

RESEARCH ON DRIED POTATO PRODUCTION BY LOW-TEMPERATURE VACUUM DRYING TECHNOLOGY

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ABSTRACT

The aim of this study was to determine technology modeling and optimize the low-temperature vacuum drying process of potatoes. Based on that, the optimal technology had been set up for low temperature vacuum drying. Potatoes were blanched at 95°C for 3 minutes and dried in optimal technology mode: drying temperature was 38.77°C, drying environment pressure was 0.02mmHg, drying time was 9.36h. Potatoes after being dried in this optimal mode consumed an energy cost of 3.82kWh / kg, moisture content was 4.03%, brittleness was 7.675N and the increase in fiber content was 38.15%. It could be seen that the product after drying was good quality, the humidity reached requirement and the energy cost was at the lowest level.

Keywords: vacuum drying; low temperature vacuum drying; potato; drying; dried potato.

1. INTRODUCTION

Potato (*Solanum tuberosum*) which belongs to Solanaceae family is a short-term, tuber crop that is widely grown in the world and the fourth most common crop in term of yield (after wheat, rice and corn) and accounts for about 12% of total dried products [1]. Potatoes are an extremely nutritious food, containing many beneficial substances such as vitamins, minerals, proteins, microelements, starch and fiber. Water content is about 78-85%, mineral salt is about 0.9-1.2%, carbohydrate (15-20%) is mainly in starch and accompanied by some reducing sugar, saccharose and pectin, protid is about 1-2% (depending on the variety) which (is) mainly composed of alumina, amino acid peptone and nucleoprotein [2].

Potato consumption is a way of supplementing a healthy diet and benefits for health. Potatoes are high in potassium which reduce(s) the risk of cardiovascular disease and hypertension [3]. The fiber content of potatoes has a great effect in absorbing excess water in the body, thereby maintaining a feeling of fullness and

preventing cravings. In addition, the research of Peikin [4] discovered a protein called PI2 (Proteinase Inhibitor II) in potatoes that suppresses appetite.

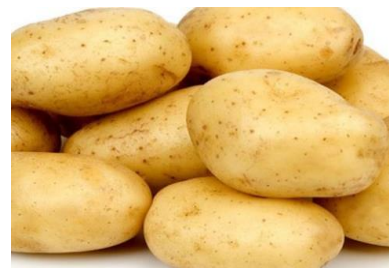


Figure 1. Raw potatoes

Besides, potatoes after being harvested without proper storage methods will germinate and rot, which quickly reduces nutrient content and quality [5]. If potatoes are refrigerated or frozen, the energy cost is high and water in potato is crystallized, which results in deterioration of structure and nutritional quality of potato when it is melt [1,6]. In addition, potatoes preserved by conventional drying method, the color, flavor, vitamins ... are destroyed by high temperatures, structure is shrink, surface of potato slice is cracked, the product is denatured and cannot revert back so product

quality is reduced [1,6,7]. Currently, potatoes are mostly used in the form of chips. Potato chips contain a lot of acrylamide that is formed during frying ; the higher the frying temperature, the higher of the acrylamide content [2,8]. Long-term use can affect the nerves and increase the risk of cancer. Moreover, potato chips are also cause of obesity, heart disease and diabetes [2,8,4]. Therefore, it is necessary to study and choose suitable methods of processing and preserving that can prolong shelf life but product quality is not changed [9,10]. Therefore, in this study, low-temperature vacuum drying method has been selected with the advantages of retaining most of th) material's original characteristics: biological properties, flavor, color, shape, porous structure, good revert ability, an) product is preserved long and less affected by external conditions. Energy cost is reduced by more than half when compared to freeze drying [10,11]. However, if the drying process is not conducted in an appropriate technology mode, product quality will while energy cost is high so it is difficult for business. Therefore, the problem is how to determine optimal technology mode. When the drying process is carried out under optimal technology mode, the products after being dried have good quality, satisfactory moisture content and energy cost is at the lowest level [12,13,14].

2. MATERIAL AND METHODS

2.1 Materials

Raw potatoes (*Solanum tuberosum*) were grown in Dalat, Vietnam (Figure 1). Fresh, whole skin and good quality potatoes were selected for experiments. Then it was cleaned, peeled and sliced.



Figure 2. Sliced potatoes

The thickness of each slice was 2.5 ± 0.5 mm (Figure 2). Potato slices were blanched at (a) temperature of 95°C in 3 minutes then drained and placed on a tray to prepare for the drying process (Figura LO, Teixeira AA, 2007).

2.2 Apparatus

Low-temperature vacuum drying system DSV-03 (Figure 3) was automatically controlled the drying process by using (a) computer program (Figura LO, Teixeira AA, 2007) at laboratory B108, Faculty of Chemical Technology and Food - HCMC University of Technology and Education. Technological parameters could be controlled in the following range: Drying temperature ($25 - 60$) $^{\circ}\text{C}$; Drying environment pressure ($0.001 - 4.58$) mmHg; Drying time ($5 - 30$) h.



