growth if not promptly dried [19]. Additionally, marungga leaves are rich in phenolic and flavonoid compounds, including chlorogenic acid, kaempferol, quercetin, and rutin, which play an important role as natural antioxidants [24]. However, these bioactive components, including proteins, are sensitive to high temperatures, humidity, and oxygen exposure, so improper postharvest handling can lead to degradation and oxidation of these functional compounds [25].

3.2 Results of marungga leaf drying optimization with RSM

The optimization of marungga leaf drying was carried out using the Response Surface Methodology (RSM) approach with a Central Composite Design (CCD), as shown in Table 2. CCD is an effective experimental design because it can be applied sequentially and provides sufficient information to test for lack of fit without requiring an excessive number of experimental runs. With this design, a quadratic surface model can be developed, which is generally very useful for process optimization [26]. In this study, CCD was employed to determine the optimal conditions for the marungga leaf powder drying process.

Analysis of variance (ANOVA) was conducted to evaluate the effects of temperature (A) and drying time (B) on various quality responses of marungga leaf powder, including moisture content, yield, antioxidant activity, total flavonoid content, protein content, solubility, and color. The ANOVA results are presented in Table 2, showing the F-values, p-values, coefficients of determination (R^2 and Adjusted R^2), and lack-of-fit test results for each model.

The 3D plot in Figure 2 for the moisture content (%) response shows a linear decrease in moisture content with increasing drying temperature (A) and drying time (B). The interaction effect (A×B) was relatively small, consistent with the ANOVA results in Table 2, which indicated a significant linear model ($p < 0.0001$) without notable interaction effects. This finding aligns with the basic drying principle, where higher temperatures increase the vapor pressure gradient and accelerate evaporation, while longer drying times allow more effective water diffusion [27][13]. However, excessively high temperatures can damage thermolabile bioactive compounds, highlighting the need for appropriate drying conditions to maintain the functional quality of the product [12][28]. The mathematical model for the moisture content response is expressed as:

$$Y_1 = 8.35–2.80A - 0.8029B \text{......................................}(8)$$

Table 2. Analysis of variance (ANOVA) results for the responses

Respon	Model	F-value	p-value	Significant Factors	R² / Adj R²	Lack of Fit
Moisture Content (%)	Linear	75.81	<0.0001	A, B	0.9381 / 0.9258	0.7667 (ns)
Yield (%)	Linear	25.63	<0.0001	A	0.8367 / 0.8041	0.1357 (ns)
Antioxidant Activity (%)	Quadratic	7.20	0.0110	A, B, AB, A^2	0.8373 / 0.7210	0.6047 (ns)
Flavonoids (mg GAE/g)	Quadratic	7.20	0.0110	A, B, AB, A^2	0.8373 / 0.7210	0.6047 (ns)
Protein (%)	Quadratic	26.20	0.0002	A, A^2, B^2	0.9493 / 0.9130	0.1616 (ns)
Solubility (%)	Quadratic	13.50	0.0018	A, A^2, B^2	0.9061 / 0.8390	0.1714 (ns)
Color (a*)	Quadratic	43.17	0.0001	A, AB, A^2, B^2	0.9686 / 0.9462	0.0884 (ns)

