ТЕХНИЧЕСКИЕ НАУКИ И ТЕХНОЛОГИИ

АҚПАРАТТЫҚ ЖӘНЕ КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАР
ИНФОРМАЦИОННО-КОММУНИКАЦИОННЫЕ ТЕХНОЛОГИИ
INFORMATION AND COMMUNICATION TECHNOLOGIES

DOI 10.51885/1561-4212_2023_3_40
IRSTI 65.01.77

S. Kamanova[1], Y. Yermekov[1], Wenhao Li[2], G. Ospankulova[1]
[1]S.Seifullin Kazakh Agrotechnical Research University, Astana, Republic of Kazakhstan
[2]Engineering Research Center of Grain and Oil Functionalized Processing in University of Shaanxi Province, College of Food Science and Engineering, Northwest A&F University, 22 Xinong Road, Shaanxi, Yangling, 712100, China
E-mail: kamanovasveta@mail.ru
E-mail: yernazyermekov@outlook.com
E-mail: liwenhao@nwsuaf.edu.cn
*E-mail: bulashevag@mail.ru**

MATHEMATICAL MODELING AND EXPERIMENTAL STUDIES OF FREEZING DRYING OF BLACKCURRANT, BLUEBERRY, STRAWBERRY, RASPBERRY AND SEA-BUCKTHORN BERRIES

ҚАРА ҚАРАҚАТ, КӨКЖИДЕК, ҚҰЛПЫНАЙ, ТАҢҚУРАЙ ЖӘНЕ ТЕҢІЗ ШЫРҒАНЫ ЖИДЕКТЕРІН МҰЗДАТЫП КЕПТІРУ ПРОЦЕСІН МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ ЖӘНЕ ЭКСПЕРИМЕНТТІК ЗЕРТТЕУ

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ И ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ПРОЦЕССА СУБЛИМАЦИОННОЙ СУШКИ ЯГОД ЧЕРНОЙ СМОРОДИНЫ, ЧЕРНИКИ, КЛУБНИКИ, МАЛИНЫ И ОБЛЕПИХИ

Annotation. *The article presents a general solution for understanding changes in the moisture content in blackcurrants, blueberries, strawberries, raspberries, and sea buckthorn berries. A model of the experiment was built using the Box- Behnken method with coded values of shelf temperatures and drying durations as input parameters during the sublimation process of berries. Output values of the obtained model are consistent and appropriate to the experimental data.*
Key words: *berries; drying; sublimation; vacuuming.*

Аңдатпа. *Мақалада қарақат, көкжидек, құлпынай, таңқурай және теңіз шырғанақ жидектеріндегі ылғалдылықтың өзгеруінің жалпы шешімі көрсетілген. Сублимация процесінде сөре температурасының кіріспе параметрлерінің кодталған мәндері мен жидектерді кептіру ұзақтығы ұсынылған Бокс-Бенкен әдісін қолдана отырып, эксперимент моделі жасалынды. Алынған нәтижелер эксперименттік мәліметтерге сәйкес келеді.*
Түйін сөздер: *жидектер; кептіру; сублимация; вакуумдау.*

Аннотация. *В статье изложено получение общего решения вопроса изменения содержания влажности в ягодах смородины, голубики, клубники, малины и облепихи. Была построена модель эксперимента с использованием метода Бокса-Бэнкена с кодированными значениями вводных параметров температуры полок в процессе сублимации и продолжительности сушки ягод. Полученные результаты адекватны экспериментальным данным.*
Ключевые слова: *ягоды; сушка; сублимация; вакуумирование.*

Introduction. Fresh berries containing biologically active compounds are easily perishable under natural conditions. Drying is one of the most effective processing methods to extend the shelf life of berries, while the nutrients and active components in them can be preserved to a larger extent. However, the taste and texture of the final product significantly depend on the drying methods used [1-3].

The drying process helps to preserve the quality of the product, enabling the production of value-added products [4, 5].

Freeze drying is a relatively new technology in the field of food preservation. It was originally developed for the pharmaceutical industry and drug drying. Simplified, freeze-drying is a process that removes water through ice sublimation from a previously frozen product [6, 7].