Figure 3. Low-temperature Vacuum Drying DSV – 03

2.3 Methods

2.3.1 Determining technological parameters affected to drying process

Drying temperature (Z_1): used temperature sensor by the dryer control system [16].

Drying environment pressure (Z_2): used pressure sensor by the dryer control system [16].

Drying time (Z_3): used timer in the dryer controlled computer and information was displayed on the screen [15].

2.3.2 Determining the product's objective functions

Energy costs

Energy cost y_1 (kWh / kg) to produce 1kg of product was measured by Watt meter [16]:

$$y_1 = \frac{P \cdot \tau}{G}, \text{ kWh/kg} \quad (1)$$

Where: G (kg) – Weight of the final product; τ (s) – Drying time; P (kW) - Number of Wattmeter.

Moisture content

Moisture content was determined by drying sample to constant weight that following the equation [16]:

$$y_2 = \frac{m_1 - m_2}{m_1 - m} \cdot 100(\%) \quad (2)$$

Where: m (g) - Weight of moisture can; m_1 (g) - Weight of moisture can and sample before drying; m_2 (g) – Weight of moisture can and sample after drying.

The crispiness

The crispiness of dried potatoes (y_3) was measured by using CT3 structure analyzer (Brookfield Engineering Laboratories, Inc., Middleboro, MA, USA). It was determined by the force to break (the) potato chip. Condition for experiment included TA41 probe, speed of 2 mm / s, distance of 5 mm, actuation force of 0.01N. The force strength to break potato chip was determined by Hooke's law [15]:

$$y_3 = F = - k \cdot \Delta l \quad (3)$$

Where: F (N) – strength force causing deformation; k (N/m) – elastic coefficient; $\Delta l = l - l_0$ (m) – deformation.

Fiber content

- Fiber content was measured by enzyme-mass method according to TCVN 9050-2012 [16]:

$$y_4 = \frac{m_2 - m_1}{m_2} \cdot 100 (\%) \quad (4)$$

Where: m_1 (g) – Fiber content before drying, m_2 (g) – Fiber content after drying.

2.3.3 Design of Experiments

After analyzing the technological objects of the cold-drying process included: product quality, product cost and product shelf life; it was affected by 3 factors: drying temperature Z_1 ($^{\circ}\text{C}$), drying environment pressure Z_2 (mmHg), drying time Z_3 (h). Then built a table of factors affecting the drying technology objects, formulated an orthogonal empirical planning matrix of level 2, three elements and experimental mathematical model in the form of Dzung [16]:

$$y_j = b_0 + \sum_{u=1}^k b_u x_u + \sum_{u \neq i; u=1}^k b_{ui} x_u x_i + \sum_{u=1}^k b_{uu} (x_u^2 - \lambda) \quad (5)$$

- The coded variable was determined:

$$x_j = \frac{Z_j - Z_j^o}{\Delta Z_j} \quad (6)$$

- The experimental number was determined:

$$N = 2^k + 2k + n_0 = 2^3 + 2 \cdot 3 + 4 = 18 \quad (7)$$

- The value of the star point:

$$\alpha = \sqrt{\sqrt{N \cdot 2^{k-2}} - 2^{k-1}} = 1.414 \quad (8)$$

- The condition of orthogonal matrix:

$$\lambda = \frac{1}{N} (2^k + 2\alpha^2) = 2/3 = 0.667 \quad (9)$$

2.3.4 Optimization method

2.3.4.1. Building the mathematical model of the one-objective optimization problems

Based on the object of technology were investigated, the objective functions to be considered were $y_j = f_j(Z)$ which is depended on the parameters, including: drying temperature (Z_1), drying environment pressure (Z_2), drying time (Z_3), in which these factors constituted the vector of influence factors or variable vectors $Z = \{Z_i\} = (Z_1, Z_2, Z_3)$. These variables varied in the defined domain Ω_Z and

values of objective function $f_j(Z)$ would form the value domain Ω_f [16].

One-objective optimization problem can be stated as follows:

Determining the root of $Z_j = \{Z_i^{jopt}\} = (Z_1^{jopt}, Z_2^{jopt}, Z_3^{jopt}) \in \Omega_Z$ in order that:

$$\begin{cases} f_{jmin} = f_j(Z^{jopt}) = f_j(Z_1^{jopt}, Z_2^{jopt}, Z_3^{jopt}) & (10) \\ = \min f_j(Z_1, Z_2, Z_3) \\ j = 1 \div m, i = 1 \div n \end{cases}$$

Solving the one-objective optimization problem by Solver function in Microsoft Excel.

