Optimization of Hot-Air Drying Assisted with Incandescent Lamp of Red Seaweed (*Chondracanthus chamissoi*) Using Response Surface Methodology

E. Elena Vivanco-Cuba[1], D. Vivanco-Pezantes[2*]

1- Faculty of Chemical and Textile Engineering, National University of Engineering, Lima, Peru
2- Faculty of Fisheries and Food Engineering, National University of Callao, Peru
(*- Corresponding Author Email: dvivancop@unac.edu.pe)
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Abstract

Seaweeds are well known for their technological, nutritional, and health values, and their preservation by drying is essential to stabilize and maintain the quality of the product during storage. The research presents the obtaining of mathematical models in polynomial functions using the response surface methodology. The influence of the independent drying variables was studied: load density (1.70-15 kg m^{-2}), incandescent lamp wattage (0-500 W), temperature (30-70 °C) and air velocity (0.5-2.5 m s^{-1}) on the response variables: global acceptance (--), total phenolic content (mg GAC/100 g_{db}) and drying time (min). The study also showed that the conditions of temperature and incandescent lamp wattage during drying significantly affected the total phenolic content. The optimum conditions were: load density 9.13 kg m^{-2}, incandescent lamp wattage 374.5 W, temperature and drying air velocity of 63.3 °C and 1.88 m s^{-1}, respectively. The results show that increasing the power of the incandescent lamps leads to a shorter drying time of approximately 40-45%. For these optimized conditions, mathematical models were applied to simulate the drying curve and kinetics of the material studied. Using the Quasi-Newton Simplex method, the models of Midilli *et al.* and Page in second place, achieved a better performance in the quality of fit of the curves to the experimental data. Under these conditions, the value of the effective diffusivity of water was of the order of 2.03×10^{-11} m^2 s^{-1}, a value very similar to those published for agro-industrial products. The information obtained can be of great help in the use of the obtained parameters and applied techniques for the development of equipment and process control in the drying of red seaweed.

Keywords: Drying kinetics, Drying optimization, Effective diffusivity, Phenolic content, Mathematical modeling, Response surface methodology

Introduction

The search for non-conventional sources of protein and the great phytological richness of Peru's marine and inland waters have motivated studies from the nutritional point of view, of the most popularly consumed seaweed through the biological nutritional evaluation of pure seaweed, and in the form of mixtures of seaweed with other proteins. (Amir, Mustajib, Gozan, & Chan, 2024; Díaz-Godínez, Peña-Solís, Diaz-Domínguez, 2023). Given the importance and interest, especially by Asian countries, there are currently multiple research works to scale up its production to a commercial and industrial level.

Hot air drying is a method widely used in the agroindustry, where it is possible to control the drying variables and obtain good quality dry goods. This preservation technique aims to prolong the shelf life of food by effectively removing water to a targeted level, thereby reducing water activity (a_W). This reduction is crucial in preventing both microbial growth and chemical degradation of the product (Wang *et al*., 2018). In addition to other advantages such as weight and volume reduction that result in a decrease in transportation and storage costs of food (Wells *et al*., 2017; Xianglu *et al*., 2021). The drying of seaweed is considered a process that demands high energy consumption due to the initial humidity of the product, so it is necessary to accelerate the drying process of this product due to the great advantages it represents for both the consumer and the producer (Tingxue, Qingying, Huabin, & Hailong, 2022). An alternative is to use technological assistance to reduce processing times for this type of food. In industrial processes, the application of statistical tools for process optimization and the use of mathematical models to simulate drying curves or in the design of efficient dryers is already commonly used (Chenlo *et al.*, 2018; Del Rosario & Mateo, 2019; Haolu *et al.*, 2018, Nazemi, Keikhosro, Denayer, 2021; Santhoshkumar, Yoha, & Moses, 2023).

Sensory analysis is decisive as a quality control parameter in food processes. The sensory analysis, a widely utilized test, assesses the hedonic acceptability of products by evaluating key attributes such as appearance, aroma, taste, flavor, texture, and the overall perception as experienced by a panel of consumers. This approach is particularly effective for gauging consumer preferences, as it engages untrained tasters and volunteers to determine the global acceptability of intermediate or finished products (Dereje & Abera 2020; Galoburda, Kruma, Ruse, 2012; Rorato, Mezzomo, & Salvador, 2014).

Knowledge of the drying parameters of biological materials is fundamental in the design and control of industrial processes. Countless studies have been carried out to investigate its production and utilization of seaweed in general, and few studies have been conducted to study the kinetics and its optimization by applying the response surface methodology in hot air drying assisted with another energy source. In relation to the use of the extra energy provided by incandescent bulbs in food drying, it is almost null in the reviewed bibliography. Therefore, the present study was conducted with the following objectives: 1) To determine the optimal parameters of load density, wattage of the incandescent lamp, temperature, and air velocity in the incandescent lamp-assisted hot-air drying process for red seaweed; 2) To determine the regression models for global acceptance, total phenolic content, and drying time; 3) To model the drying curve and calculate the effective diffusivity under the optimized conditions.

Materials and Methods

Raw materials and pretreatment

Red Seaweed (*Chondracanthus chamissoi*) was acquired at the Frigorífico Pesquero Zonal de Ventanilla in the Constitutional Province of Callao-Lima-Peru. The seaweed was conditioned in a cooler with ice and transported to the university city of Universidad Nacional del Callao in Peru. It was then placed in a refrigerator and kept at a temperature of 1 ºC, in sufficient quantity for the experimental runs. The degree of freshness standardized for the experimental runs was taken into account. The samples were washed with running water at room temperature, and the damaged seaweed branches were separated. The selected samples, once washed, were previously subjected to a treatment with saturated water vapor at 100 ºC for 60 seconds then drained. The excess surface moisture was removed with soft paper towels. The sample was placed on a stainless-steel sample-holder grid (0.15 × 0.20 m), with a 20M mesh previously tared, and the whole was weighed in such a way as to obtain the load density for each drying test. The initial information was recorded in a spreadsheet (EXCEL) for data collection of the corresponding experimental run.

Hot-air assisted drying system with incandescent lamps

Fig. 1 shows the laboratory-scale dryer used for the experimental runs, designed and built for this study, which is installed in the Process Engineering and Unit Operations Laboratory of the Faculty of Fisheries and Food Engineering of the Universidad Nacional del Callao.

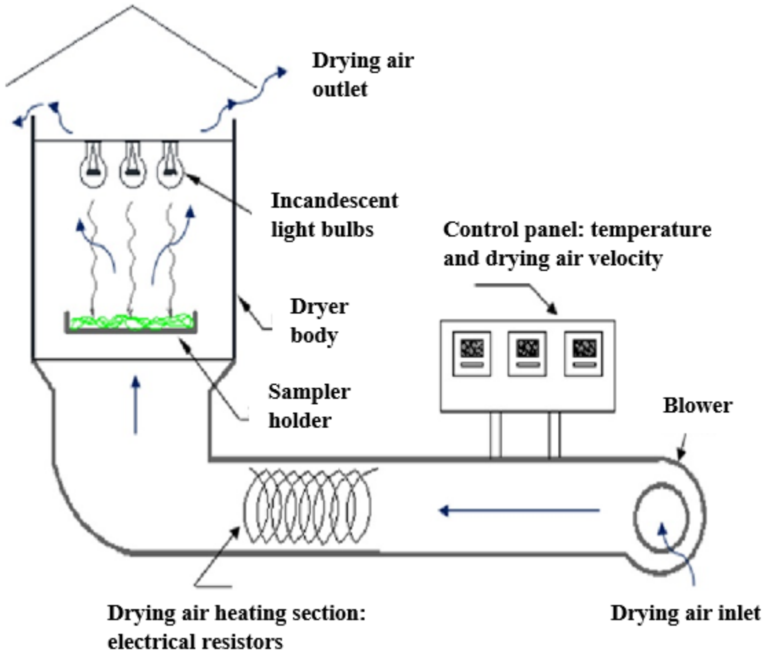


Fig. 1. Schematic of a laboratory-scale convective dryer with hot air assisted by incandescent lamps