Vacuum freeze-drying or lyophilization is characterized by a high speed of the drying process, high oxygen deficiency, and low process temperature, which maintains the structural integrity and preserves most of the original organoleptic properties of raw materials, including shape, aroma, color, taste, texture, biological activity, nutritional value, vitamins and minerals. Substances dissolved in water are deposited in the sublimation process, and inorganic salts dissolved in water are uniformly present, which avoids the nutrient loss caused by the migration of internal moisture to the surface, as observed in the conventional drying methods [8].

By keeping the product temperature lower than conventional drying methods and preventing contact with air, vacuum drying reduces product oxidation. Vacuum drying is used for dehydration of citrus juices, apple flakes, and various heat-sensitive products, where the preservation of ascorbic acid is important [9].

Some studies have investigated the impact of freeze-drying on the active ingredients and phytochemical composition of berries [10]. However, the efficiency of the drying process of products depends on a set of parameters, including the sublimation vacuum drying time, temperature conditions, and vacuum parameters. Therefore, it is important to experimentally determine the complex effect of all parameters on the final product.

The study of drying parameters requires expensive laboratory and experimental work, as well as a significant amount of time [11]. Ndisanze M. A. & Koca I. (2022) dried Tree Tomatoes using 350W, 500W, and 650W power outputs and then Freeze-Dried them to find the most appropriate mathematical modeling among various expressions of the moisture ratio [12]. Mathematical models are useful in optimizing drying conditions in addition, drying conditions and simulation model parameters are interconnected [13, 14].

This work is devoted to the mathematical modeling of drying various types of berries through sublimation.

Materials and methods of research. strawberries, raspberries, blackcurrants, sea buckthorn, and blueberries. All samples of berries were harvested during the period of active vegetation and fruiting period. A model of the experiment was built using the Box- Behnken method [15] with coded values of shelf temperatures and drying durations in the process of berry sublimation as input parameters.

Results and discussion. In order to obtain a general solution for changing the moisture content in the berries of currant, blueberry, strawberry, raspberry and sea buckthorn, an experimental model was built using the Box-Behnken method with coded values of temperature and drying time as input parameters. The coded values of the model are given in Table 1.

Table 1. Coded values for sublimation temperature and time

Parameter					
Time	Actual	18 o'clock	20 o'clock	22 o'clock	
	Encoded value	-1	0	1	
Temperature	Factual	35^{o} C	40^{o} C	45^{o} C	50^{o} C

	Encoded value	-1	0	1	2

The results of empirical observations carried out in accordance with experience are shown in Tables 2, 3, 4, 5, 6.

To obtain a descriptive model of the sublimation process for each berry, an analysis was conducted by fitting empirical data into various types of equations. These equations included a polynomial equation with multiple unknowns, a Lorentz plane curve, a Gaussian plane curve, and a paraboloid plane equation (equations 1, 2, 3, 4, 5). It has been established that the process of sublimation of currant and blueberry berries is best described by curves of the Gaussian plane, as indicated by high coefficients of determination, which were 0.9413 and 0.8883 for currant and blueberry, respectively (Figure 1, 2).

At the same time, changes in humidity observed in raspberries, strawberries, and sea buckthorn depending on the temperature and drying time are best described by paraboloid planes. The coefficients for the equations obtained in the course of the research were 0.9992, 0.9018, and 0.9696, respectively (Figures 3, 4, 5).

