Research Article
Vol. 21, No. 6, Jan.-Feb. 2026, p.

Incandescent Lamp-assited Convective Drying of Potato Slices: Optimization Using RSM

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Received: 12.04.2025 Revised: 10.06.2025 Accepted: 26.06.2025 Available Online: 02.12.2025	**How to cite this article:** Vivanco Pezantes, D. (2025). Incandescent lamp-assited convective drying of potato slices: Optimization using RSM. *Iranian Food Science and Technology Research Journal, 21*(6),. https://doi.org/10.22067/ifstrj.2025.92986.1423

Abstract

This research focuses on the application of response surface methodology (RSM) in the optimization and mathematical modeling of potato slice drying in a laboratory-scale convective dryer assisted by incandescent lamps. The relationships between the independent variables in terms of temperature (°C), incandescent lamp power (W), and slice thickness (mm) were studied in relation to the responses of interest or dependent variables, consisting of drying time (min), overall product acceptance, and effective water diffusivity (m^2s^{-1}). A high value of overall product acceptance is considered to be the optimizing parameter for drying potato sheets. The response surface methodology was applied using a rotational central composite design (RCCD) to optimize the dependent variable. Second-order polynomial regression equations were obtained for each response variable. The optimal drying conditions were established for the maximum value of overall acceptance and were: 69.33 °C, 328.80 W, and 4.40 mm, for temperature, power, and thickness, respectively, with the optimized drying time for the product being approximately 130 min. Drying was carried out during the decreasing drying rate period, and the results show that the addition of energy from incandescent lamps reduces the drying time by 30%. Using the Quasi-Newton Simplex method, the constants of the mathematical models were determined to simulate the drying curve, and the conjugate model of two terms and five constants presented the best fit. Using Fick's law equation, the effective diffusivity of water ranged from $4.48x10^{-10}$ to $3.38x10^{-9}$ m^2s^{-1}, and under optimal drying conditions, it was $2.46x10^{-9}$ m^2s^{-1}. The information obtained contributes fundamentally to the development of dryers and the control of drying processes on a commercial and industrial scale.

Keywords: Kinetics, Mathematical modeling, Potato drying, RSM

Introduction

The potato is a tuber that is grown all over the world, the world production of potatoes is approximately 341 million tons and statistically China is the main producer whose production reaches between 66 and 71 million tons, whereas Peru became the first potato producer in Latin America, with a production of 5,7 million tons registered in 2021. The Yungay potato (*Solanum tuberosum* L.) contains interesting nutritional characteristics that make it, according to nutrition specialists, a food of high nutritional value and is already an alternative for developing countries with food shortages (Midagri, 2023; Flores & León, 2019; FAO, 2023).

High moisture content in foods is a major factor affecting quality, physicochemical properties and nutrients during the postharvest stage and one way to stabilize food and extend

https://doi.org/10.22067/ifstrj.2025.92986.1423

its shelf life is to partially remove its water content, thereby reducing the product's water activity (a_W) to a level that prevents the growth of microorganisms such as fungi and inactivates enzymes. This is essentially what is achieved in the unit operation of drying used in the food industry (Tahmasebi *et al*., 2025; Konar, Durmaz, Genc Polat, & Mert, 2022; Kushwah, Kumar, & Gaur, 2023; Madukasi, Onyenanu, Oghenekaro, Nzenwa, & Madu, 2025).

Hot air drying is a widely used method in agroindustry, where it is possible to control drying variables and obtain good quality dry products. This has the additional benefits such as weight and volume reduction that result in a decrease in food transportation and storage costs (García, Muniz, Hernandez, Gonzales, & Fernandez, 2013; Gongora, 2012; Gudiño & Calderon, 2014).

The drying of agro-industrial products requires high energy consumption due to the initial moisture content of the product, so it is necessary to accelerate the drying process due to the significant advantages for both the consumer and the producer. One alternative is to use technological assistance such as microwaves and/or infrared to reduce drying times and improve product quality (Huang, Yang, Tang, Luo, & Sunden, 2021; Bouhile *et al*., 2025; Ouyang *et al*., 2025), However, almost no research has been conducted using incandescent lamps.

The product leaving the dryer must be analyzed sensorily to establish its quality as a final product or intermediate manufacturing product. Sensory analysis is an important tool for quality control in food manufacturing processes. One of the tests frequently used to measure the degree of product acceptability is the hedonic scale. The consumer panel (known as consumer analysis) analyzes the respective hedonic attributes of the product: smell, taste, aroma, texture, and overall impression. This test is used to measure the degree of liking or disliking of the product and is acceptable and valid even when untrained tasters and volunteers are used to analyze and define the overall acceptability of the product. (Espinaco, Niizawa, Cuffia, Zorrilla, & Sihufe, 2025; Höhl & Dreyer, 2025; Tangkham, Vuong, Bui, Nooritthi, & Shields, 2025).

In industrial processes, the application of statistical tools for process optimization is common practice. Mathematical modeling is a very important tool that aids in the design, development, optimization, and control of food drying systems, enabling the creation of more sustainable food production systems. Experimental data from agricultural products at various drying temperatures using several well-known mathematical models yield very high R^2 and the lower values of the relatives error (Simal, Femenia, Garau, & Rosello, 2005; Midilli, Kucuk, & Yapar, 2002; Vega, Lemus, Tello, Miranda, & Yagnam, 2009; Ravi, Prashant, Nishant, & Om Prakash, 2025; Van der Werf, Cavalera, Delpech, Chapuis, & Courtois, 2023; Chen & Pan, 2023).

Knowledge of optimized drying parameters of biological materials is critical in the design and control of industrial processes. Countless studies have been conducted to investigate their production and utilization of potatoes in general, however, to date, no study has been found and reported on the application of the response surface methodology in hot air drying assisted with incandescent lamps on Yungay potato slices. Therefore, the present study was conducted with the following objectives: 1) To dry Yungay potato slices using the response surface methodology and to investigate the effect of temperature, lamp power and slice thickness on the response variables: drying time, global product acceptance and effective water diffusivity, 2) To determine the optimum parameters of the drying process and 3) to model the drying and calculate the effective diffusivity under the optimized conditions.

Materials and Methods

Raw Materials and Pretreatment

The samples were taken "in situ" in the market of the district of Bellavista Constitutional Province of Callao-Lima-Peru. The Yungay potato with an initial moisture content of 76.97 +/- 0.517 % on a wet basis, was transported to the university city of the National University of Callao and then placed in a refrigerator and kept at a cold storage temperature of 5ºC, the quantity was sufficient for the experimental runs, considering the dimensions and capacity of the dryer tray at the laboratory scale of the Process Engineering and Unit Operations Laboratory, the loads were approximately 140 g of Yungay potato slices on average. The moisture of the potato was determined via oven at 105ºC until constant weight according to the AOAC method. The potato samples were washed with running water at room temperature and the damaged samples were separated. The selected samples, once washed, peeled and cut into slices were previously subjected to an immersion treatment in a citric acid solution (0,5% w/w) for 60 seconds to prevent enzymatic browning and then were drained and the remaining surface moisture was removed with soft paper towels. The sample was then placed in a stainless-steel sample holder, the sample holder was previously conditioned so that the slices with an average diameter of 60 mm and thicknesses of 2, 2.81, 4, 5.19 and 6 mm were vertically (Fig. 1) and conveniently separated to create the conditions for "drying on both sides". The initial information was recorded in a spreadsheet (EXCEL) for data collection of the corresponding experimental run.