2.3.4.2. Building the mathematical model of the multi-objective optimization problems

Every objective function $f_j(Z)$ with Z variable vector $Z = \{Z_i\} = (Z_1, Z_2, \dots, Z_n) \in \Omega_Z$ ($i = 1 \div n$) was formed as the one-objective optimization problem. Therefore, to be simple but not to lose the generality, the m-objective optimization problem could be simply transformed into the problem to find the minimum value for the set of m one-objective optimization problems [16]:

Determining the root of $Z_j = \{Z_i^{opt}\} = (Z_1^{opt}, Z_2^{opt}, Z_3^{opt}) \in \Omega_Z$ in order that:

$$\begin{cases} f_{jmin} = f_j(Z^{opt}) = f_j(Z_1^{opt}, Z_2^{opt}, Z_3^{opt}) & (11) \\ = \min f_j(Z_1, Z_2, Z_3) \\ j = 1 \div m, i = 1 \div n \end{cases}$$

If the multi-objective optimization problem had a common root then the utopian optimal problem appeared. In contrast, the multi-objective optimization problem without common root, the utopian optimal solution did not exist root then using the prohibited operating zones method with the combination standard R to find root for optimal Paréto [16].

In fact, many multi-objective optimization problems were posed with constraint on the values of the component objective functions $f_j(Z)$ [16].

$$f_j(Z) < C_j, \forall j = 1 \div m \quad (12)$$

Normally for the minimum finding problem, C_j was the upper bound of the component objective function $f_j(Z)$, and for maximum finding problem, C_j was the lower bound of the component objective function $f_j(Z)$, when value of the objective function $f_j(Z)$ outside value range was called prohibited zone.

The conditions of (12) formed the prohibited zone:

$$C = \{f_j(Z) < C_j\} \quad (13)$$

The prohibited operating zones method was used to solve m-objective optimization problem with the optimal combination $R(Z)$ which is defined by the following expression [16]:

$$\begin{aligned} R(Z) &= \sqrt[m]{r_1(Z) \cdot r_2(Z) \dots r_m(Z)} & (14) \\ &= \sqrt[m]{\prod_{j=1}^m r_j(Z)} \end{aligned}$$

Where:

$$r_j(Z) = \frac{C_j - f_j(Z)}{C_j - f_{jmin}} \text{ when } f_j(Z) \leq C \quad ./ \quad (15)$$

$$r_j(Z) = 0 \text{ when } f_j(Z) > C \quad (16)$$

From (11) it can be seen that when $f_j(Z) \rightarrow f_{jmin}$ then $r_j(Z) \rightarrow r_{jmax} = 1$. Therefore, with the optimal combination of $R(Z)$, the m-objective optimization problem is restated: Find root of $ZR = (Z_1R, Z_2R, \dots, Z_nR) \in \Omega_Z$ so that the objective function $R(Z)$ reaches maximum value in value domain Ω_f [16].

$$\begin{aligned} R_{max} &= R(ZR) & (17) \\ &= \max \left\{ \sqrt[m]{r_1(Z) \cdot r_2(Z) \dots r_m(Z)} \right\} \\ &= \max \left\{ \sqrt[m]{\prod_{j=1}^m r_j(Z)} \right\} \end{aligned}$$

With $Z = (Z_1, Z_2, \dots, Z_n) \in \Omega_Z$

3. RESULTS AND DISCUSSION

3.1 Determination of chemical composition in fresh materials

The chemical composition in 100 g of fresh potato from Dalat City, Vietnam was shown in Table 1.

Table 1. Chemical composition of fresh potato

N _o	Components	Unit	Values
01	Moisture content	%	83.09 ± 0.35
02	Carbohydrate	%	13.49 ± 0.28
03	Fiber content	%	1.07 ± 0.12
04	Ash	%	0.8 ± 0.09
05	Vitamin C	mg/100g	12 ± 0.22
06	Potassium	mg/100g	404 ± 0.43

According to Table 1, moisture content in fresh potato from Dalat City, Vietnam was around 83.09%, followed by carbohydrates which accounted for 13.49%. Other components, such as fiber, vitamins and minerals were matched with the research of José [2]. However, there were some differences due to various varieties, species and cultivars of potatoes, as well as other factors, such as harvesting methods and storing techniques. During storage, physiological (respiration, especially germination process) and biochemical changes (hydrolysis and redox reaction) still occurred inside potatoes and led to a drop in nutritional contents of those tubers [17].

Therefore, fresh potatoes after being harvested needed to be well preserved by appropriate techniques to limit the changes in chemical composition as well as to ensure the homogeneity of raw materials. The aim of this process was creating high quality products which raised the economic value of Vietnamese agricultural commodities, for not only domestic consumption, but also exportation to other countries.

3.2 Investigation of the change of characteristics of potato during pre-treatment before drying

There were plenty of glycoalkaloids (solanine, chaconine...) and enzymes (catalase, protease...) in fresh potatoes. Those chemicals could be considered as toxics or could lead to the change of potatoes' colors during processing or storage [2,17].. Sliced and dried potatoes without pre-treatment could cause dark-color,

increase glycoalkaloids in the products and could be harmful for consumers [2]. Therefore, potatoes needed to be pre-treated by blanching before further processes [17]. Blanching aimed to denature glycoalkaloids and inactivate enzymes, including catalase and protease in order to remove toxics as well as prevent hydrolysis and browning reactions during processing and storage [17]. However, blanching could also cause the decrease of vitamin C [2]. Thus, the appropriate temperature and duration of blanching needed to be investigated to make good quality potatoes with the loss of vitamin C is at least [2,17].