Determination of total phenolic content

The determination of total polyphenols was analyzed according to the Folin-Ciocalteu colorimetric method described by Burneo, Mora-Medina, and Figueroa (2021), Dong, Hu, Li, and Zhou (2019), Lopez-Hortas, Florez-Fernandez, Mazon, Domínguez, and Dolores-Torres (2023), Torrenegra-Alarcón, Granados-Conde, and León-Mendez (2019), and Vigasini *et al*. (2023) using gallic acid as a standard. The absorbance was read at 760 nm using a Hitachi High-Tech Analytical brand UV2000 spectrophotometer.

Determination of global acceptance

The sensory analysis of the dependent variable of global acceptance was carried out using an 09-point hedonic scale, having as limits I extremely liked it and I extremely disliked it. The sensory evaluation was carried out by randomly selecting 20 untrained panelists, consisting of senior students, faculty, and administrative staff from the Faculty of Fisheries and Food Engineering. The observations of organoleptic properties were always made at midday after the drying experiments. The panelists were asked to evaluate the descriptors. Color, texture, and overall acceptability of the dried seaweed sample were analyzed (Desa, 2025; Gonzales, Rodeiro, San Martin, & Vila, 2014; Upaep, 2025).

Response surface methodology (RSM)

Experimental planning was used to obtain a quadratic polynomial function mathematical equation, as shown in Eq. 1, where the response variable of drying time, global acceptance, and total polyphenol content depended on the independent variables: temperature and velocity of the drying air, wattage of the incandescent lamps, and load density. Regression coefficients were calculated using Statistica 7.0 software (Statsoft®) for professionals.

$$y = \beta_o + \sum_{i}^{k} \beta_i x_i + \sum_{i}^{k} \beta_{ii} x_i^2 \sum_{i<j} \sum_{j} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

where ε is the error term, β_i are the linear effects, β_{ii} are the quadratic effects, and β_{ij} are the linear interactions.

Research design

Table 1 shows the design of the rotatable central composite with the coded and real variables for the study of incandescent lamp-assisted hot-air drying process for red seaweed.

Table 1- Rotatable central composite design with coded and real values for the study of incandescent lamp-assisted hot-air drying process for red seaweed (*Chondracanthus chamissoi*)

	Coded variables				Real variables			
Test number	**x_1**	**x_2**	**x_3**	**x_4**	**Loading Density (kg m^{-2})**	**Lamp Wattage (W)**	**Temperature (°C)**	**Air Velocity (m s^{-1})**
1	-1	-1	-1	-1	5	125	40	1
2	1	-1	-1	-1	11.7	125	40	1
3	-1	1	-1	-1	5	375	40	1
4	1	1	-1	-1	11.7	375	40	1
5	-1	-1	1	-1	5	125	60	1
6	1	-1	1	-1	11.7	125	60	1
7	-1	1	1	-1	5	375	60	1
8	1	1	1	-1	11.7	375	60	1
9	-1	-1	-1	1	5	125	40	2
10	1	-1	-1	1	11.7	125	40	2
11	-1	1	-1	1	5	375	40	2
12	1	1	-1	1	11.7	375	40	2
13	-1	-1	1	1	5	125	60	2
14	1	-1	1	1	11.7	125	60	2
15	-1	1	1	1	5	375	60	2
16	1	1	1	1	11.7	375	60	2
17	-2	0	0	0	1.7	250	50	1.5
18	2	0	0	0	1.5	250	50	1.5
19	0	-2	0	0	8.4	250	50	1.5
20	0	2	0	0	8.4	500	50	1.5
21	0	0	-2	0	8.4	250	30	1.5
22	0	0	2	0	8.4	250	70	1.5
23	0	0	0	-2	8.4	250	50	0.5
24	0	0	0	2	8.4	250	50	2.5
25	0	0	0	0	8.4	250	50	1.5
26	0	0	0	0	8.4	250	50	1.5
27	0	0	0	0	8.4	250	50	1.5
28	0	0	0	0	8.4	250	50	1.5
29	0	0	0	0	8.4	250	50	1.5
30	0	0	0	0	8.4	250	50	1.5

The study coded operation variables: load density (x_1), incandescent lamp wattage (x_2), temperature (x_3), and drying air velocity (x_4), were investigated at five levels each. The complete design consisted of 30 experimental trials, including 16 factorial trials at levels -1 and +1, 8 axial trials at levels -2 and +2, and 6 central points at level 0; the central points were specifically conducted for accurate pure error estimation. They were carried out in duplicate, totaling 60 trials, which were randomized in order to minimize experimental systematic errors.

Effective water diffusivity in drying under optimum conditions

Considering that the solid is a flat plate with both surfaces exposed throughout the drying process, constant diffusivity, negligible volume variation, and disregarding the effect of the temperature gradient inside the sample, the following analytical solution is obtained (Crank, 1975; Treybal, 1980):

$$MR = \frac{X - X_e}{X_o - X_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}exp\left[-(2n+1)^2\frac{\pi^2 \cdot D_{eff} \cdot t}{4L^2}\right] \quad (2)$$

where MR is the dimensionless moisture, X, X_o, and X_e is the moisture at time t, initial, and equilibrium, respectively, D_{eff} is the effective diffusivity, t is the time, and L is the half-thickness of the sample.

The terms of the infinite series of Eq. 2 converge rapidly with increasing drying time. Considering that only the first term of the series results in small errors, even not considering the effect of shrinkage (Castro & Coelho-Pinheiro, 2015):

$$MR = \frac{8}{\pi^2}exp\left[-\frac{\pi^2 \cdot D_{eff} \cdot t}{4 \cdot L^2}\right] \quad (3)$$

Therefore, linearizing Eq. 3 results in:

$$Ln(MR) = Ln\frac{8}{\pi^2} - \frac{\pi^2 \cdot D_{eff}}{4 \cdot L^2} \cdot t \quad (4)$$

With the experimental data of the drying kinetics at the optimum conditions of the drying process and with the value of the slope of Eq. 4, it was possible to estimate the effective diffusivity of water: D_{eff} ($m^2 s^{-1}$).

Mathematical simulation of the drying curve

Six mathematical models (Table 2) were used to simulate the drying curve under optimal conditions, such as: Henderson-Pabis, modified Henderson-Pabis, Page, modified Page, Newton, and Midilli et al. (Eqs. 6-11, respectively) (Botelho *et al.*, 2011; Celma, Rojas, & López-Rodríguez, 2008; Lopez-Hortas *et al.*, 2023; Sharma, Verma, & Pathare, 2005; Uribe *et al.*, 2011; Vivanco-Pezantes & Nieto-Freire, 2021).

The adjustment of the constants of the equations used was determined using the SOLVER software package that estimates the calculation of the nonlinear parameters by the application of the Quasi-Newton Simplex method of Microsoft Corporation MS-Excel®.