Fig. 1. Vertical arrangement of potato slices in the sample holder

Hot-air assisted drying system with incandescent lamps

Fig. 2, shows the laboratory-scale dryer used for the experimental runs, designed and built by the researcher of this study, which is installed in the Laboratory of Process Engineering and Unit Operations of the Faculty of Fisheries and Food Engineering of the National University of Callao.

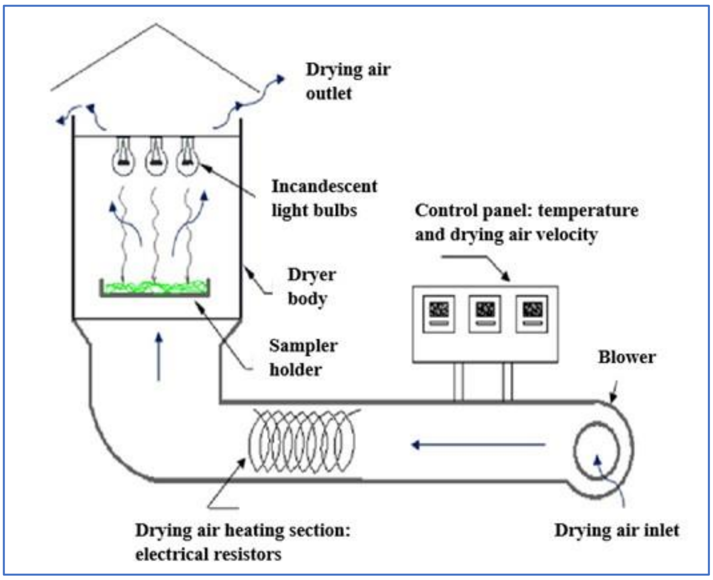


Fig. 2. Schematic of laboratory scale dryer

Determination of Global Acceptance

The Global Acceptance Test was conducted with 30 untrained panelists (15 men and 15 women), including students, professors, and administrative staff from the Professional School of Food Engineering at the National University of Callao. A structured 9-point hedonic scale was used, with 9 corresponding to extreme liking and 1 to extreme dislike for the properties of color, aroma, flavor, texture, and overall impression. The organoleptic property evaluations were always carried out at midday and after the experimental drying runs. Panelists were presented with samples labeled with a three-digit code on plastic plates and given an evaluation form to fill out.

Response Surface Methodology-Research design

Experimental design (Montgomery, 2004) was used to obtain a quadratic polynomial function mathematical equation, as shown in equation 1, where the response variable of drying time depended on the independent variables and the 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, βi are the linear effects, βjj the quadratic effects, and βij the linear interactions.

In Table 1, 2 and 3, the rotatable central composite design is presented with the coded and actual variables and the values of the response variables of global product acceptance, drying time and effective diffusivity of water, experimental and calculated respectively. The independent variables are: temperature (x_1), power of the incandescent lamps (x_2) and slice thickness (x_3), which were investigated at five levels each. The complete design consisted of 20 experimental trials, 08 factorial trials (levels -1 and +1), 06 axial (levels -1.68 and +1.68) and 06 center points (level 0), the latter were made for error estimation. They were carried out in duplicate, totaling 40 trials, which were randomized in order to minimize experimental systematic errors.

Table 1- Rotatable central composite experimental design with the coded and actual values and the response variable of global product acceptance of dried Yungay potato (*Solanum tuberosum* L.) slices

Test	Coded variables			Real variables			Global acceptance(--)		
	x_1	x_2	x_3	Temperature (°C)	Power (W)	Thickness (mm)	Observed value	Estimated value	Relative deviation (%)
1	-1	-1	-1	48.1	91.7	2.81	6	5.6	6.0
2	1	-1	-1	71.9	91.7	2.81	7	6.3	10.6
3	-1	1	-1	48.1	358.9	2.81	8	7.0	12.3
4	1	1	-1	71.9	358.9	2.81	9	8.6	4.1
5	-1	-1	1	48.1	91.7	5.19	6	6.1	1.4
6	1	-1	1	71.9	91.7	5.19	7	7.7	10.1
7	-1	1	1	48.1	358.9	5.19	6	6.5	7.6
8	1	1	1	71.9	358.9	5.19	9	9.1	0.9
9	-1.68	0	0	40	225	4	5	5.3	6.8
10	+1.68	0	0	80	225	4	8	8.1	0.7
11	0	-1.68	0	60	0	4	6	6.0	0.8
12	0	+1.68	0	60	450	4	8	8.4	4.4
13	0	0	-1.68	60	225	2	6	7.3	22.1
14	0	0	+1.68	60	225	6	9	8.1	10.3
15	0	0	0	60	225	4	9	8.7	3.8
16	0	0	0	60	225	4	8	8.7	8.2
17	0	0	0	60	225	4	9	8.7	3.8
18	0	0	0	60	225	4	9	8.7	3.8
19	0	0	0	60	225	4	8	8.7	8.2
20	0	0	0	60	225	4	9	8.7	3.8

Table 2- Rotatable central composite experimental design with the coded and actual values and the response variable of drying time of Yungay potato (*Solanum tuberosum* L.) slices

Test	Coded variables			Real variables			Drying time (min)		
	x_1	x_2	x_3	Temperature (°C)	Power (W)	Thickness (mm)	Observed value	Estimated value	Relative deviation (%)
1	-1	-1	-1	48.1	91.7	2.81	248	227.7	8.2
2	1	-1	-1	71.9	91.7	2.81	89	92.4	3.8
3	-1	1	-1	48.1	358.9	2.81	245	221.8	9.5
4	1	1	-1	71.9	358.9	2.81	88	70.0	20.4
5	-1	-1	1	48.1	91.7	5.19	350	344.3	1.6
6	1	-1	1	71.9	91.7	5.19	170	169.5	0.3
7	-1	1	1	48.1	358.9	5.19	353	326.0	7.7
8	1	1	1	71.9	358.9	5.19	138	134.6	2.4
9	-1.68	0	0	40	225	4	336	370.0	10.1
10	+1.68	0	0	80	225	4	96	95.6	0.4
11	0	-1.68	0	60	0	4	194	196.4	1.2
12	0	+1.68	0	60	450	4	131	162.2	23.8
13	0	0	-1.68	60	225	2	81	104.2	28.6
14	0	0	+1.68	60	225	6	246	256.4	4.2
15	0	0	0	60	225	4	179	184.0	2.8
16	0	0	0	60	225	4	183	184.0	0.6
17	0	0	0	60	225	4	189	184.0	2.6
18	0	0	0	60	225	4	184	184.0	0.0
19	0	0	0	60	225	4	190	184.0	3.2
20	0	0	0	60	225	4	185	184.0	0.5

Table 3- Rotatable central composite experimental design with the coded and actual values and the response variable of the effective diffusivity of water during drying of Yungay potato (*Solanum tuberosum* L.) slices