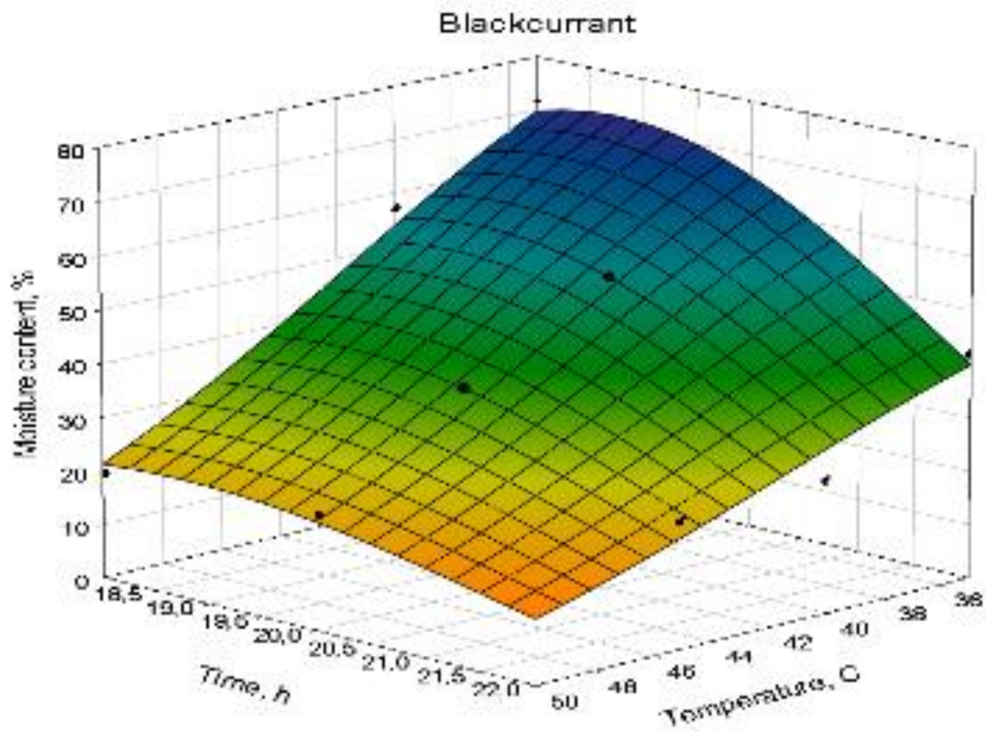

Figure 1. Graph of the equation describing the process of freeze-drying currant berries, depending on the temperature and duration of the process

Currant:

$$Moisture\ content = 83{,}6706 * e^{\left(\left(\frac{x-27.4415}{13.7919}\right)*\left(\frac{x-27.4415}{13.7919}\right)+\left(\frac{y-18.7426}{3.0336}\right)*\left(\frac{y-18.7426}{3.0336}\right)\right)} \quad (1)$$

Where: x – time in hours

y is the temperature of the shelves in degrees Celsius

e – Euler number, constant value

The topology of the regression equation indicates the natural dependence of sample moisture content on each parameter, with an increase to a maximum and a decrease to a minimum of a function similar to a 3rd-order sigmoid. It can be seen from the equation graph that drying below 42°C is impractical due to high humidity values. Determination is R^2 =0.9413, standard error of predictions is 5.7495.

Table 2. Results of the ANOVA test for the regression equation of the drying process of currant berries

<table>
<tr><td colspan="6">ANOVA</td></tr>
<tr><td></td><td>D.F.</td><td colspan="2">SS</td><td colspan="2">MS</td></tr>
<tr><td>Regression</td><td>5</td><td colspan="2">21220.2281</td><td colspan="2">4244.0456</td></tr>
<tr><td>Residuals</td><td>7</td><td colspan="2">231.4003</td><td colspan="2">33.0572</td></tr>
<tr><td>Outcome</td><td>12</td><td colspan="2">21451.6284</td><td colspan="2">1787.6357</td></tr>
<tr><td colspan="6">With correction to the average values of observations</td></tr>
<tr><td></td><td>D.F.</td><td>SS</td><td>MS</td><td>F</td><td>P</td></tr>
<tr><td>Regression</td><td>4</td><td>3709.3481</td><td>927.3370</td><td>28.0525</td><td>0.0002</td></tr>
<tr><td>Residuals</td><td>7</td><td>231.4003</td><td>33.0572</td><td></td><td></td></tr>
<tr><td>Outcome</td><td>11</td><td>3940.7484</td><td>358.2499</td><td></td><td></td></tr>
</table>