Table 2- Mathematical models for simulation of the drying curve

Model	Equation	N°
Henderson-Pabis	$MR = a \cdot exp(-k \cdot t)$	(5)
Modified Henderson-Pabis	$MR = a \cdot exp(-k \cdot t) + b \cdot exp(-g \cdot t) + c \cdot exp(-h \cdot t)$	(6)
Page	$MR = exp(-k \cdot t^n)$	(7)
Modified Page	$MR = exp(-k \cdot t)^n$	(8)
Newton	$MR = exp(-k \cdot t)$	(9)
Midilli et al.	$MR = a \cdot exp(-k \cdot t^n) + bt$	(10)

Results and Discussion

Experimental planning results using the response surface methodology

Tables 3, 4, and 5 present the analysis of variance for the sources of variation in the regression equation of the response surfaces related to drying time, global acceptance, and total phenolic content of the dried red seaweed. The calculated F values (Fc) are 15.135, 12.688, and 2.699, respectively. When compared to the tabulated F value (Ft): F(0.95,14,15)= 2.43, it is evident that Fc exceeds Ft by ratios of 6.23, 5.22, and 1.11, respectively. This indicates that the mathematical model derived from the response surface methodology is statistically valid for estimating the response variable values within the ranges proposed in this study.

Table 3- Analysis of variance of the drying time of red seaweed (*Chondracanthus chamissoi*)

Source of variance	Sum of squares	N° degrees of freedom	Quadratic mean	Calculated F-value
Regression	226052.10	14	16146.579	15.135
Residues	16002.10	15	1066.807	

Lack of fit	14814.60	10	1481.460	6.238
Pure erro	1187.50	5	237.500	
Total	242054.20	29		

Table 4- Analysis of variance of the global acceptance of red seaweed (*Chondracanthus chamissoi*)

Source of variance	Sum of squares	N° degrees of freedom	Quadratic mean	Calculated F-value
Regression	20.887	14	1.492	12.688
Residues	1.764	15	0.118	
Lack of fit	1.622	10	0.162	5.707
Pure erro	0.142	5	0.028	
Total	22.651	29		

Table 5- Analysis of variance of the total phenolic content of red seaweed (*Chondracanthus chamissoi*)

Source of variance	Sum of squares	N° degrees of freedom	Quadratic mean	Calculated F-value
Regression	28842.920	14	2060.209	2.699
Residues	11449.250	15	763.283	
Lack of fit	9955.920	10	995.592	3.333
Pure erro	1493.330	5	298.666	
Total	40292.170	29		

Table 6 shows the experimental and estimated values for the response variables of drying time, global product acceptance, and total phenolic content. Table 7 shows the values of the regression coefficients for the mathematical model of the response surface for drying time, global product acceptance, and total phenolic content of red seaweed (*Chondracanthus chamissoi*).

Table 6- Results of drying time, global acceptance, and total phenolic content of red seaweed (*Chondracanthus chamissoi*) drying process with hot air assisted by incandescent lamps

Test number	Drying time (min)				Global acceptance (--)				Total phenolic content (mg GAC/100 g_{db})			
	Experimental value	Calculated value	Residue	Error (%)	Experimental value	Calculated value	Residue	Error (%)	Experimental value	Calculated value	Residue	Error (%)
1	245	233.52	11.48	4.69	8.35	7.75	0.60	7.19	323	287	36	11.15
2	390	398.43	-8.43	-2.16	8.15	8.35	-0.20	-2.45	335	323	12	3.58
3	180	175.63	4.37	2.43	8.05	8.75	-0.70	-8.70	290	323	-33	-11.38
4	300	324.74	-24.74	-8.25	6.85	7.15	-0.30	-4.38	285	267	18	6.32
5	180	158.81	21.19	11.77	7.15	8.25	-1.10	-15.38	267	230	37	13.86
6	230	212.03	17.97	7.81	7.05	8.05	-1.00	-14.18	277	290	-13	-4.69
7	150	174.67	-24.67	-16.45	7.55	6.25	1.30	17.22	250	308	-58	-23.20
8	240	212.08	27.92	11.63	6.45	7.55	-1.10	-17.05	245	250	-5	-2.04
9	100	146.43	-46.43	-46.43	8.75	7.05	1.70	19.43	323	215	108	33.44
10	350	320.48	29.52	8.43	8.95	8.75	0.20	2.23	335	323	12	3.58
11	90	102.29	-12.29	-13.66	6.25	7.75	-1.50	-24.00	308	285	23	7.47
12	220	260.53	-40.53	-18.42	6.15	8.05	-1.90	-30.89	315	297	18	5.71
13	70	40.47	29.53	42.19	8.25	8.79	-0.54	-6.55	230	245	-15	-6.52
14	80	102.83	-22.83	-28.54	7.56	7.56	0.00	0.00	237	285	-48	-20.25
15	60	70.08	-10.08	-16.80	7.05	7.05	0.00	0.00	215	300	-85	-39.53
16	110	116.63	-6.63	-6.03	7.15	6.35	0.80	11.19	218	220	-2	-0.92
17	40	33.12	6.88	17.20	7.75	8.15	-0.40	-5.16	287	335	-48	-16.72
18	250	243.01	6.99	2.80	8.05	8.95	-0.90	-11.18	263	335	-72	-27.38
19	185	207.83	-22.83	-12.34	8.75	7.05	1.70	19.43	323	277	46	14.24
20	200	163.50	36.50	18.25	6.35	7.56	-1.21	-19.06	220	237	-17	-7.73
21	380	343.31	36.69	9.66	7.75	6.85	0.90	11.61	285	285	0	0.00
22	100	123.03	-23.03	-23.03	7.05	6.15	0.90	12.77	300	315	-15	-5.00
23	280	299.37	-19.37	-6.92	8.05	6.45	1.60	19.88	297	245	52	17.51
24	150	116.96	33.04	22.03	7.56	7.15	0.41	5.42	285	218	67	23.51
25	140	157.53	-17.53	-12.52	8.90	8.05	0.85	9.55	245	263	-18	-7.35
26	160	157.53	2.47	1.54	8.95	8.05	0.90	10.06	255	263	-8	-3.14
27	165	157.53	7.47	4.53	8.65	8.05	0.60	6.94	230	263	-33	-14.35
28	180	157.53	22.47	12.48	8.55	8.05	0.50	5.85	220	263	-43	-19.55
29	140	157.53	-17.53	-12.52	8.75	8.05	0.70	8.00	257	263	-6	-2.33
30	160	157.53	2.47	1.54	8.95	8.05	0.90	10.06	265	263	2	0.75

Since the degree of acceptance of the dried product was decisive and a maximum value of this was obtained, the critical values of the drying parameters were evaluated for this condition: load density, incandescent lamp wattage, temperature, and drying air velocity, obtained with the Statistica program and presented in Table 8.