Test	Coded variables			Real variables			Effective diffusivity (10^{10} m^2/s)		
	x_1	x_2	x_3	Temperature (°C)	Power (W)	Thickness (mm)	Observed value	Estimated value	Relative deviati (%)
1	-1	-1	-1	48.1	91.7	2.81	5.12	5.98	16.8
2	1	-1	-1	71.9	91.7	2.81	13.76	13.68	0.6
3	-1	1	-1	48.1	358.9	2.81	4.48	5.77	28.8
4	1	1	-1	71.9	358.9	2.81	15.68	16.39	4.5
5	-1	-1	1	48.1	91.7	5.19	12.01	11.81	1.6
6	1	-1	1	71.9	91.7	5.19	27.29	26.51	2.8
7	-1	1	1	48.1	358.9	5.19	15.28	15.87	3.9
8	1	1	1	71.9	358.9	5.19	33.84	33.49	1.0
9	-1.68	0	0	40	225	4	7.78	6.51	16.3
10	+1.68	0	0	80	225	4	27.24	27.78	2.0
11	0	-1.68	0	60	0	4	12.32	12.68	2.9
12	0	+1.68	0	60	450	4	19.45	18.36	5.6
13	0	0	-1.68	60	225	2	7.62	6.21	18.5
14	0	0	+1.68	60	225	6	24.80	25.48	2.7
15	0	0	0	60	225	4	14.91	15.88	6.5
16	0	0	0	60	225	4	16.21	15.88	2.1
17	0	0	0	60	225	4	14.27	15.88	11.3
18	0	0	0	60	225	4	16.28	15.88	2.5
19	0	0	0	60	225	4	16.86	15.88	5.8
20	0	0	0	60	225	4	16.60	15.88	4.4

Effective Diffusivity of Water 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 M, is the dimensionless humidity, X, X_o and X_{eq} is the humidity at time t, initial and equilibrium, respectively, D_{eff} is the effective diffusivity, t is the time and L is the sample semi-thickness.

The terms of the infinite series of eq. 2, converge rapidly with increasing drying time and considering only the first term of the series results in small errors even without considering the effect of shrinkage (Celma, Rojas, & Lopez-Rodriguez, 2008), eq. 3, Therefore, linearizing eq. 3, results in eq. 4,

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

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

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^2s^{-1}).

Mathematical Simulation of the Drying Curve

Ten mathematical models (Table 4) were used to simulate the drying curve of the optimum conditions proposed in the literature sources, such as: Lewis, Diffusional , Henderson-Pabis two-term, Sigmoid model, Page, Page modified I and II, Henderson-Pabis, Midilli *et al.* and Two-term conjugate model (Uribe *et al*., 2011; Celma *et al*., 2008; Erbay & Icier, 2009; Botelho *et al*., 2011; Sharma, Verma, & Pathare, 2005; Vivanco & Nieto, 2021; Vivanco, 2023).

Table 4- Mathematical models for the simulation of the drying curve

Model	equation	Bibliographic source
Lewis or Newton model	$MR = e^{(-k\cdot t)}$	Marinos-Kouris & Maurolis (1995)
Diffusional Model	$MR = ae^{(-k_1\cdot t)} + (1-a)e^{(-k_2\cdot t)}$	Verma et al. (1985)
Drying with double kinetics or modified Henderson and Pabis equation with two terms	$MR = ae^{(-k_1\cdot t)} + be^{(-k_2\cdot t)}$	Karathanos (1999)
Sigmoid Model	$MR = \frac{a}{1+e^{\frac{t-b}{c}}}$	Oviedo-Lopera et al (2017)
Page Model	$MR = e^{(-k\cdot t^n)}$	Page (1949)
Modified Page-I	$MR = e^{(-k\cdot t)^n}$	Overhults et al. (1973)
Modified Page-II	$MR = e^{\left[-k\left(\frac{t}{l^2}\right)^n\right]}$	Diamante & Munro(1993)
Henderson-Pabis model	$MR = a\cdot e^{(-k\cdot t)}$	Henderson-Pabis (1961)
Midilli et al.	$MR = a\cdot e^{(-k\cdot t)} + b\cdot t$	Midilli et al.(2002)
Two-term conjugate model	$MR = a\cdot e^{(-k_1\cdot t^n)} + b\cdot e^{(-k_2\cdot t^n)}$	Vivanco (2023)

The adjustment of the constants of the equations used was determined using the SOLVER computer package that estimates the calculation of the nonlinear parameters by the application of the Quasi-Newton Simplex method of the Microsoft Corporation MS-Excel®. The least squares regression technique was applied to study the behavior of the drying kinetics.

Results and Discussion

Experimental Design Result Using the Response Surface Methodology (RSM)

Tables 5, 6, and 7 present the analysis of variance for the sources of variation in the regression equations that generate the response surfaces related to overall acceptance, drying time, and effective diffusivity, respectively. The F values calculated in this relationship are: 4.657, 28.430, and 79.898, respectively. When these values are compared with the F value in Table: F (5%, 9,10) = 3.02; the calculated F value exceeds the Table F value by ratios of: 1.54, 9.41, and 26.46, respectively. The result indicates that the mathematical regression models of the response surfaces are statistically valid for predicting the response variables within the ranges established in the research.

Table 5- Analysis of variance of global acceptance of dried Yungay potato (*Solanum tuberosum* L.) slices

	Sum of squares	N° degrees of freedom	Quadratic mean	Calculated F-value
Regression	28.10	9	3.122	4.657
Residues	6.70	10	0.670	
Lack of fit	5.371	5	1.074	4.03
Pure erro	1.333	5	0.267	
Total	34.80	19		

Table 6- Analysis of variance of the drying time of dried Yungay potato (*Solanum tuberosum* L.) slices

Source of variance	Sum of squares	N° degrees of freedom	Quadratic mean	Calculated F-value
Regression	125961.00	9	13995.667	28.430
Residues	4922.80	10	492.280	
Lack of fit	4840.80	5	968.160	59.034
Pure erro	82.00	5	16.400	
Total	130883.80	19		

Table 7- Analysis of variance of effective diffusivity of dried Yungay potato (*Solanum tuberosum* L.) slices

Source of variance	Sum of squares	N° degrees of freedom	Quadratic mean	Calculated F-value
Regression	1075.67	9	119.519	79.898
Residues	14.96	10	1.496	
Lack of fit	9.682	5	1.936	1.83
Pure erro	5.277	5	1.055	
Total	1090.63	19		

Tables 1, 2 and 3 show the values of the response variables that were obtained experimentally during the hot air-drying tests assisted with incandescent lamps. Table 8 shows the regression coefficients of the coded models developed in the estimation of the response variables: global acceptance of the product, drying time and effective diffusivity of water with values of the coefficients of determination of 0,807; 0,962 and 0,986; respectively.