P≤0.05

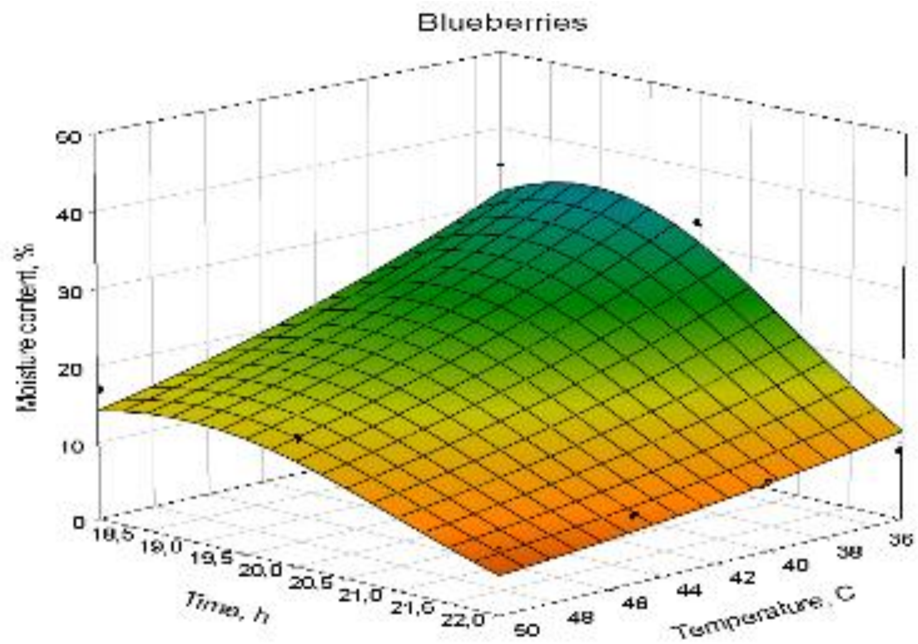

Figure 2. Graph of the equation describing the process of freeze-drying of blueberries, depending on the temperature and duration of the process

Blueberry:

$$Moisture\ content = 7910.069 * e^{\left(\left(\frac{x-5.7643}{2.0870}\right)*\left(\frac{x-5.7643}{2.0870}\right)+\left(\frac{y-18.9504}{1.9621}\right)*\left(\frac{y-18.9504}{1.9621}\right)\right)} \quad (2)$$

Where: x – time in hours

y is the temperature of the shelves in degrees Celsius

The topology of the regression equation indicates a natural dependence of the moisture content of the samples depending on each parameter, with an increase to a maximum and a decrease to a minimum of a function similar to a 3rd order sigmoid. However, as the drying time increases, the temperature dependence becomes linear. It can be seen from the graph of the equation that durations shorter than 19 hours are impractical due to high humidity values below this limit. The coefficient of determination of the regression equation is $R^2=0.8883$, the standard prediction error is 3.7511.

Table 3. Results of the ANOVA test for the regression equation of the process of drying blueberries

ANOVA					
	D.F.	SS	MS		
Regression	5	4407.0556	881.4111		
Residuals	7	98.4973	14.0710		
Outcome	12	4505.5529	375.4627		
With correction to the average values of observations					
	D.F.	SS	MS	F	P
Regression	4	783.3255	195.8314	13.9173	0.0019
Residuals	7	98.4973	14.0710		
Outcome	11	881.8228	80.1657		

$P \leq 0.05$

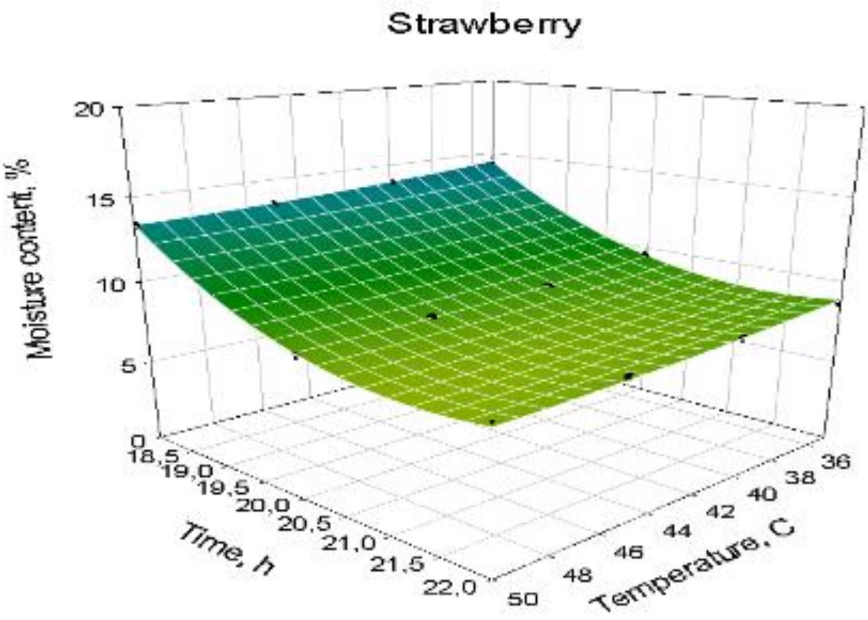

Figure 3. Graph of the equation describing the process of freeze-drying strawberries, depending on the temperature and duration of the process