Potatoes were blanched for 1, 2, 3 and 4 minutes at 95°C, the results were shown in Table 2. If blanching at a temperature lower than 95°C, the glycoalkaloids were difficult to be destroyed, whereas temperature higher than 95°C, vitamin C was completely deteriorated. Therefore, sliced potatoes could only be blanched at 95°C.

The result in Table 2 indicated that there was not significant difference by ANOVA test (5% of confidence interval) in the loss of vitamin C in potatoes blanched for 1, 2 and 3 minutes at 95°C which accounted for 26.89 ÷ 27.05%. However, blanching for 1 and 2 minutes caused unwell cooked potatoes with paled color, while blanching for 4 minutes led to the loss of 35% vitamin C, which was not acceptable. Thus, blanching for 4 minutes was not appropriate.

Table 2. Sliced potatoes after blanching

Duration of blanching (minute)	Moisture content (%)	Loss of vitamin C (%)	Sensory evaluation
1	83.10 ± 0.81 ^a	26.89 ± 0.62 ^a	Unwell cooked, paled color.
2	83.16 ± 0.52 ^b	27.00 ± 0.61 ^b	Unwell cooked, moderate dark-yellow color.
3	83.19 ± 0.66 ^c	27.05 ± 0.77 ^c	Well cooked, dark-yellow color.

4	83.27 ±0.55°	35.00 ±0.58°	Well cooked, dark-yellow color.
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Another experiment was also done to investigate the appropriate blanching durations. Sliced potatoes were divided into 5 groups, varied from 1 to 5 minutes of blanching with an interval of 1 minute. The result was shown in Figure 4.

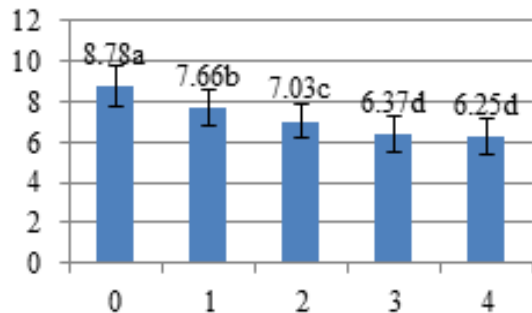


Figure 4. The loss of vitamin C during blanching

According to Figure 4, the loss of vitamin C in samples without blanching was 8.78%, this loss was steadily dropped which accounted for 7.66, 7.03, 6.37 and 6.25% of samples with 1, 2, 3 and 4 minutes of blanching, respectively. Obviously, samples without blanching showed the highest loss of vitamin C compared to blanched samples. Blanching caused the gelatinization of potatoes' starch and that gel structure protected molecules of ascorbic acid and preserved the amount of vitamin C in potatoes. However, if the duration lasted for 4 minutes, the gel structure would also be destroyed and led to the huge loss of vitamin C.

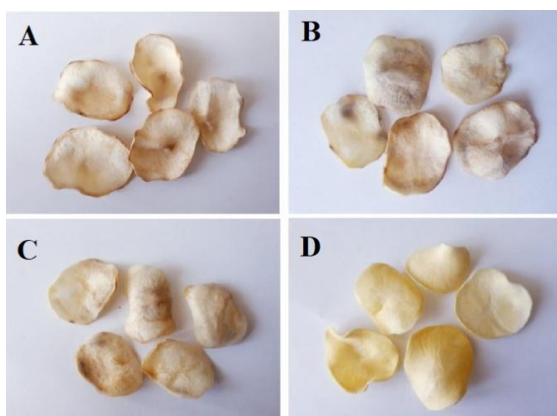


Figure 5. Dried potatoes

Figure 5 indicated the change of color of potatoes after being vacuum dried at low temperature, namely Sample A – not blanching, B – blanching for 1 minute, C – blanching for 2 minutes and D – blanching for 3 minutes. The result showed that samples A, B and C occurred browning reactions after being dried, while sample D had qualified yellow color.

Thus, blanching fresh potatoes for 3 minutes at 95°C was appropriate before applying low temperature vacuum drying.

3.3 Building mathematical model of drying process

Table 3. Data on technological factors

Technological factors	Levels					ΔZ
	$-\alpha$	-1	0	+1	$+\alpha$	
Z_1 (°C)	25.86	30	40	50	54.14	10
Z_2 (mmHg)	0.006	0.01	0.02	0.03	0.034	0.01
Z_3 (h)	9.293	9.5	10	10.5	10.707	0.5

Low temperature vacuum drying was affected by technological factors, such as drying temperature Z_1 (°C), pressure of drying environment Z_2 (mmHg), drying time Z_3 (h) to objective functions which were energy cost y_1 (kWh), moisture content of product y_2 (%), crispness y_3 (N) and dietary fiber y_4 (%). When experiments for each factor were conducted, the results showed that the extreme domain of y_j ($j = 1 \div 4$) was always changing in the determination domain Z_i ($i = 1 \div 3$) which was presented in Table 3 [16]. Two-level orthogonal experimental matrix was built based on Table 3 and shown in Table 4.