Table 8- Regression coefficients for the response variables of the drying process of Yungay potato (*Solanum tuberosum* L.) slices with hot air assisted by incandescent lamps

Encoded parameter	Regression coefficient		
	Global acceptance (--)	Drying time (min)	Effective diffusivity (m^2/s)
β_o	8,655	184,007	15,877
x_1	0,809	-81,657	6,330
x_2	0,686	-10,175	1,691
x_3	0,223	45,307	5,735
x_1^2	-0,693	17,279	0,450
x_2^2	-0,515	-1,676	-0,126
x_3^2	-0,338	-1,322	-0,011
$x_1 \cdot x_2$	0,250	-4,125	0,730
$x_1 \cdot x_3$	0,250	-9,875	1,750
$x_2 \cdot x_3$	-0,250	-3,125	1,067
R^2	0,8074	0,9624	0,9863
$MQ - pure\ error$	0,267	16,400	1,055
$F_{calculated}/F_{table}$	1,54	9,41	26,5

Equations 5, 6 and 7 are presented to estimate the values of global product acceptance (AG), drying time (ϑ) and effective water diffusivity (D_{eff}) respectively, are:

$$AG = 8{,}6548 + 0{,}8091\left(\frac{T-60}{11{,}90}\right) - 0{,}6925\left(\frac{T-60}{11{,}90}\right)^2 + 0{,}6860\left(\frac{P-225}{133{,}93}\right) - 0{,}5154\left(\frac{P-225}{133{,}93}\right)^2 + 0{,}2228\left(\frac{E-4}{1{,}19}\right) - 0{,}3382\left(\frac{E-4}{1{,}19}\right)^2 + 0{,}2500\left(\frac{T-60}{11{,}90}\right)\left(\frac{P-225}{133{,}93}\right) + 0{,}2500\left(\frac{T-60}{11{,}90}\right)\left(\frac{E-4}{1{,}19}\right) - 0{,}2500\left(\frac{P-225}{133{,}93}\right)\left(\frac{E-4}{1{,}19}\right)\ (--) \quad (5)$$

$$\vartheta = 184{,}0069 - 81{,}6575\left(\frac{T-60}{11{,}90}\right) + 17{,}2793\left(\frac{T-60}{11{,}90}\right)^2 - 10{,}1753\left(\frac{P-225}{133{,}93}\right) - 1{,}6762\left(\frac{P-225}{133{,}93}\right)^2 + 45{,}3066\left(\frac{E-4}{1{,}19}\right) - 1{,}3219\left(\frac{E-4}{1{,}19}\right)^2 - 4{,}1250\left(\frac{T-60}{11{,}90}\right)\left(\frac{P-225}{133{,}93}\right) - 9{,}8750\left(\frac{T-60}{11{,}90}\right)\left(\frac{E-4}{1{,}19}\right) - 3{,}1250\left(\frac{P-225}{133{,}93}\right)\left(\frac{E-4}{1{,}19}\right)\ (\text{min}) \quad (6)$$

$$D_{eff} = \left[15{,}8766 - 6{,}330\left(\frac{T-60}{11{,}90}\right) + 0{,}4499\left(\frac{T-60}{11{,}90}\right)^2 + 1{,}6914\left(\frac{P-225}{133{,}93}\right) - 0{,}1260\left(\frac{P-225}{133{,}93}\right)^2 + 5{,}7344\left(\frac{E-4}{1{,}19}\right) - 0{,}01104\left(\frac{E-4}{1{,}19}\right)^2 + 0{,}730\left(\frac{T-60}{11{,}90}\right)\left(\frac{P-225}{133{,}93}\right) + 1{,}750\left(\frac{T-60}{11{,}90}\right)\left(\frac{E-4}{1{,}19}\right) + 1{,}0675\left(\frac{P-225}{133{,}93}\right)\left(\frac{E-4}{1{,}19}\right)\right]10^{-10}(m^2s^{-1}) \quad (7)$$

Results of the Response Variable: Global Product Acceptance

Since the global acceptance of the product is a determining factor in the drying process, the process optimization analysis will be defined with the maximum value reached in the degree of acceptance of the product as the dependent variable in the response surface. It will start by evaluating the effects of the independent variables: Temperature, Power and Thickness, on the variable: Global Acceptance.

Fig. 3 shows the pareto diagram of the influence of the independent variables on the response variable of global product acceptance. It can be observed that the independent variables of temperature and power of the incandescent lamps in their linear and square form directly influence the global acceptance of the product, but not so much the thickness of the product. Fig. 4 shows a considerable distribution of the experimental values (observed) and the calculated values (estimated) by means of equation 1 of the mathematical model obtained to generate the response surface. An acceptable approximation of the coordinate pair of data to the straight line is visualized, whose coefficient of determination obtained was R^2 =0,8074, being equation (5) that models the behavior of the global acceptance of the potato slices (AG) of the Yungay potato slices of the experimental design achieved.

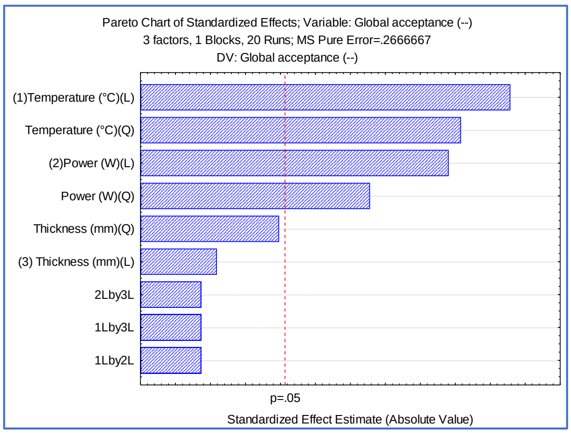


Fig. 3. Pareto diagram of the independent variables on the response variable of global product acceptance of Yungay potato (*Solanum tuberosum* L.) slices

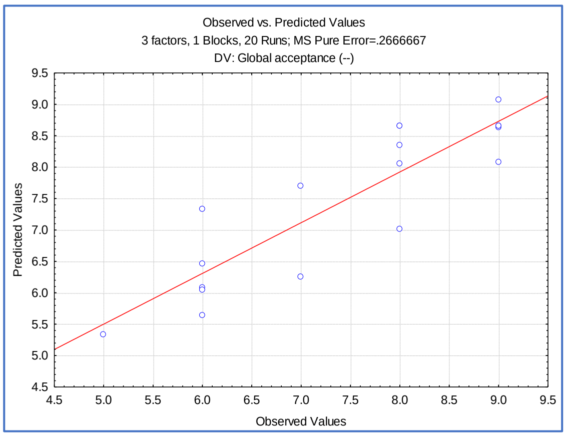
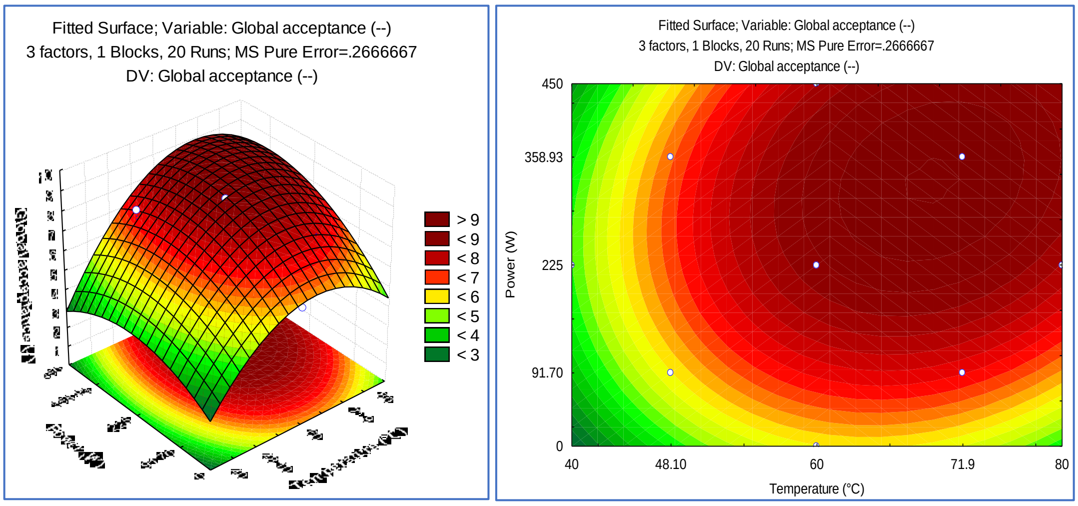


Fig. 4. Observed and calculated values of the global acceptability of Yungay potato (*Solanum tuberosum* L.) slices

In the response and contour surface shown in Fig. 5 (a, b), the maximum critical values correspond to the coded variables of x_1 x_2 y x_3 of 0,784; 0,775 and 0,333; which are corresponding to their real variables of: Temperature= 69,33 °C, Power = 328,8 W and Slice thickness = 4,40 mm respectively. Using the Statistica program, the estimated value of the drying time for these conditions is 130,75min (being the 95% confidence level interval: 125,7-135,8min).