Table 7- Regression coefficient values of the response surface for drying time, global acceptance, and total phenolic content in the incandescent lamp-assisted hot-air drying process for red seaweed (*Chondracanthus chamissoi*)

Coded parameter	Drying time (min)	Global acceptance (--)	Total phenolic content (mg GAC/100 g_{db})
K_0	157.500	8.7917	245.333
x_1	52.708	-0.1038	-0.292
x_2	-11.042	-0.2532	6.719
x_3	-54.792	-0.5630	-16.959
x_4	-45.625	-0.3408	5.844
x_1^2	-4.948	-0.1954	-22.708
x_2^2	6.927	-0.3783	11.094
x_3^2	18.802	-0.0196	-4.792
x_4^2	12.552	-0.2770	10.719
$x_1 \cdot x_2$	-4.063	-0.0944	-2.563
$x_1 \cdot x_3$	-27.813	-0.0306	-0.688
$x_1 \cdot x_4$	2.188	0.1319	1.063
$x_2 \cdot x_3$	18.438	0.3181	2.188
$x_2 \cdot x_4$	3.438	-0.3194	3.938
$x_3 \cdot x_4$	-7.813	0.1944	-11.688
R^2	0.9339	0.9221	0.7158
MQ (Pure error)	237.450	0.028	298.667

Note: Relation of the coded variables with the real ones: $Load\ density: x_1 = \frac{D-8.40}{3.30}$; $Wattage: x_2 = \frac{P-250}{125}$; $Temperature: x_3 = \frac{T-50}{10}$; and $Velocity: x_4 = \frac{v-1.50}{0.50}$

Table 8- Critical values of the drying process to obtain a maximum value of the global acceptance of the product

Process variables	Value	
	Encoded	Real
Load density (kg m^{-2})	0.29119	9.36
Incandescent lamp wattage (W)	-1.516	60.50
Drying air temperature (°C)	-0.74120	42.59
Drying air velocity (m s^{-1})	0.64795	1.824

Result of the response surface for the determination of global acceptability of the product

Fig. 2 shows the Pareto analysis for the study of the effects of the process variables on the global acceptance of the product, where it is shown that the independent variables have a linear (L) and quadratic (Q) effect on the global acceptance. While the variable Velocity (L) and the conjugate variables: Load density (L) × Wattage (L) and Load density (L) × Temperature (L) were not significant on the global acceptance of the product. In Fig. 3, the distribution of the observed values and those calculated with the regression equation of Table 4 is presented. A good linear approximation of the data pair can be observed qualitatively.

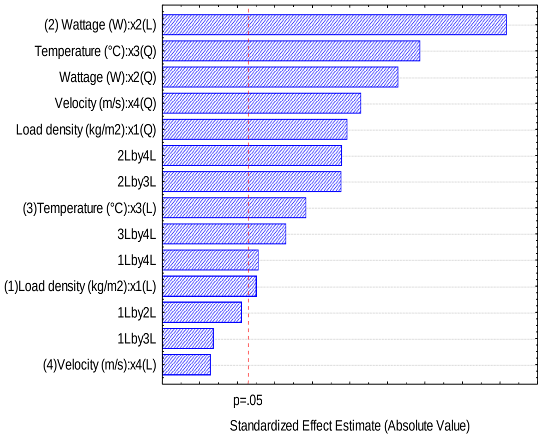


Fig. 2. Pareto analysis for global product acceptance

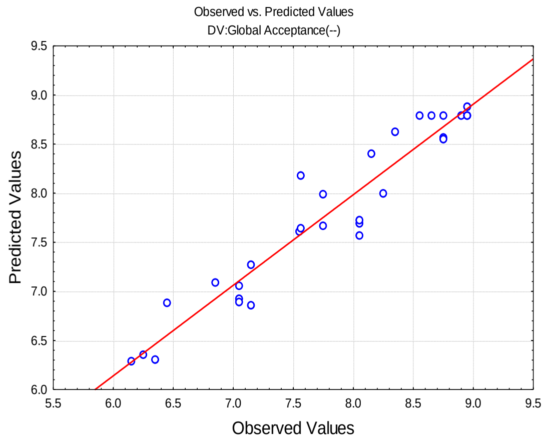
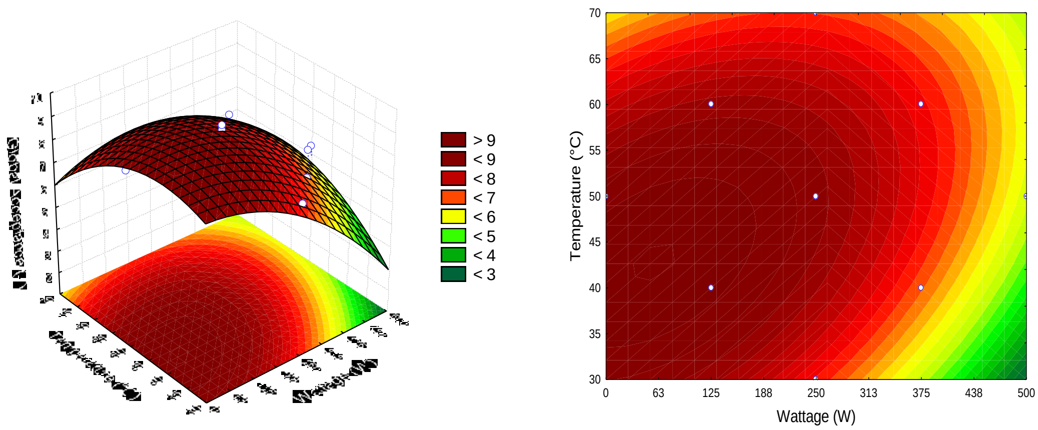


Fig. 3. Observed and estimated values of global product acceptance

Fig. 4 (a and b) shows the response surface of the Global (--) and contour acceptance, respectively, maintaining the critical values of load density (9.36 kg m^{-2}) and velocity air (1.82 m s^{-1}). The values of the global acceptance reach the maximum values at low values of the incandescent lamp wattage and the temperature of the drying air.



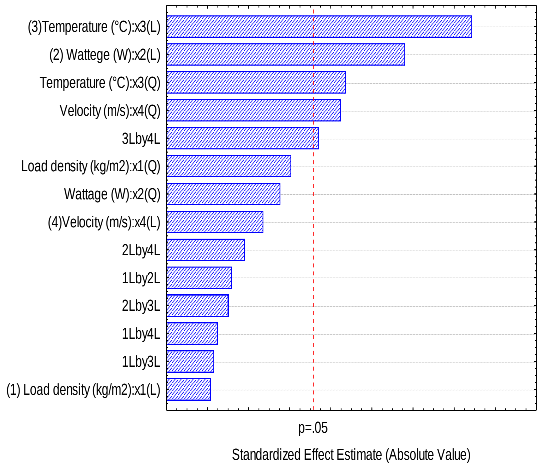
(a) (b)

Fig. 4. (a) Response surface and (b) contour of the global acceptance of the dried red seaweed (*Chondracanthus chamissoi*) product with hot air assisted by incandescent lamps

Result of the response surface for the determination of total phenolic content

In Fig. 5, the Pareto analysis for the study of the effects of the process variables are presented, where the important effect of the thermal process of temperature (L, Q), incandescent lamp wattage (L), and air velocity (Q) on the total phenolic content during the drying process is evidenced. The load density was not significant on the content of polyphenols in the experiments.

In Fig. 6, the distribution of the observed values and the estimated values with the regression equation of Table 4 are presented.