After empirical analysis, the regression equation coefficients were calculated, the significance of the regression equation coefficients was tested based on Student standard, the compatibility of regression equations of results was checked based on the Fisher standard [16], the regression equation was obtained as following:

Table 4. Two-level orthogonal experimental matrix ($k = 3, n_o = 4$)

Number of experiments		Real variable			Biến ảo			Target function			
N		Z ₁ (°C)	Z ₂ (mmHg)	Z ₃ (h)	x ₁	x ₂	x ₃	y ₁ (kW/h)	y ₂ (%)	y ₃ (N)	y ₄ (%)
2 ^k	1	50	0.03	10.5	1	1	1	4.71	2.96	6.820	29.61
	2	30	0.03	10.5	-1	1	1	4.57	4.52	5.493	26.21
	3	50	0.01	10.5	1	-1	1	4.91	3.13	9.693	37.06
	4	30	0.01	10.5	-1	-1	1	4.81	4.33	6.103	24.65
	5	50	0.03	9.5	1	1	-1	3.85	5.58	5.125	30.07
	6	30	0.03	9.5	-1	1	-1	3.82	4.65	4.535	26.71
	7	50	0.01	9.5	1	-1	-1	3.82	3.95	11.298	29.14
	8	30	0.01	9.5	-1	-1	-1	3.77	4.07	6.990	23.02
2k	9	25.86	0.02	10	1.414	0	0	4.31	2.42	5.705	31.41
	10	54.14	0.02	10	-1.414	0	0	4.07	6.01	4.132	25.17
	11	40	0.03	10	0	1.414	0	4.02	2.75	6.143	28.19
	12	40	0.006	10	0	-1.414	0	4.61	3.82	5.283	26.71
	13	40	0.02	10.707	0	0	1.414	5.52	2.97	6.583	34.36
	14	40	0.02	9.293	0	0	-1.414	3.59	3.17	5.610	27.21
n _o	15	40	0.02	10	0	0	0	4.20	2.91	5.507	20.15
	16	40	0.02	10	0	0	0	4.23	2.61	6.257	17.05
	17	40	0.02	10	0	0	0	4.33	2.3	6.153	20.74
	18	40	0.02	10	0	0	0	4.24	2.45	5.370	18.32

Mathematical model for calculating energy cost of drying process:

$$y_1 = 4.3 + 0.055x_1 - 0.099x_2 + 0.539x_3 - 0.063x_2x_3 - 0.071x_1^2 + 0.11x_3^2 \quad (18)$$

Mathematical model for calculating moisture content of products for drying process:

$$y_1 = 4.643 - 0.586x_1 - 0.299x_2 - 0.446x_1x_3 + 0.873x_1^2 + 0.408x_2^2 + 0.3x_3^2 \quad (19)$$

Mathematical model for calculating crispness of products for drying process:

$$y_1 = 5.83 + 1.003x_1 - 0.908x_2 - 0.748x_1x_3 + 0.643x_2x_3 + 0.655x_3^2 \quad (20)$$

Mathematical model for calculating the increase of fiber content of products for drying process:

$$y_1 = 32.586 + 2.842x_1 + 1.557x_3 + 2.802x_1^2 + 2.381x_2^2 + 4.048x_3^2 \quad (21)$$

3.4 Determination of technological mode for drying process

3.4.1 Solving one-objective optimization problem

One-objective optimization problem aimed to investigate the lowest cost of energy $y_{1\min} = f_1(x_1, x_2, x_3)$, optimal moisture content $y_{2\min} = f_2(x_1, x_2, x_3)$, highest crispness $y_{3\max} = f_3(x_1, x_2, x_3)$ and highest increase of

dietary fiber $y_{4max} = f_4(x_1, x_2, x_3)$ in limited domain $\Omega_x = \{-1.414 \leq x_1, x_2, x_3 \leq 1.414\}$. Therefore, one-objective optimization problem was presented as following:

Determination of $x_j^{opt} = (x_1^{opt}, x_2^{opt}, x_3^{opt}) \in \Omega_x$ with $\{-1.414 \leq x_1, x_2, x_3 \leq 1.414\}, j = 1 \div 4$, in which:

$$\begin{cases} y_{1min} = f_1(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min f_1(x_1, x_2, x_3) \\ y_{2min} = f_2(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min f_2(x_1, x_2, x_3) \\ y_{3max} = f_3(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \max f_3(x_1, x_2, x_3) \\ y_{4max} = f_4(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \max f_4(x_1, x_2, x_3) \end{cases} \quad (22)$$

Solving equations (22) by Excel Solver Software to obtain the results in Table 5.