Strawberry:

$$Moisture\ content = 254.0158 - 0.2452x - 22.5156y + 0.0022x^2 + 0.5291y^2 \quad (3)$$

Where: x – time in hours

y is the temperature of the shelves in degrees Celsius

The topology of the regression equation indicates that the equation takes on a leveled character, which indicates that the humidity has come to equilibrium, which is especially noticeable in the areas described, in terms of drying time, which is longer than 20.5 hours. Any drying parameters chosen within the time limits above 20.5 hours lead to the same, within the statistical error, the final moisture values. Determination coefficient is R^2 =0.9992, standard prediction error is 0.1313.

Table 4. Results of the ANOVA test for the regression equation of the process of drying strawberries

ANOVA					
	D.F.	SS		MS	
Regression	5	1345.2496		269.0499	
Residuals	7	0.1207		0.0172	
Outcome	12	1345.3703		112.1142	
With correction to the average values of observations					
	D.F.	SS	MS	F	P
Regression	5	71.9636	17.9909	1043.4548	<0.0001
Residuals	7	0.1207	0.0172		
Outcome	1 2	72.0843	6.5531		

P≤0.05

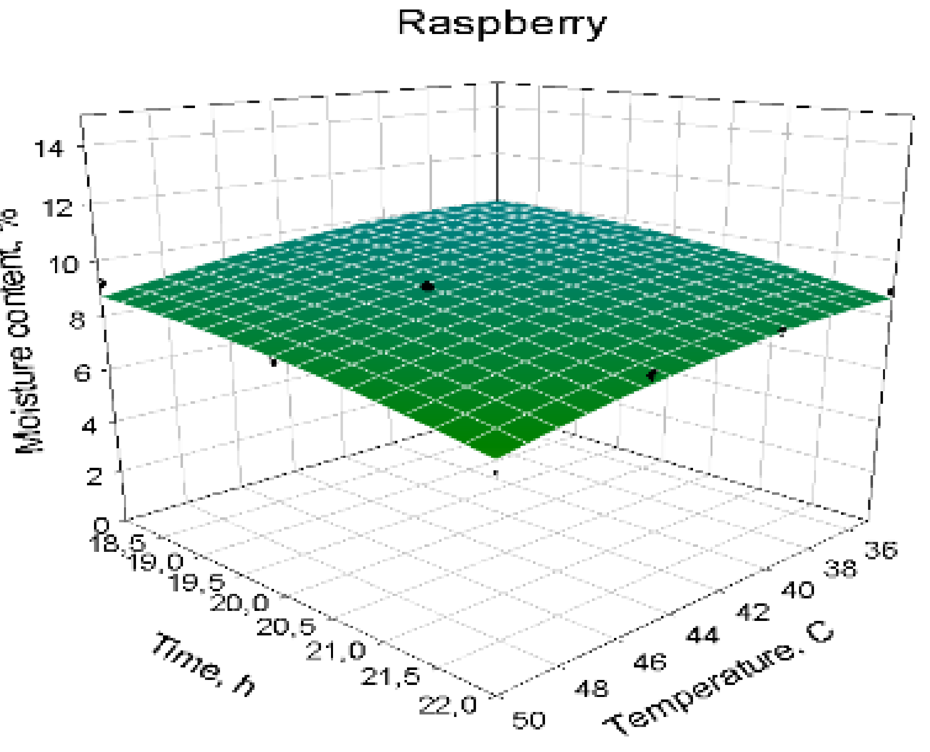

Figure 4. Graph of the equation describing the process of freeze-drying of raspberries, depending on the temperature and duration of the process

Raspberries:

$$Moisture\ content = -20.2073 + 0.4605x + 2.5075y - 0.0065x^2 - 0.0712y^2 \qquad (4)$$

Where: x – time in hours

y is the temperature of the shelves in degrees Celsius

The topology of the regression equation for the process of drying raspberries is leveled and does not have significant topological features. This phenomenon indicates that any combination of input parameters leads to the same, within the statistical error, values of the final moisture content. Coefficient of determination is $R^2 = 0.9018$, standard error of prediction is 0.3362.