(a) (b)

Fig. 5. Response surface (a) and contour surface (b) for the global product acceptance as a function of the power of the incandescent lamps and the air temperature in the drying of Yungay potato slices

Results of the Response Variable: Drying Time

Fig. 6 shows the Pareto plot for the analysis of the effect of the independent variables of the drying air temperature, incandescent lamp power and slice thickness of the Yungay potato on the response variable of drying time (min). It can be observed that the three independent variables have a linear effect on the response variable, as follows: temperature, incandescent lamp power and slice thickness have a significant effect on the drying time of the potato slices.

Likewise, the independent variables in its squared form, temperature, and jointly the power of the lamps and thickness are in the limit of affectation. Even so, in order that the mathematical regression model does not lose precision, all the variables in linear, conjugate and quadratic form were considered in the equation of the mathematical model. In Fig. 7, the experimental values (observed) and the calculated values (estimated) are distributed in coordinate points very close to the straight line whose coefficient of determination obtained was R^2 =0,9624, being the equation (6) that models the behavior of the drying time $(\vartheta)(min)$ of the Yungay potato slices of the experimental plan obtained.

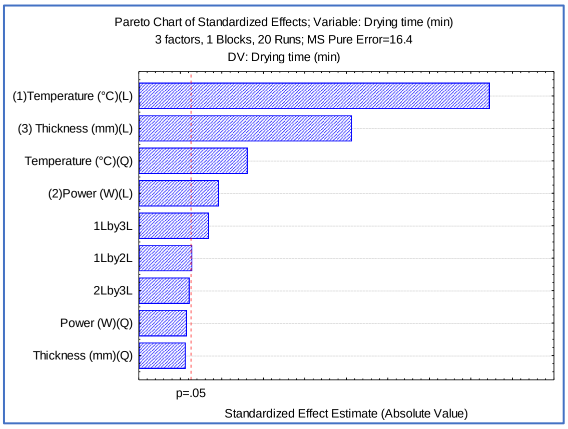


Fig. 6. Pareto diagram of the independent variables on the response variable drying time of Yungay potato (*Solanum tuberosum* L.) slices

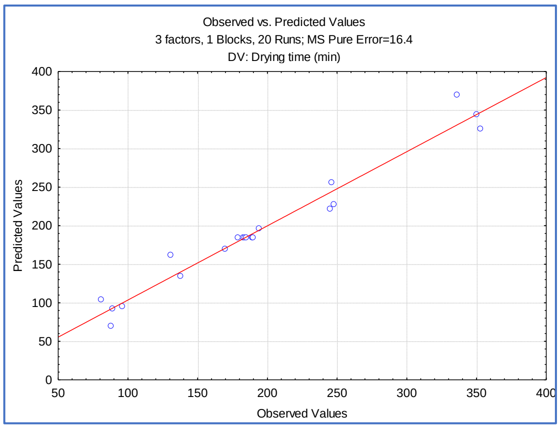
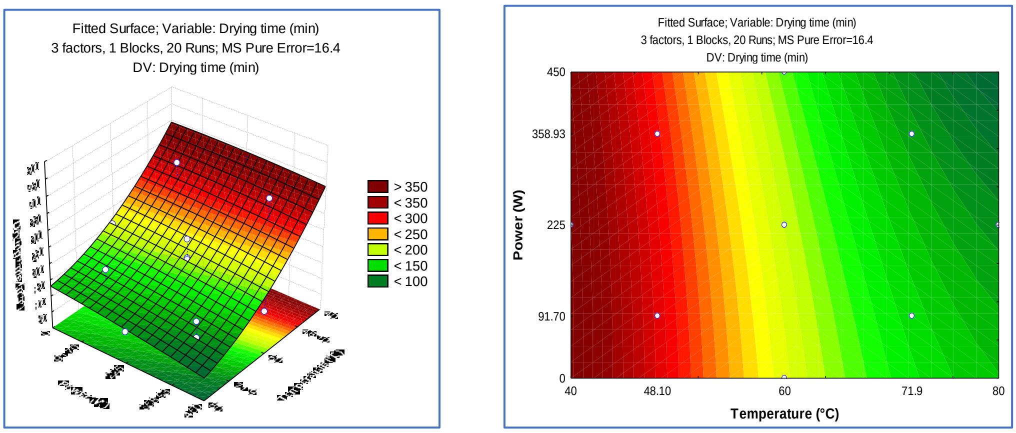


Fig. 7. Observed and calculated values of the drying time of Yungay potato (*Solanum tuberosum* L.) slices

Fig. 8 (a and b) shows the response and contour surface of the drying time (min).



(a) **(b)**

Fig. 8. Response surface (a) and contour (b) of the drying time of Yungay potato (*Solanum tuberosum* L.) slices for the independent variables: drying air temperature and lamp power, maintaining the slice thickness at optimum conditions

For the drying air temperature and power of the lamps for the optimum conditions of 4.40 mm slice thickness (or coded variable of 0,333) to achieve approximately 12% wet basis (13,6% of dry basis), they are reduced to lower values of drying at 150 minutes of drying. The independent variables behave inversely proportional to the drying time, as the values of the independent variables increase the drying times decrease.

Results of the Response Variable: Effective Diffusivity of Water

Fig. 9 shows the Pareto plot for the analysis of the effect of the independent variables of the drying air temperature, power of the incandescent lamps and thickness of the Yungay potato slice on the response variable of the effective diffusivity of water during drying of the Yungay potato slices. It can be observed that the three independent variables linearly affect the response variable, while in the combined-interactive form, temperature with thickness and power with thickness have the greatest effect on the effective diffusivity of water in the drying of Yungay potato slices.

Fig. 10 shows the observed and estimated values of the effective diffusivity of water during the process of drying with hot air assisted by incandescent lamps of Yungay potato slices according to the experimental design obtained with Equation 7. The pair of values are distributed in coordinate points very close to the straight line whose coefficient of determination obtained was R^2 =0,9863, so a high degree of prediction of this variable has been obtained according to the experimental design.