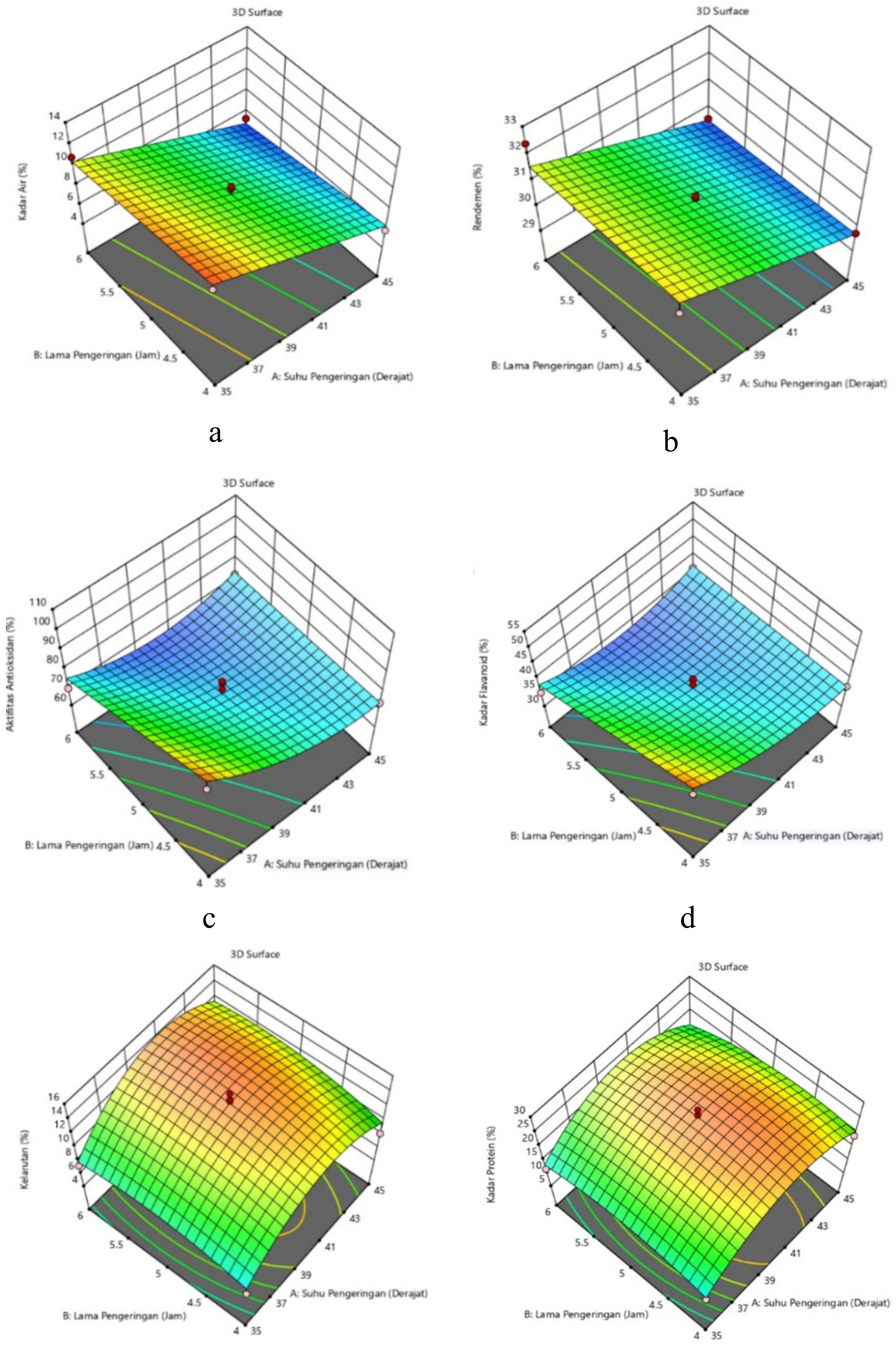
Note: *A = drying temperature (°C); B = drying time (hours); AB = interaction between temperature and drying time; A^2 and B^2 = quadratic effects of each factor. The symbol (ns) indicates that the lack of fit is not significant, meaning the model is adequate for predicting the responses.*

The 3D plot in Figure 2 for the yield (%) response shows a decreasing trend in yield with increasing drying temperature (A) and drying time (B). The relatively flat surface pattern indicates that the interaction effect between temperature and drying time (A×B) was not significant, consistent with the ANOVA results in Table 2, which revealed a significant linear model ($p < 0.0001$) without notable interaction effects. This result aligns with previous findings that drying at higher temperatures accelerates moisture diffusion but also increases the loss of volatile and thermolabile compounds, leading to a reduction in the final product weight [29][30]. Mathematical model for the yield response is expressed as:

$$Y_2 = 30.63–1.02A - 0.1034B \text{......................................}(8)$$

The 3D plot in Figure 2 for the antioxidant activity (%) response shows a quadratic dome-shaped pattern, where antioxidant activity increases at moderate drying temperatures and times, then declines again at higher temperatures and longer durations. The upward-curved surface indicates a significant interaction effect (A×B), consistent with the ANOVA results in Table 1, which showed a significant quadratic model ($p = 0.011$) with notable contributions from factors A, B, the AB interaction, and the quadratic effect of A^2. In extraction and processing, moderate temperatures (around 60–80 °C) often enhance the release or extraction of phenolic compounds from plant matrices without causing substantial degradation. This occurs because the bonds between phenolics and plant matrices break, making phenolics more easily extracted and increasing the antioxidant activity of the material [27]. However, phenolic antioxidant activity decreases linearly with further temperature increases; heat-stable phenolics remain active at higher temperatures, while less stable ones degrade rapidly [31]. The mathematical model for antioxidant activity is expressed as:

$$Y_3 = 72.80 - 7.68A - 7.13B + 6.83AB + 8.48A^2 + 0.1424B^2 \text{....................}(10)$$