Table 5. Optimal values of objective functions

	x_1	x_2	x_3	y^{opt}
y_{1min}	-1.414	1.414	-1.414	3.496
y_{2min}	0.571	0.000	0.923	2.229
y_{3max}	1.414	-1.414	-1.414	12.623
y_{4max}	1.414	-1.414	1.414	40.550

From Table 5, it is shown that the one-objective optimization problem (22) had no common root to simultaneously satisfy four objectives y_j ($j = 1 \div 4$). Therefore, in this case the utopian root and the utopian optimal solution did not exist.

3.4.2 Solving multi-objective optimization problem

Low temperature vacuum drying with technological factors, namely x_1, x_2 , and x_3 did not affect the values of y_1, y_2 and y_3 individually, but simultaneously. Thus, there was multi-objective optimization problem as following:

Determination of $(x_1^{opt}, x_2^{opt}, x_3^{opt}) \in \Omega_x$ in which:

$$\begin{cases} y_{1min} = f_1(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min f_1(x_1, x_2, x_3) \\ y_{2min} = f_2(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min f_2(x_1, x_2, x_3) \\ y_{3max} = f_3(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \max f_3(x_1, x_2, x_3) \\ y_{4max} = f_4(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \max f_4(x_1, x_2, x_3) \end{cases} \quad (23)$$

Because there was no common root to satisfy all the values of $y_{1min}, y_{2min}, y_{3max}, y_{4max}$, the optimal problem was finding the optimal root of Paréto solution for $y_{PR} = (f_{1PR}, f_{2PR}, f_{3PR}, f_{4PR})$ which was near the utopia point and farthest from the restricted area.

In the problem of multi-objective optimization problem (23) has both max and min, to simplify in the solution, the equations were rewritten as following:

Determination of $(x_{1opt}, x_{2opt}, x_{3opt}) \in \Omega_x$, in which

$$\begin{cases} I_{1min} = I_1(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min I_1(x_1, x_2, x_3) \\ I_{2min} = I_2(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min I_2(x_1, x_2, x_3) \\ I_{3min} = I_3(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min I_3(x_1, x_2, x_3) \\ I_{4min} = I_4(x_1^{opt}, x_2^{opt}, x_3^{opt}) = \min I_4(x_1, x_2, x_3) \end{cases} \quad (24)$$

$I_1 = y_1, I_2 = y_2, I_3 = 1/y_3, I_4 = 1/y_4$, thus $I_{1min} = 3.496, I_{2min} = 2.229, I_{3min} = 0.079, I_{4min} = 0.025$.

Based on economical and technological constraints, the technological mode of low temperature vacuum drying was $y_1 \leq 5$ kWh/kg; $y_2 \leq 5\%$; $y_3 \geq 0.29N, y_3 \geq 0.067$ (=6.7%) and the restricted the area was investigated:

$$I_1 \leq C_1 = 5$$

$$I_2 \leq C_2 = 8$$

$$I_3 \leq C_3 = 3.47$$

$$I_4 \leq C_4 = 14.95$$

Building a combination of target functions R as following:

$$\begin{cases} R(x_1, x_2, x_3) = \left[\prod_{j=1}^4 r_j(x_1, x_2, x_3) \right]^{1/4} \\ \Omega_x = \{-1.414 \leq x_1, x_2, x_3 \leq 1.414\} \end{cases}$$

In which,

$$\begin{cases} r_1(x_1, x_2, x_3) = \frac{5 - I_1}{5 - 3.496} & \text{when } I_1 \leq 5 \\ r_1(x_1, x_2, x_3) = 0 & \text{when } I_1 > 5 \end{cases}$$

$$\begin{cases} r_2(x_1, x_2, x_3) = \frac{8 - I_2}{8 - 2.229} & \text{when } I_2 \leq 8 \\ r_2(x_1, x_2, x_3) = 0 & \text{when } I_2 > 8 \end{cases}$$

$$\begin{cases} r_3(x_1, x_2, x_3) = \frac{3.47 - I_3}{3.47 - 0.079} & \text{when } I_2 \leq 3.47 \\ r_3(x_1, x_2, x_3) = 0 & \text{when } I_2 > 3.47 \end{cases}$$

$$\begin{cases} r_4(x_1, x_2, x_3) = \frac{14.95 - I_4}{14.95 - 0.025} & \text{when } I_2 \leq 14.95 \\ r_4(x_1, x_2, x_3) = 0 & \text{when } I_2 > 14.95 \end{cases}$$

Then, the multi-objective optimization problem was presented as following:

Determination of $x^{\text{opt}} = (x_1^{\text{opt}}, x_2^{\text{opt}}, x_3^{\text{opt}}) \in \Omega_x$ with $\{-1.414 \leq x_1, x_2, x_3 \leq 1.414\}$, $j = 1 \div 4$ where:

$$R_{\max} = \max \left\{ \sqrt[4]{\prod_{j=1}^4 r_j(Z)} \right\} \quad (25)$$

Excel – Solver software was used to solve equation (25). The maximum value with $(-1.414 \leq x_1, x_2, x_3 \leq 1.414)$ was successfully determined as:

$$x_1^R = -0.123, x_2^R = 0.022, x_3^R = -1.282$$

$$R_{\max} = \text{MaxR}(x_1, x_2, x_3) = 0.885$$

In correlation with above roots, there were:

$$Z_1 = 38.77^\circ\text{C},$$

$$Z_2 = 0.02 \text{ mmHg},$$

$$Z_3 = 9.36 \text{ h}$$

Substituting x_1^R, x_2^R, x_3^R into regression equations (18), (19), (20), (21) to determine:

$$y_1^R = 3.753,$$

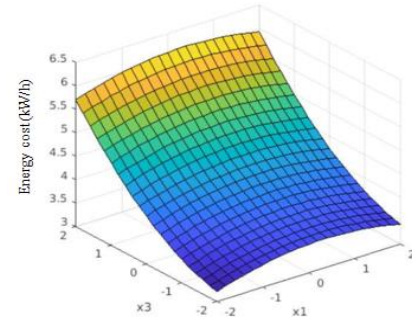
$$y_2^R = 3.426,$$

$$y_3^R = 6.747,$$

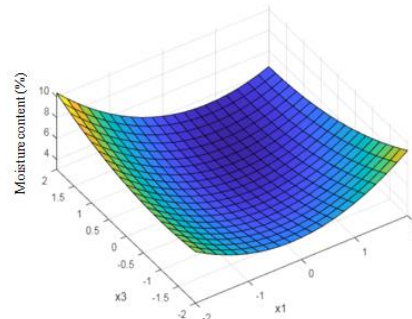
$$y_4^R = 24.628$$

The optimal technological mode of drying process was investigated, including temperature at 38.77°C ; pressure of the drying environment was 0.02 mmHg and

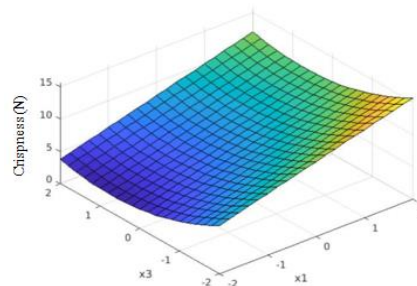
drying duration for 9.36 h . Cost of energy was found as $y_1 = 3.753 \text{ kWh}$, moisture content of product was 3.426% , crispness was 6.747 N and fiber content increased by 24.628% .



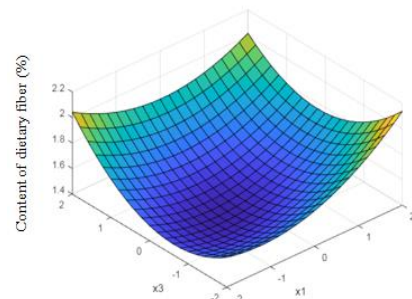
A)



B)



C)



D)

Figure 6. Models of response surface indicated the effects of experimental factors, $x_2 = -1.414$, A: Energy cost, B: Moisture content, C: Crispness, D: Content of dietary fiber

When the pressure of drying environment was fixed at $x_2^R = -1.414$, equivalent to $Z_2 = 0.02$ mmHg and the relation between y_1, y_2 , and y_3 with x_1, x_3 on models of response surface (Figure 6), the optimization point of combination function R satisfied all objectives. Based on theory, it was proven that there was no other point, except the optimization point which was near the utopia point and farthest from the restricted area.

Various experiments had been conducted to verify the above calculations.

3.5 Experiments for verification

Low temperature vacuum drying was conducted at optimization points which had been investigated, including $Z_1 = 38.65^\circ\text{C}$, $Z_2 = 0.02$ mmHg, $Z_3 = 9.38$ h. The result was shown in Table 6.

Table 6. Result of verification

Cost of energy (kWh)	Moisture content (%)	Crispness (N)	The increase of fiber content (%)
3.82	4.03	7.675	38.15

The results indicated that investigated optimization of technological values $Z_1 = 38.65^\circ\text{C}$, $Z_2 = 0.02$ mmHg, $Z_3 = 9.38$ h in correspondence with $y_1 = 3.82$ kWh; $y_2 = 4.03\%$; $y_3 = 7.675$ N; $y_4 = 38.15\%$ were completely consistent with the results of experiments. Thus, those results could be applied to calculate and establish technological modes as well as design and manufacture low temperature vacuum drying systems.

3.6 Evaluation of product's quality

Dried potatoes were evaluated by the criteria of quality and food safety. The results were presented in Table 7, Table 8, Table 9 and Table 10.