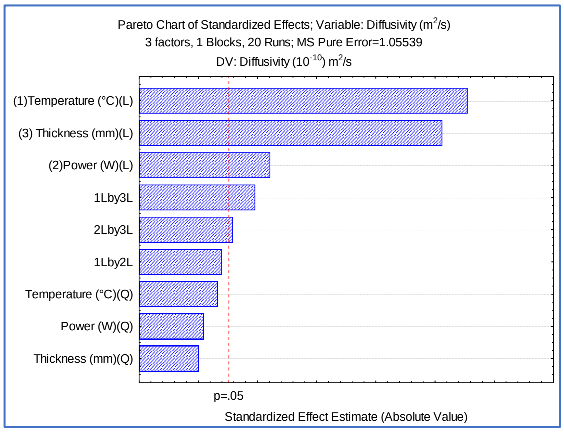


Fig. 9. Pareto diagram of the independent variables on the response variable of the effective diffusivity of water in drying

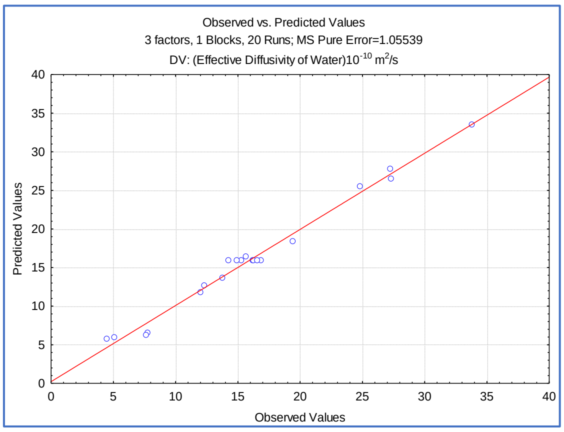
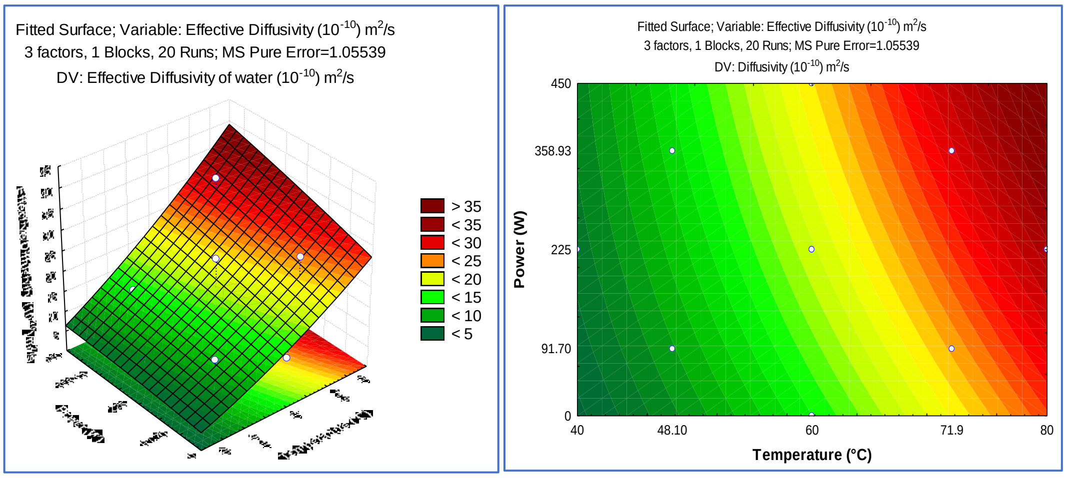


Fig. 10. Observed and calculated values of the effective diffusivity of water in the drying of Yungay potato slices

Fig. 11 (a and b) presents the response and contour surface of the effective diffusivity (x10^{-10} m^2s^{-1}) during the drying process with dry air assisted with incandescent lamps for the proposed experimental design of the drying air temperature and power of the lamps for the optimal conditions of the thickness of the slice cutting of 4,40 mm (or coded variable of 0,333) until the moisture of approximately 12% wet basis is achieved, the values of the effective diffusivity of the drying water show higher values (>35x10^{-10} m^2s^{-1}) as temperature and power increase, i.e. the relationship is directly proportional.



(a) **(b)**

Fig. 11. Response surface (a) and contour (b) of the effective diffusivity of water during the drying process of Yungay potato (*Solanum tuberosum* L.) slices for the independent variables: the drying air temperature and the power of the lamps, maintaining the thickness of the slice in the optimum conditions

Drying Curve Result and Effective Diffusivity Value of Water

To characterize the drying curve at optimum conditions (T=69,33 °C, P=328,80 W and E=4,40 mm) two experimental runs were carried out with the indicated parameters, whose result or average value represents the experimental drying curve, as shown in Fig. 12 with the mathematical adjustment proposed in this study, the variation of moisture content on a dry basis as a function of drying time of the Yungay potato slices with hot air assisted by incandescent lamps.

Fig. 13 shows the adjustment of the drying curve obtained with the diffusional equation of Ficks' second law. From the beginning of drying, it can be observed that the drying rate is decreasing non-linearly, a typical characteristic of this type of agro-industrial product.

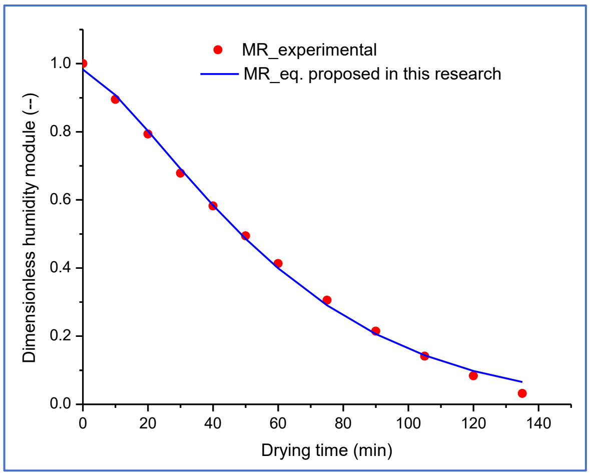


Fig. 12. Drying curve and mathematical model of drying of Yungay potato (*Solanum tuberosum* L.) slices under optimum drying conditions with hot air assisted by incandescent lamps.

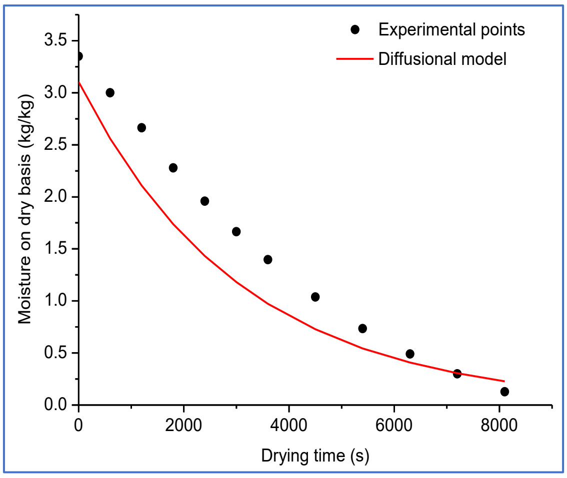


Fig. 13. Drying curve and simulation with the Fick diffusional model for Yungay potato (*Solanum tuberosum* L.) slices under optimum conditions

From the statistical values obtained (Table 9), it can be affirmed that all the equations are competent in that they present a good fit to the experimental data in the drying of Yungay potato slices, since they are in the order of 0,99.

If we compare the results in the fourth and fifth decimal fraction, we can state that the equation of the Conjugate Model of two terms and five constants, the sigmoidal model and the modified Page II equation present the best fits due to the high values of the coefficient of determination of 0,99936; 0,99935 and 0,99907 and the lower values of the relative errors calculated as: SSE, RMSE, MPE and χ^2 respectively.