3D Surface
Kadar Air (%)
14
12
10
8
6
4
B: Lama Pengeringan (Jam)
6
5.5
5
4.5
4
A: Suhu Pengeringan (Derajat)
35
37
39
41
43
45
3D Surface
Rendemen (%)
33
32
31
30
29
3D Surface
Aktifitas Antioksidan (%)
110
100
90
80
70
60
3D Surface
Kadar Flavanoid (%)
55
50
45
40
35
30
3D Surface
Kelarutan (%)
16
14
12
10
8
6
4
3D Surface
Kadar Protein (%)
30
25
20
15
10
5

a

b

c

d

e

f

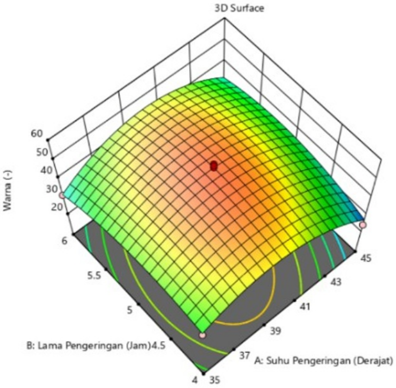


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Fig. 2. 3D surface plots showing the effects of drying time and temperature on the responses: a) moisture content, b) yield, c) antioxidant activity, d) total flavonoid content, e) protein content, f) solubility, and g) color.

The 3D plot in Figure 2 for the flavonoid content (mg GAE/g) response shows a quadratic dome-shaped pattern, where flavonoid content increases at moderate drying temperatures and times, then decreases again at higher temperatures and longer durations. The upward-curved surface indicates a significant interaction effect (A×B), consistent with the ANOVA results in Table 1, which revealed a significant quadratic model ($p = 0.011$) with notable contributions from factors A, B, the AB interaction, and the quadratic effect of A^2. This phenomenon demonstrates that moderate heating (around 65 °C) significantly enhances the total flavonoid content in herbs such as mint, parsley, basil, white pepper, and njangsa. However, higher temperatures (75–85 °C) lead to a decrease in flavonoid content due to thermal degradation of these heat-sensitive compounds [32]. This increase is presumed to result from the breakdown of complex compounds into simpler flavonoids and the inactivation of polyphenol oxidase enzymes, which helps prevent flavonoid degradation. Other studies have also reported that phenolic and flavonoid compounds in Moringa leaves undergo significant degradation at drying temperatures above 60 °C [33][13]. The mathematical model for the flavonoid content response is expressed as:

$$Y_4 = 36.52 - 3.84A - 3.57B + 3.41AB + 4.24A^2 + 0.0712B^2 \text{.................}(11)$$

The 3D plot in Figure 2 for the protein content (%) response shows a quadratic dome-shaped pattern, where protein content increases at low to moderate drying temperatures, then decreases again at higher temperatures and longer drying times. The upward-curved surface indicates a significant interaction effect (A×B), consistent with the ANOVA results in Table 1, which revealed a significant quadratic model ($p = 0.0002$) with notable contributions from factor A and the quadratic effects of A^2 and B^2. This finding is logical because proteins are prone to denaturation when exposed to heat [34], [35], [36]. An increase in temperature beyond a certain threshold can trigger changes in the secondary and tertiary structures of proteins, thereby reducing the measurable protein content [37], [38]. Conversely, at excessively low temperatures, the drying process is not optimal, resulting in flour that retains high moisture content, which can affect the protein concentration [33], [39]. Temperature control is therefore a crucial factor in maintaining protein stability during the drying process of moringa leaves [40], [41]. A decrease in protein content occurs at both excessively low and high temperatures: low temperatures lead to incomplete drying, where the high moisture content can trigger enzymatic or oxidative degradation of proteins [42]. The mathematical model for the protein content response is expressed as:

$$Y_5 = 27.53 + 2.40A - 1.14B - 1.11AB - 8.86A^2 - 2.95B^2 \text{....................}(12)$$