Table 7. Chemical composition of dried potatoes

N _o	Components	Values
01	Moisture content, %	4.03 ± 0.39

02	Carbohydrate, %	74.01 ± 0.36
03	Fiber content, %	1.73 ± 0.52
04	Ash, %	0.76 ± 0.08
05	Vitamin C, mg/100g	8.21 ± 1.05
06	Potassium, mg/100g	393 ± 11.12

Table 8. Limitation of pollution caused by heavy metal

N _o	Criteria	QCVN 8-2:2011/BYT	Dried potatoes
01	Asenic (As), mg/kg	1	0
02	Lead (Pb), mg/kg	2	0

Table 9. Limitation of mycotoxins

N _o	Criteria	QĐ 46/QĐ-BYT	Dried potatoes
01	Aflatoxin B ₁ , μg/kg	5	0
02	Aflatoxin B ₁ B ₂ G ₁ G ₂ , μg/kg	15	0

Table 10. Limitation of pollution caused by microorganisms

N _o	Criteria	QĐ 46/QĐ-BYT	Dried potatoes
01	Total aerobic plate count, cfu/g	10 ⁴	1,2 x 10 ³
02	Coliforms, cfu/g	10	< 10
03	Clostridium perfringens, cfu/g	10	< 10
04	Escherichia coli, MPN/g	0	< 10
05	Bacillus cereus, cfu/g	10 ²	< 10
06	Total spores of yeast and mold, cfu/g	10 ²	< 10

3.7 Technological process of low temperature vacuum drying for potatoes

According to the solving of multi-objective optimization problem, the

technological process of low temperature vacuum drying for potatoes was presented in Figure 7 and products of this process could be seen in Figure 8.



Figure 7. Dried potatoes

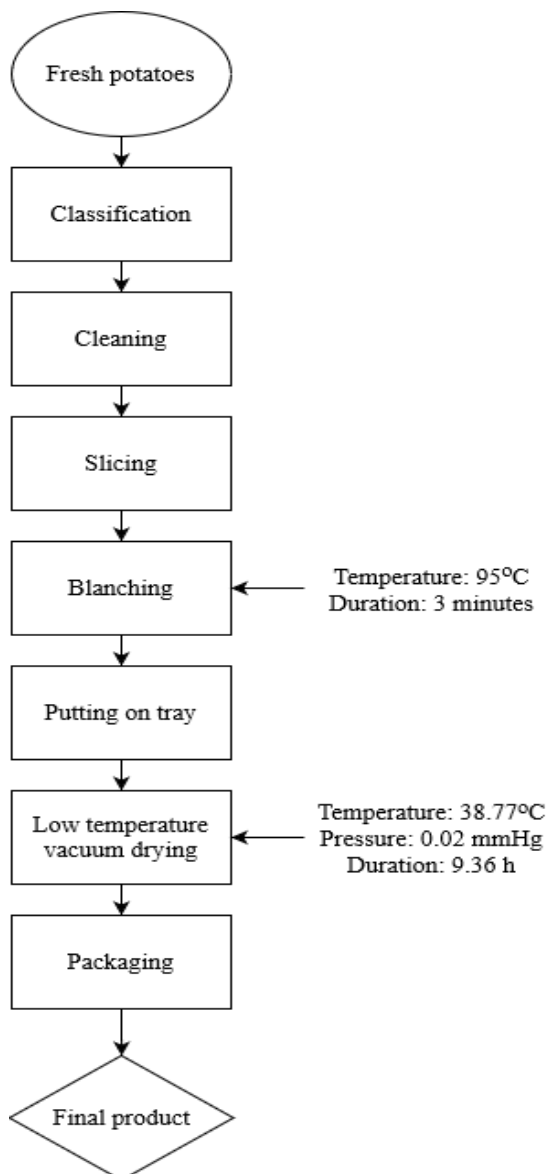


Figure 8. Flowchart of low temperature vacuum drying for potatoes

Fresh potatoes were chosen, washed thoroughly to remove dirt and other contaminants, peeled, sliced and blanched in water at 95°C for 3 minutes. Then, they were put on trays and dried at 38.77°C, pressure of the drying environment was 0.02 mmHg, and duration was 9.36 h. Product was collected, packaged and preserved.

4. CONCLUSION

Study on the production of dried potatoes by low temperature vacuum drying had solved some scientific and practical problems, including:

- Chemical composition of potatoes was determined and contributed as scientific knowledge for the drying process in order to preserve the quality of the product.

- Investigation of pre-treatment of potatoes before drying, potatoes were blanched at 95°C for 3 minutes.

- Mathematical models (18), (19), (20), (21) were successfully built and described the process of low temperature vacuum drying for potatoes.

- Multi-objective optimization problem (25) was solved and investigated the optimal technological mode: temperature was 38.77°C, pressure of the drying environment was 0.02 mmHg, and duration was 9.36 h. When drying at optimal mode, cost of energy was lowest (3.82 kWh), moisture content of product was lowest (4.03%), but crispness was highest (7.675 N) and the increase of fiber content was also highest (38.15%).

- Technological process of low temperature vacuum drying for potatoes was successfully constructed (Figure 7).

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