Using equation 4 and the least squares regression technique, the value of the effective diffusivity of water during the drying of the optimum conditions was determined, as shown in Fig. 12. The coefficient of determination calculated with the diffusional model to the experimental data was R^2 = 0,9568. Being the value of the effective diffusivity of $2{,}46 \cdot 10^{-9}$ (m^2s^{-1}). The value found in this study is in relation to the values of effective diffusivity reported by different authors for agro-industrial products, as shown in Table 10.

Table 9- Results of statistical analysis in modeling the variation of dimensionless moisture modulus and drying time

Mathematical Model	Constantes del modelo		R^2	SSE	$RMSE$	$EMR(\%)$	χ^2
Lewis or Newton's model	k	0,01492	0,99122	0,00259	0,05088	43,20	0,00282
Diffusional model	a	0,50000	0,99365	0,00239	0,04887	37,89	0,00318
	k_1	0,01563					
	k_2	0,01563					
Drying with double kinetics or Modified Henderson & Pabis two-term equation	a	0,52280	0,99337	0,00196	0,04428	38,12	0,00294
	b	0,52280					
	k_1	0,01580					
	k_2	0,01580					
Sigmoidea Model	a	1,46780	0,99935	0,00015	0,01217	10,63	0,00020
	b	25,8897					
	c	35,1959					
Page's model	k	0,00520	0,99823	0,00033	0,01814	17,32	0,00039
	n	1,26080					
Page model modified I	k	0,02730	0,99122	0,00259	0,05088	43,20	0,00311
	n	0,54630					
Page model modified II	k	0,07948	0,99907	0,00025	0,01583	13,02	0,00033
	n	1,31500					
	l	3,04788					
Henderson-Pabis model	a	1,06052	0,99518	0,00178	0,04218	32,73	0,00213
	k	0,01671					
Midilli *et al.* model	a	1,06050	0,99518	0,00178	0,04218	32,73	0,00237
	b	0,00000					
	k	0,01671					
Conjugated two-term model	a	0,40915	0,99936	0,00022	0,01476	12,01	0,00037
	b	0,57365					
	k_1	0,00351					
	k_2	0,00350					
	n	1,35549					

Table 10- Some values of the effective diffusivity of water in agro-industrial products

Product	Temperature	Effective Diffusivity (m^2/s)	Reference
Rice husk	30 a 60°C	$8{,}42 \cdot 10^{-9} - 1{,}69 \cdot 10^{-8}$	Thakur-Gupta (2006)
Peanut shell powder	50 a 90°C	$9{,}60 \cdot 10^{-9} - 2{,}26 \cdot 10^{-8}$	Chen et al. (2012a)
Diced apple 1cm³	45 a 90°C	$6{,}7 \cdot 10^{-10} - 2{,}7 \cdot 10^{-9}$	Lewiski & Korczak (1996)
Blueberries	30 a 70°C	$1{,}0 \cdot 10^{-10} - 2{,}0 \cdot 10^{-10}$	Ramaswamy & Nsonzi (1998)
Gracilaria Chilensis Algae	30 a 70°C	$2{,}76 \cdot 10^{-9} - 22{,}41 \cdot 10^{-9}$	Vega et al. (2009)
Red algae-Chondracanthus Chamissoi	55°C	$2{,}03 \cdot 10^{-11}$	Vivanco P. D. (2023)

Results of the Additional Heat Load from the Incandescent Lamps during the Drying Period

In Fig. 14, the values and the curve for estimating the drying time of the Yungay potato slices (min) have been simulated. The data were simulated with the regression equation for the values of the optimum conditions: keeping the drying speed of 1,5 ms^{-1} constant. It is observed that the drying time decreases progressively with the additional radiant energy provided by the incandescent lamps. Fig. 15 shows the moisture distribution on a dry basis of Yungay potato slices in two systems, hot air drying and hot air drying assisted with incandescent lamps, maintaining a constant drying air temperature of 60°C and a thickness of the slices of 4mm and a drying air speed of 1,50 ms^{-1}, for the conditions, the first without assistance (0W), and the second with assistance (450 W) of power from the incandescent lamps, respectively. It is observed that the drying curve of the Yungay potato slices assisted with incandescent lamps decreases at a faster rate until reaching the final moisture content of 12% wet basis or 0,136 kg/kg in approximately 131 min, while without additional energy assistance the time used was 194 min, that is, using the additional energy assistance in the drying air, for these two cases, the drying times are reduced by approximately 30%.

Bouhile *et al*., (2025) applied infrared blanching (IRB) on various fruits and vegetables (tomatoes, sweet potatoes, carrots, mangoes, strawberries) found that IRB can reduce drying times by up to 50%, increase drying rates, and reduce energy consumption by approximately 17%, achieving thermal efficiency levels of 80-90%.

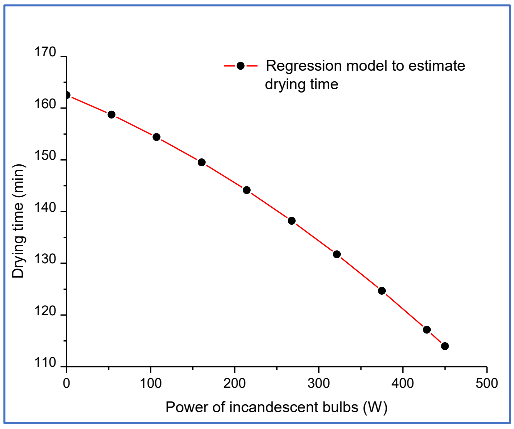


Fig. 14. Graphical simulation of the drying times of the Yungay potato slices for variations in the power of the incandescent lamps

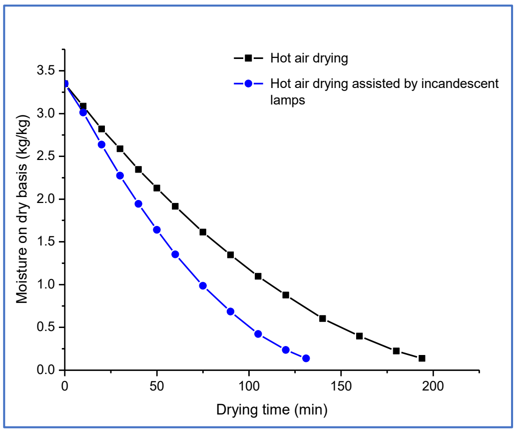


Fig. 15. Drying curves of Yungay potato slices with hot air and assisted with incandescent lamps

Results of the Additional Heat Load by Incandescent Lamps on the Value of the Effective Diffusivity of Water

Fig. 16 shows the trend of the values of water diffusivity during the drying of the Yungay potato slices assisted with incandescent lamps. A progressive increase in the values of the effective diffusivity of water during the drying of the Yungay potato slices is observed as the power values of the incandescent lamps increase. The simulation was made with the regression equation (equation 7) and for values of 0-450W of power, keeping constant the values of the independent variables in the optimum conditions.