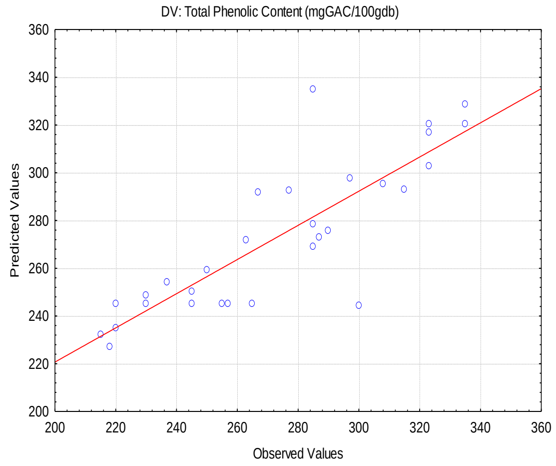
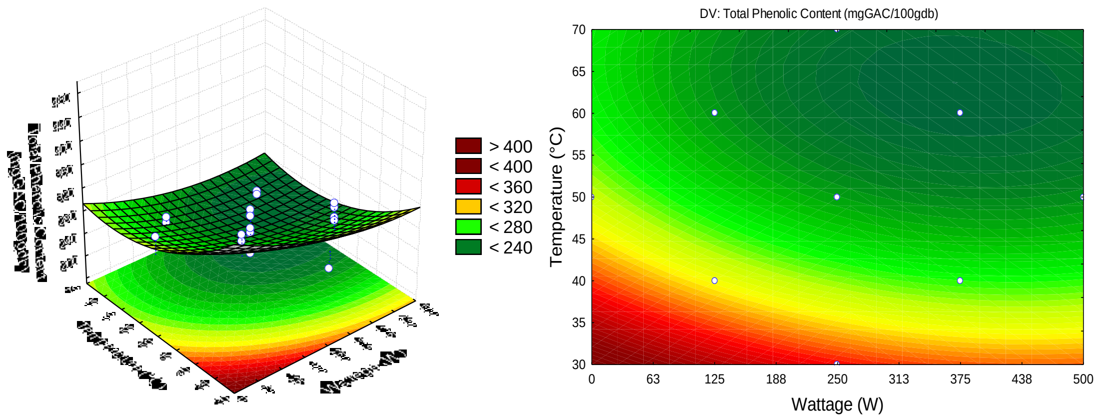


Fig. 5. Pareto analysis for total phenolic content **Fig. 6.** Observed and estimated values of total phenolic content

Fig. 7 (a and b) presents the response surface of total and contour phenolic content (mg GAC/100 g_{db}), respectively. Keeping the critical values of Load density (9.36 kg m^{-2}) and air velocity (1.82 m s^{-1}) constant, the values of phenolic content vary from a minimum (< 240 mg GAC/100 g_{db}) to a maximum (> 400 mg GAC/100 g_{db}) at high and low values of temperature and wattage, respectively.



(b)

Fig. 7. (a) Response surface and (b) contour of the total phenolic content (mg GAC/100 g_{db}) of red seaweed (*Chondracanthus chamissoi*) dried with hot air assisted by incandescent lamps

Fig. 8 shows the decrease of the total phenolic content versus temperature, maintaining the critical values of the load density, drying air velocity, and wattage of the incandescent lamps in the temperature range of the drying process tested (30-70 °C), with the minimum critical value of the total phenolic content being 219.95 mg GAC/100 g_{db}, which was due to the effect of the thermal treatment of the drying process on the polyphenols.

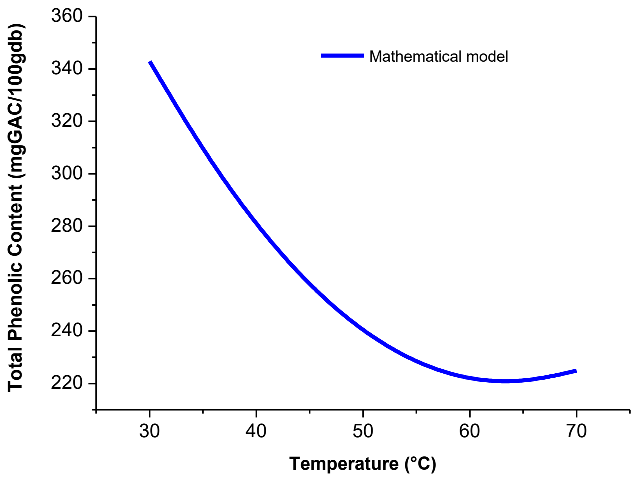


Fig. 8. Variation of total polyphenol content with temperature in the drying of red seaweed (*Chondracanthus chamissoi*) with hot air assisted by incandescent lamps

Result of the response surface for the determination of the drying time

Fig. 9 shows the Pareto analysis for the study of the effects of the process variables on the drying time, where it is shown that all the independent variables in their linear form (L) and the conjugate variables: load density (L) and temperature (L), wattage (L) and temperature (L), and the velocity and temperature variables in their quadratic form (Q) have an effect on the drying time. While wattage (Q), load density (Q), and the conjugate variables: temperature (L) and velocity (L), load density (L) and wattage (L), and load density (L) and temperature (L) were not significant on the drying time. In Fig. 10, the distribution of the observed and calculated values for the drying time using the regression equation of Table 4 is presented.

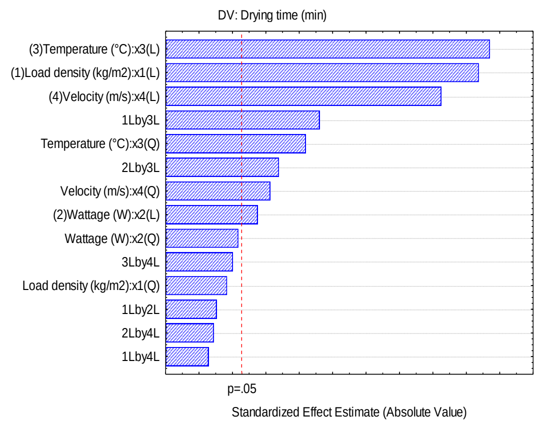


Fig. 9. Pareto analysis for drying time

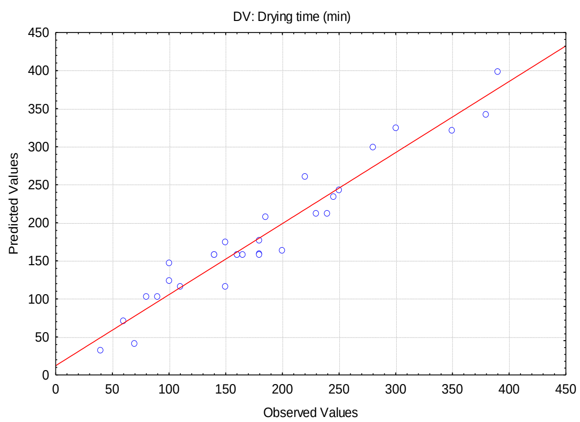
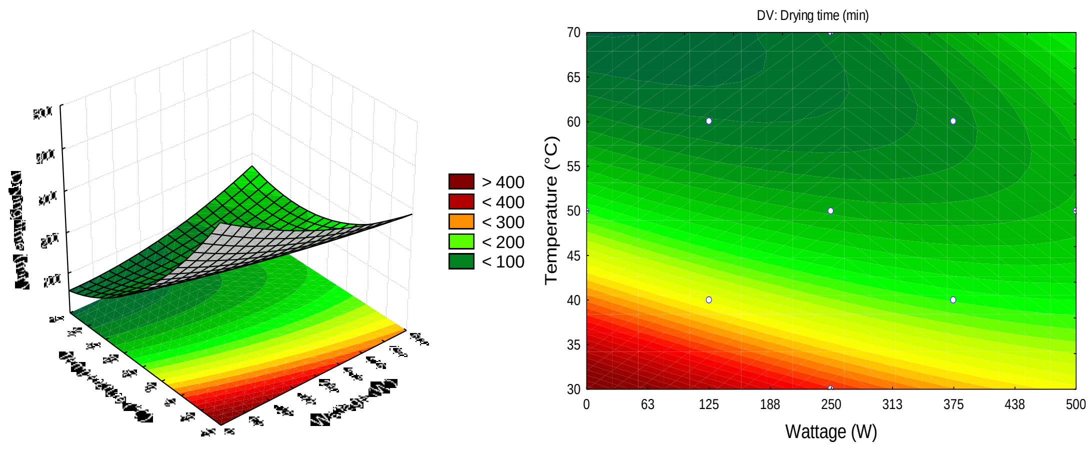


Fig. 10. Observed and estimated values of drying time

Fig.11 (a and b) shows the response surface of the drying time (min) and contour, respectively, of the independent variables: drying air temperature and the wattage of the incandescent lamps. It is observed that the values of the drying time are reduced to minimum values of 100 minutes until the humidity of approximately 10%bh is achieved.