The 3D plot in Figure 2 for the solubility (%) response shows a quadratic dome-shaped pattern, where solubility increases at moderate drying temperatures and times, then decreases again at higher temperatures and longer durations. The upward-curved surface indicates a significant interaction effect (A×B), consistent with the ANOVA results in Table 1, which revealed a significant quadratic model ($p = 0.0018$) with notable contributions from factor A and the quadratic effects of A^2 and B^2. At low temperatures (±35 °C), drying proceeds slowly, causing water to remain trapped within the leaf tissues and hindering the release of water-soluble active compounds. As a result, the flour particles tend to clump together and disperse poorly, leading to reduced solubility [43], [44]. Meanwhile, drying at moderate temperatures can reduce the moisture content below the hygroscopic limit, preventing the formation of aggregates that impede solubility [22], [45]. However, at excessively high temperatures (>43 °C), solubility decreases due to protein denaturation, thermal degradation of polysaccharides, and early Maillard reactions between reducing sugars and amino acids [46], [47]. These processes can lead to the formation of a more hydrophobic surface layer, reducing the ability of the powder to interact with water [48]. The mathematical model for the solubility response is expressed as:

$$Y_6 = 14.20 + 1.59A + 0.6777B + 0.2750AB – 4.14A^2 – 1.06B^2 \ldots\ldots\ldots\ldots(13)$$

The 3D plot in Figure 2 for the color response (a* value) shows a quadratic concave-shaped pattern, where the a* value tends to decrease (indicating a loss of green hue) at higher drying temperatures and longer drying times. The downward-curved surface indicates a significant interaction effect (A×B), consistent with the ANOVA results in Table 1, which revealed a significant quadratic model ($p = 0.0001$) with notable contributions from factor A, the AB interaction, and the quadratic effects of A^2 and B^2.

At low temperatures (around 35 °C), the drying process proceeds slowly, allowing the chlorophyll pigments to remain stable because the temperature is not high enough to induce the conversion of chlorophyll to pheophytin [49], [50]. When the drying temperature increases to about 40–43 °C, the heat accelerates water evaporation and lowers leaf moisture to safer levels [51]. At this stage, chlorophyll begins to degrade slightly but is not completely lost; some pigments remain intact, while others convert into pheophytin and pheophorbide derivative compounds that impart a yellowish or dull green hue [52]. Under these conditions, the powder appears brighter and more uniform in color due to reduced moisture content and drier particles, which enhance light reflectance often regarded as the optimum point for color quality [53]. However, higher temperatures accelerate phenolic oxidation and Maillard reactions between residual amino acids and reducing sugars [54]. Leading to the formation of brown melanoidin pigments that darken the color of the moringa leaf powder [46]. The mathematical model for the color response is expressed as:

$$Y_7 = 51.00 – 2.46A – 0.3536B + 3.00AB – 12.87A^2 – 5.88B^2 \ldots\ldots\ldots\ldots(14)$$

3.3 Specific Moisture Extraction Rate (SMER) Analysis

The energy efficiency of the dehumidified cold-air drying system was evaluated using the Specific Moisture Extraction Rate (SMER). Based on Equations (6) and (7), the total evaporated water for 5.0 kg marungga leaf under the optimal RSM drying condition (37.75 °C for 4 h) as 3.68 kg. With a measured electricity consumption of 5.04 kWh for the compressor–blower system, the resulting SMER value was 0.73 kg/kWh. This value falls within the typical range reported for dehumidified and heat pump drying systems, indicating that the applied system exhibits a moderate-to-high energy efficiency. The SMER results complement the physicochemical optimization findings by demonstrating that the optimized drying parameters also support favorable energy performance[23].

4 Conclusion

The optimization of the drying process of *Moringa oleifera* leaves using a dehumidified cold-air drying method combined with a Response Surface Methodology (RSM) approach demonstrated that the optimum conditions were achieved at a drying temperature of 37.75°C and a drying time of 4 hours. Under these conditions, the predicted responses included a moisture content of 10.42%, yield of 31.19%, antioxidant activity of 88.32%, flavonoid content of 44.28 mg GAE/g extract, protein content of 25.44%, solubility of 66.24%, and a color value (a*) of 52.00. Experimental verification produced comparable results, with a moisture content of 11.72%, yield of 30.14%, antioxidant activity of 72.74%, flavonoid content of 31.87 mg GAE/g extract, protein content of 23.81%, solubility of 63.41%, and a color value (a*) of 49.36. Additionally, the energy efficiency assessment showed that the optimum condition generated an SMER value of 0.73 kg/kWh, indicating a moderately efficient energy performance for the dehumidified cold-air drying system. The agreement between predicted and experimental results indicates that the developed RSM model effectively predicts the influence of temperature and drying time on the physicochemical characteristics and bioactive properties of Moringa leaves. Therefore, the identified optimum conditions can be recommended as effective parameters for producing high-quality Moringa leaf powder with well-preserved antioxidant activity.

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