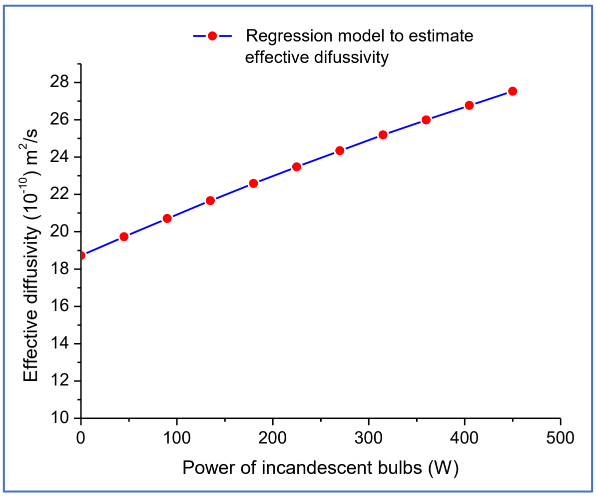


Fig. 16. Graphical simulation of water diffusivity during the drying of Yungay potato slices for variations in the power of the incandescent lamps

For the optimization of the drying process of Yungay potato slices, with hot air assisted by incandescent lamps, using the experimental design of rotatable central composite, a second order polynomial order mathematical equation could be obtained, which allowed estimating the global acceptance of the product, the drying time and the value of water diffusivity. In the optimum drying conditions, the drying times are less than or equal to 135min, the statistical procedures applied indicate that the equations generated by means of the experimental data are reliable due to the high values of the determination coefficients they present, so the regression equations predict the values with enough precision as observed to obtain the optimized parameters of the drying process.

Conclusion

Through the use of the response surface methodology, in the drying process of Yungay potato slices, the optimized parameters were determined to achieve drying times of less than or approximately 135 minutes, being: Temperature of 64,33 °C, Power of the incandescent lamps of 328,80 W and Thickness of the slices of 4,40 mm, maintaining the drying air speed constant and equal to 1,50 ms^{-1}. The values of the constants of the 10 proposed equations were determined to simulate the drying curve under optimum conditions. It is confirmed that the mathematical models of Newton, Diffusional, Henderson & Pabis modified, sigmoid model, Page, Page modified I, Page modified II and Henderson-Pabis, Midilli et al., and the equation of conjugate model of two terms and five constants (R^2 =0,99936), have described with quite good quality the behavior of the evolution of the moisture content of the product during the drying time in the optimal conditions and in second place the equation of the sigmoid model (R^2 =0,99935). It was determined that the drying of Yungay potato slices by means of hot air and assisted with incandescent lamps has a period of decreasing rate. The value of the average effective diffusivity of water in the hot air-drying process assisted by incandescent lamps for Yungay potato slices, carried out under optimum conditions, was determined numerically: $2{,}46 \cdot 10^{-9}$ (m^2s^{-1}), very similar to those published on the drying of other agro-industrial products. The use of this technological proposal demonstrated that it is possible to obtain dry Yungay potato slices by means of additional energy provided by incandescent lamps, which allows for shorter drying times.

Funding Sources

This research project was funded by the research fund of the National University of Callao– Lima- Peru (Resolution No. 469-24R).

Author Contributions

- Conceptualization: ideas, formulation of research objectives.
- Data curation: maintenance of data and its interpretation for development and subsequent reuse.
- Formal analysis: application of statistical, mathematical, and computational techniques in the analyses.
- Funding acquisition: Obtaining financial support from the research fund of the National University of Callao (Resolution No. 469-24R).
- Investigation: Carrying out the research project from which the scientific article is generated.
- Methodology: Development of the methodology and research design.
- Project administration: Responsibility for managing and coordinating the planning and execution of the research activity.
- Resources: Provision of study materials, reagents, equipment and materials, computer resources, and analytical tools.
- Software: Spreadsheet programming for data collection.
- Supervision: Sole responsibility for the supervision, planning, and execution of the research.
- Validation: Verification of the reproducibility of the experimental results.
- Visualization: Preparation of the scientific article for publication.
- Writing – original draft: Drafting of the initial draft of the research work.
- Writing – review and editing: Preparation and presentation of the research work for subsequent publication.

Acknowledgment

The studies were carried out with the support of the Laboratory of Process Engineering and Unit Operations (LIPOU-FIPA) of the Faculty of Fisheries and Food Engineering and thanks to funding from the Special Fund for Research Development of the National University of Callao (Resol. N°469-24R), Constitutional Province of Callao, Lima, Peru.

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مقاله پژوهشی
جلد ۲۱، شماره ٦، بهمن- اسفند ١٤٠٤، ص.

خشک کردن ورقه‌های سیب‌زمینی با هوای گرم به کمک لامپ رشته‌ای: بهینه‌سازی فرآیند با استفاده از روش سطح پاسخ

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تاریخ دریافت: ۱۴۰۴/۰۱/۲۳
تاریخ پذیرش: ۱۴۰۴/۰۴/۰۵

چکیده

مطالعه حاضر کاربرد روش سطح پاسخ جهت بهینه سازی و مدلسازی ریاضی خشک کردن ورقه‌های سیب‌زمینی در یک خشک کن آزمایشگاهی هوای گرم به کمک لامپ های رشته‌ای را بیان می‌کند. تأثیر دما، توان لامپ‌های رشته‌ای و ضخامت ورقه به‌عنوان متغیرهای مستقل بر سطح پاسخ متغیرهای وابسته شامل زمان خشک شدن، پذیرش کلی محصول و ضریب نفوذ مؤثر آب مورد بررسی قرار گرفت. ارزش بالای پذیرش کلی محصول به‌عنوان پارامتر بهینه برای خشک کردن ورقه‌های سیب‌زمینی در نظر گرفته شد. روش سطح پاسخ با استفاده از طرح مرکب مرکزی چرخشی برای بهینه‌سازی متغیر وابسته اعمال شد. معادلات رگرسیون چند جمله‌ای درجه دوم برای هر متغیر پاسخ به‌دست آمد. شرایط بهینه خشک کردن جهت دسترسی به بالاترین پذیرش در ارتباط با دما، توان و ضخامت به‌ترتیب برابر ۶۹/۳۳ درجه سانتی‌گراد، ۳۲۸/۸۰ وات و ضخامت ۴/۴۰ میلی‌متر بود. زمان بهینه خشک کردن حدودا ۱۳۰ دقیقه بود. خشک کردن در مدت زمان کاهش سرعت خشک‌کنندگی صورت گرفت. نتایج نشان داد که افزایش انرژی توسط لامپ‌های رشته‌ای منجر به کاهش ۳۰ درصدی زمان خشک کردن شد. با استفاده از روش شبه نیوتن سیمپلکس، ثابت‌های مدل‌های ریاضی برای شبیه‌سازی منحنی خشک کردن تعیین شدند و مدل مزدوج دو جمله‌ای و پنج ثابت، بهترین برازش را نشان داد. با استفاده از معادله قانون فیک، ضریب نفوذ مؤثر آب از ۱۰-۱۰ ۴/۴۸ تا ۹-۱۰ ۳/۳۸ متر مربع برثانیه متغیر بود و در شرایط خشک کردن بهینه ۹-۱۰ ۲/۴۶ متر مربع بر ثانیه بود. اطلاعات به‌دست‌آمده از این پژوهش درتوسعه خشک‌کن‌ها و کنترل فرآیندهای خشک کردن در مقیاس تجاری و صنعتی کمک اساسی می‌کند.

واژه‌های کلیدی: خشک‌کردن سیب‌زمینی، سینتیک، مدل‌سازی ریاضی، RSM

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https://doi.org/10.22067/ifstrj.2025.92986.1423