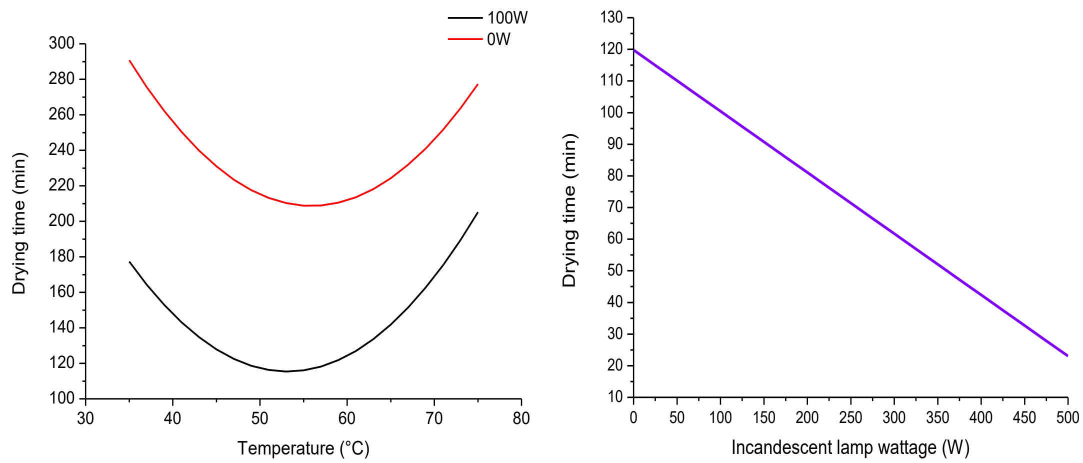
(a) (b)

Fig. 11. (a) Response surface and (b) contour of the drying time of red seaweed (*Chondracanthus chamissoi*) for the independent variables of drying air temperature and incandescent lamp wattage, keeping the critical values of load density and drying air velocity fixed

The result of the additional heat load from the incandescent lamps during the drying period

In Fig. 12 (a and b), the progression of the drying time was simulated, using the regression equation obtained (Table 7) for two different values of the incandescent lamps wattage: 0 and 100 W (Fig. 12a), keeping constant the drying air velocity at 1.5 m s^{-1} and the load density at 4.0 kg m^{-2}, and in a temperature range of 53-55 °C, the minimum values reached of the drying time to reach the moisture value in wet basis of 10% in the product, was approximately 208 and 115 minutes for the 0 and 100 W incandescent lamp wattage, respectively.

Data were simulated for the values of: Temperature and drying air velocity of 60 °C and 1.5 ms^{-1}, respectively, and load density of 4 kg m^{-2} (Fig. 12b). Using the regression equation (Table 7), it is observed that the drying time decreases progressively when the drying process is assisted by the additional energy provided by the incandescent lamps. The drying time decreases by approximately 40-45% for the ranges of values tested.



(a) (b)

Fig. 12. (a) Behavior of the drying times versus air temperature for two values of the incandescent lamp wattage with constant drying air velocity (1.5 m s^{-1}) and charge density (4.0 kg m^{-2}); (b) Graphical simulation of the drying times of the red seaweed for variations of the incandescent lamp wattage

Effective diffusivity results of water

The effective diffusivity of water was

calculated on the basis of Fick's second law (Eq. 5, Fig. 13a), The effective diffusivity of water was calculated for an average thickness of 0.5 mm of the seaweed layer, obtaining the value of 2.03×10^{-11} $m^2\ s^{-1}$.

The drying curve (Eq. 3) was simulated, as shown in Fig. 13b, demonstrating a coefficient of determination R^2 = 0.9275. The diffusivity value found is in concordance with the values reported by different authors in the drying of agro-industrial products and residues, as presented in Table 9.

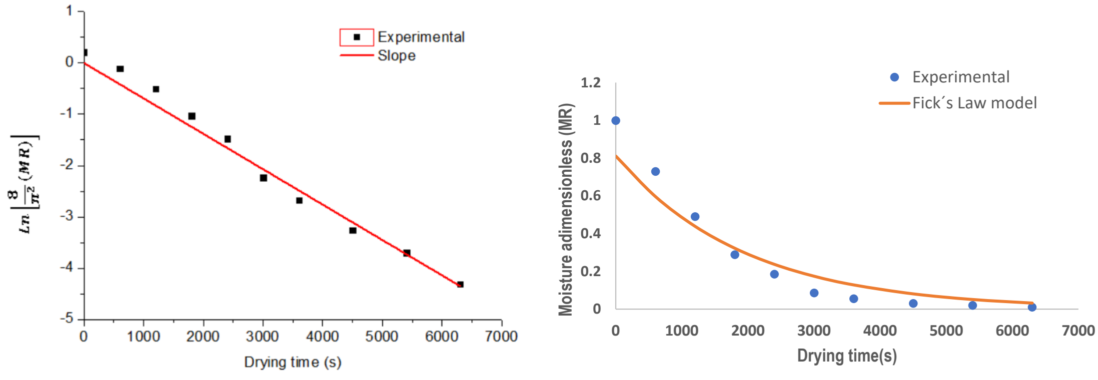


Fig. 13. (a) Determination of the slope for the calculation of diffusivity; (b) Drying curve and simulation with the Fick equation of red seaweed (*Chondracanthus chamissoi*)

Table 9- Some values of effective diffusivity of water in agro-industrial products

Product	Temperature	Effective diffusivity D_{eff} ($m^2\ s^{-1}$)	Reference
Rice husk	30 a 60 °C	$8{,}42\cdot10^{-9} - 1{,}69\cdot10^{-8}$	(Thakur & Gupta, 2006)
Powdered peanut shell	50 a 90 °C	$9{,}60\cdot10^{-9} - 2{,}26\cdot10^{-8}$	(Chen, Li, & Zhu, 2012)
Cut apple 1cm^3	45 a 90 °C	$6{,}7\cdot10^{-10} - 2{,}7\cdot10^{-9}$	(Lewicki & Korczak, 1996)
Blueberries	30 a 70 °C	$1{,}0\cdot10^{-10} - 2{,}0\cdot10^{-10}$	(Ramaswamy & Nsonzi, 1998)
Gracilaria chilensis seaweed	30 a 70 °C	$2{,}76\cdot10^{-9} - 22{,}41\cdot10^{-9}$	(Vega, Lemus, Tello, Miranda, & Yagnam, 2009)

Result of mathematical modeling of drying curve

In Fig. 14, the fit of the experimental data of moisture on the dry basis versus drying time, with the continuous line of the mathematical model using the equation of Midilli et al. is presented, which gave the best mathematical fit. The data of the equation constants are shown in Table 10. Additionally, the values of the coefficients of determination (R^2), the sum of squared errors (SSE), the root mean squared errors (RMSE), the relative mean percentage error (ERM), and the reduced Chi-square value (χ^2) are shown in Table 10.

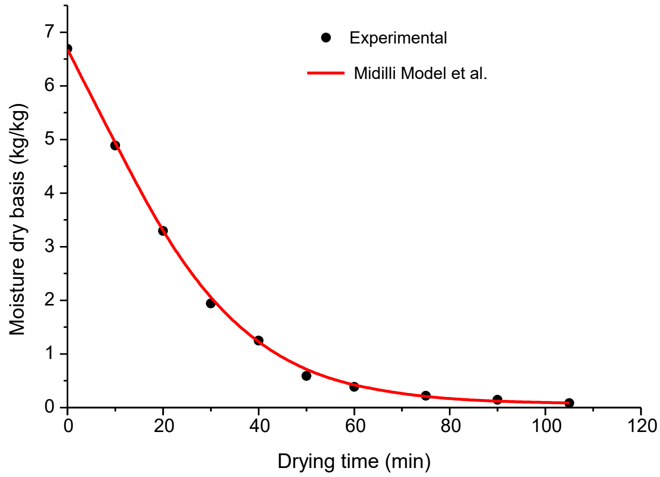


Fig. 14. Drying curve and mathematical model of red seaweed (*Chondracanthus chamissoi*) drying under optimum conditions.

We can also affirm that Page's model is competent for the results found in the adjustment of the experimental data. Thus, Midilli et al. and Page, are the mathematical models that best simulate the distribution of the data to the red seaweed drying curve, since they presented the highest values of the coefficient of determination and the lowest values of the relative errors calculated as: SSE, RMSE, ERM, and χ^2. Midilli's mathematical model is being referred to as a suitable model to represent the drying behavior of agro-industrial products (Midilli, Kucuk, & Yapar, 2002; Vivanco-Pezantes & Nieto-Freire, 2021).

Table 10- Parameter values and statistics of the mathematical models for modeling the drying curve of red seaweed (*Chondracanthus chamissoi*)

Model	Constants		R^2	SSE	RMSE	EMR (%)	χ^2
Henderson-Pabis	a	0.7445	0.9016	0.0085	0.0924	29.8322	0.0104
	k	0.0479					
Modified Henderson-Pabis	a	0.0000	0.9016	0.7999	0.8944	29.7987	1.7598
	k	0.9995					
	b	0.1695					
	g	0.0479					
	c	0.5750					
	h	0.0479					
Page	k	0.0174	0.9994	0.0030	0.0550	9.9102	0.0035
	n	1.2484					
Modified Page	k	0.0362	0.9914	0.0402	0.2006	23.0535	0.0492
	n	1.1139					
Newton	k	0.0404	0.9914	0.0402	0.2006	23.0535	0.0443
Midilli et al.	a	0.9982	0.9995	0.0023	0.0483	0.75871	0.00366
	k	0.0165					
	n	1.2675					
	b	0.0001					

Results of drying kinetics

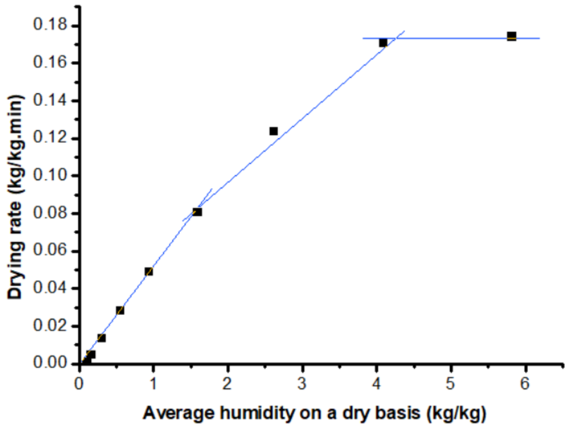
With the experimental data obtained using the mean parameters of the optimized independent variables, the drying rate is plotted versus the mean dry basis moisture (Fig. 15). It can be seen qualitatively that the seaweed, while drying, presents three drying periods: a period of constant rate and two periods of decreasing rate. The constant drying rate is presented with an average value of 0.172 kg kg^{-1} min^{-1} and a duration of 20 minutes, then follows two diffusional periods represented by the slopes. The first slope starts with a humidity of 4.0 kg kg^{-1} and ends at an average humidity of about 1.50 kg kg^{-1}. The second slope ends at a humidity of 0.10 kg kg^{-1} and in these stages, the drying rate is observed to be decreasing linearly with the drying rate versus time.

The continuous curve of drying rate versus drying time (Fig. 16) was obtained using the calculated values of drying rate with the equation of Midilli *et al.* It is observed that the maximum rate of water removal during the drying process occurs at minute 20, i.e., during the short period of constant rate reaching a value of about 0.172 kg kg^{-1} min^{-1}.

The mathematical modeling of the variation of drying rate versus average dry moisture, for the first (I) and second (II) diffusional periods of drying rate is presented in Eqs. 11 and 12, respectively:

$$R_I = 0.0357X + 0.0269 \quad (R^2 = 0.9938) \tag{11}$$

$$R_{II} = 0.0540X - 0.0027 \quad (R^2 = 0.9970) \tag{12}$$



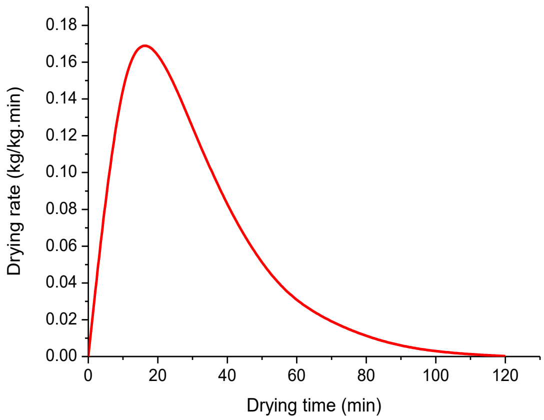


Fig. 15. Red seaweed drying kinetics (*Chondracanthus chamissoi*) with hot air assisted by incandescent lamps: drying rate versus average moisture on a dry basis

Fig. 16. Drying kinetics of red seaweed (*Chondracanthus chamissoi*) with hot air assisted with incandescent lamps: drying rate versus drying time

Drying technologies have been extensively studied for their ability to optimize both efficiency and product quality. For instance, Purnomo and Fzahruddin (2024) developed a cabinet-type dryer for corn, utilizing incandescent-halogen lamps and varying blower speeds. Their findings demonstrated a significant reduction in drying time, ranging from 20% to 30%. Similarly, Patil *et al.* (2019) designed a tunnel-type solar dryer equipped with high-powered incandescent lamps for nighttime drying of coriander. This system maintained an average temperature of 32.5 °C and successfully met drying performance expectations, highlighting the versatility of combined drying approaches.

The influence of specific drying techniques on moisture diffusion and drying kinetics has also been investigated. Soysal, Keskin, Arslan, and Sekerli (2018) explored the effects of maturity stages and infrared drying on green pepper slices. They observed that infrared drying significantly shortened drying times and enhanced moisture diffusivity, with values ranging from 0.5363×10^{-10} to 1.1369×10^{-10} m^2 s^{-1} at temperatures between 50 °C and 70 °C. These findings align with our observations, where drying kinetics of *Chondracanthus* *chamissoi* revealed similar improvements in efficiency under optimized conditions.

The preservation of bioactive compounds during drying remains a critical challenge. Aladag *et al.* (2020) reported substantial reductions in total phenolic content, with levels decreasing from 83.07% in fresh fruit to 52.13% post-drying. Similarly, Snoussi *et al.* (2021) demonstrated that drying methodology strongly influenced phenolic content and antioxidant activity in *Myrtus communis* leaves. While microwave drying preserved higher phenolic levels, temperatures above 100 °C caused significant degradation. These findings emphasize the importance of controlling drying parameters to balance efficiency and quality.

In this study, the drying process of *Chondracanthus chamissoi* was optimized using response surface methodology. Second-order polynomial equations were developed to predict global acceptance, total phenolic content, and drying time. Optimal conditions were: a load density of 9.13 kg m^{-2}, lamp wattage of 374.5 W, temperature of 63.3 °C, and air velocity of 1.88 ms^{-1}. Under these conditions, drying time was reduced to approximately 100 minutes, with a phenolic content of 250 mg GAC/100 g_{db} and a global acceptance score of 8.9.

Statistical analysis confirmed the reliability of the mathematical models, with high determination coefficients validating the regression equations. The drying kinetics revealed a constant rate phase followed by two decreasing rate periods, consistent with previous studies. Furthermore, the Midilli *et al.* model provided the best fit for the drying curves, achieving an R^2 value of 0.93. The calculated effective water diffusivity of 2.03×10^{-11} m² s^{-1} aligns with values reported for other agro-industrial products.

These findings not only validate the application of hot air drying assisted with incandescent lamps for red seaweed but also provide a foundation for future studies aiming to optimize drying processes while preserving product quality.

Conclusion

The different types of dryers used in agribusiness play a crucial role in the production of dry products, most of them using convective drying with hot air. One of the critical variables in the process is the drying time, due to the high humidity of the food. Drying studies are currently being developed, which are assisted by additional energy (infrared, microwaves, ultrasound, etc.) to improve the quality and decrease the drying time of food products. In this research, radiant energy was added through incandescent lamps in the drying chamber, and the optimum conditions for this process were determined using Response Surface Methodology, by means of a Rotational Central Composite Design (RCCD), which were: load density 9.13 kg m^{-2}, power of the incandescent lamps 374.5 W, and temperature and drying air velocity of 63.3 °C and 1.88 m s^{-1}, respectively. Using mathematical regression, it allowed us to predict that the drying time decreases approximately 40-45% for the range of the tested values during experimental planning. In the same way, it was observed that the phenolic content of the red seaweed decreases as the drying air temperature increases. In optimal conditions, the drying curve of the red seaweed was studied and simulated, and it was found that it presents a constant drying rate and two periods of decreasing rate, being the maximum moisture migration of 0.172 kg kg^{-1} min^{-1} at 20 minutes of drying. It was confirmed that the model of Midilli *et al*. presented the best adjustment of the simulated drying curve to the experimental data (R^2 = 0.9995). In the same way, all the constants of the mathematical models tested were determined. Likewise, the effective water diffusivity under these conditions was 2.03×10^{-11} m^2 s^{-1}, a value very similar to those published in the drying of other agro-industrial products. The use of this technological proposal demonstrated that it is possible to obtain dried seaweed by means of the contribution of additional energy provided by the incandescent bulbs, which allows to obtain shorter drying times. Future research should carry out studies on the optimization of food drying processes with variants of extra energy assistance that will make it possible to develop more efficient processes to improve the nutritional and sensory quality of the food.

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Authors Contribution

Emily Elena Vivanco-Cuba: Review of the conceptualization and Methodology of the research project. She carried out laboratory determinations and analyses of the research project tests. Assisted in the data acquisition process and was responsible for filling in the data in a spreadsheet. Reviewed the statistical analyses and the obtained mathematical models.

David Vivanco Pezantes: Supervision, Conceptualization, and Methodology of the research project. He acquired technical advice in the laboratory activities. The data acquisition and its subsequent processing were carried out in a spreadsheet, and he was responsible for the pre- and post-processing of the data. The statistical analyses were carried out using free software available on the Internet, with which the mathematical simulations were achieved using response surface methodology

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بهینه‌سازی خشک کردن جلبک قرمز دریایی (*Chondracanthus chamissoi*) با هوای گرم و با کمک لامپ رشته‌ای با استفاده از روش سطح پاسخ

ای. النا ویوانکو-کوبا[۱]، دی. ویوانکو-پزانتس[۲*]

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چکیده

جلبک‌های دریایی به‌خاطر ارزش‌های تکنولوژیکی، تغذیه‌ای و سلامتی آن‌ها شناخته می‌شوند. برای تثبیت و حفظ کیفیت محصول در طول انبارداری خشک کردن آن‌ها ضروری است. در این تحقیق، با استفاده از روش سطح پاسخ مدل‌های ریاضی خشک کردن به‌صورت توابع چندجمله‌ای ارائه شده‌اند. تاثیر متغیرهای مستقل خشک کردن شامل چگالی بار (۱/۷۰-۱۵ کیلوگرم بر متر مربع)، توان لامپ رشته‌ای (۰-۵۰۰ وات)، دما (۳۰-۷۰ درجه سانتی‌گراد) و سرعت هوا (۰/۵-۲/۵ متر بر ثانیه) بر متغیرهای پاسخ شامل پذیرش جهانی (--)، محتوای فنلی کل (معادل میلی‌گرم گالیک اسید در ۱۰۰ گرم وزن خشک) و زمان خشک کردن (دقیقه) مورد مطالعه قرار گرفت. این مطالعه نشان داد که دما و توان لامپ رشته‌ای در طی خشک کردن به‌طور قابل‌توجهی بر محتوای فنلی کل تاثیر می‌گذارند. خشک کردن بهینه در شرایط چگالی بار ۹/۱۳کیلوگرم بر متر مربع، وات لامپ رشته‌ای ۳۷۴/۵وات، دما و سرعت هوای خشک‌کن به‌ترتیب ۶۳/۳ درجه سانتی‌گراد و ۱/۸۸ متر بر ثانیه حاصل شد. نتایج همچنین نشان می‌دهد که افزایش توان لامپ‌های رشته‌ای منجر به کوتاه‌تر شدن زمان خشک شدن تا ۴۰-۴۵ درصد می‌شود. برای شرایط بهینه از مدل‌های ریاضی برای شبیه‌سازی منحنی خشک کردن و سینتیک ماده مورد مطالعه استفاده شد. با استفاده از روش شبه نیوتن سیمپلکس، دو مدل میدیلی و همکاران و پیج به‌ترتیب عملکرد بهتری در برازش منحنی‌ها با داده‌های تجربی به‌دست آوردند. تحت این شرایط، مقدار ضریب نفوذ موثر آب در حدود ۲.۰۳×۱۰^{-۱۱} متر مربع بر ثانیه به‌دست آمد که مقداری بسیار شبیه به مقادیر اعلام شده برای محصولات مرتبط با صنایع کشاورزی می‌باشد. اطلاعات به‌دست‌آمده در این پژوهش می‌تواند برای استفاده از پارامترهای به‌دست‌آمده و تکنیک‌های استفاده‌شده برای توسعه تجهیزات و کنترل فرآیند در خشک کردن جلبک دریایی قرمز کمک زیادی کنند.

واژه‌های کلیدی: بهینه‌سازی خشک کردن، روش سطح پاسخ، سینتیک خشک کردن، ضریب نفوذ موثر، محتوای فنلی، مدل‌سازی ریاضی

۱- دانشکده مهندسی شیمی و نساجی، دانشگاه ملی مهندسی، لیما، پرو
۲- دانشکده مهندسی شیلات و مواد غذایی، دانشگاه ملی کالائو، پرو
(*- نویسنده مسئول: Email: dvivancop@unac.edu.pe)

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