Table 5. Results of the ANOVA test for the regression equation of the process of drying raspberries

ANOVA					
	D.F.	SS		MS	
Regression	5	966.3510		193.2702	
Residuals	7	0.7912		0.1130	
Outcome	12	967.1422		80.5952	
With correction to the average values of observations					
	D.F.	SS	MS	F	P
Regression	4	7.2678	1.8169	16.0745	0.0012
Residuals	7	0.7912	0.1130		
Outcome	11	8.0590	0.7326		

p≤0.05

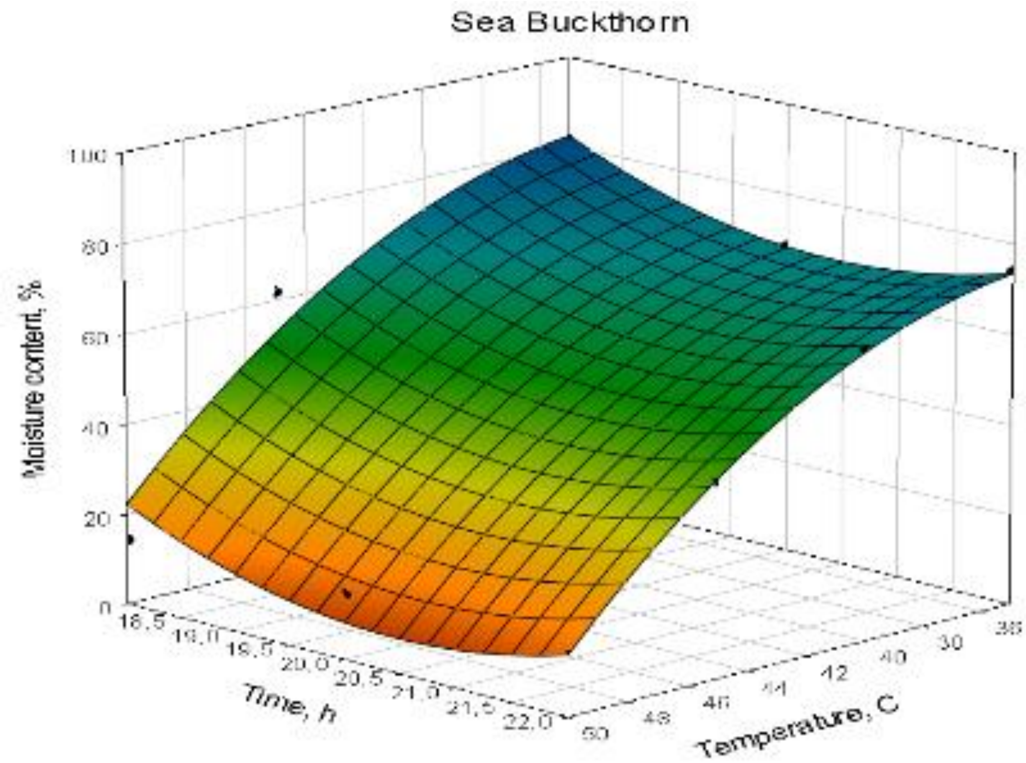

Figure 5. Graph of the equation describing the process of freeze-drying of sea buckthorn berries, depending on the temperature and duration of the process

Sea buckthorn:

$$Moisture\ content = 88.0694 + 13.9011x - 20.7706y - 0.2106x^2 + 0.4309y^2 \quad (5)$$

Where: x – time in hours

y is the temperature of the shelves in degrees Celsius

The topology of the regression equation has a natural character along the temperature axis, and a linear dependence along the time axis, which indicates that the drying process of sea buckthorn berries has a greater dependence on the drying temperature than on the drying time. Determination coefficient is R^2 =0.9696, standard prediction error is equal to 5.4951.

Table 6. Results of the ANOVA test for the regression equation of the process of drying sea buckthorn berries

ANOVA					
	D.F.	SS		MS	
Regression	5	36675.3738		7335.0748	
Residuals	7	211.3705		30.1958	
Outcome	12	36886.7443		3073.8954	
With correction to the average values of observations					
	D.F.	SS	MS	F	P
Regression	4	6748.3294	1687.0824	55.8715	<0.0001
Residuals	7	211.3705	30.1958		
Outcome	11	6959.6999	632.7		

p≤0.05

In further studies, the change in the limiting drying temperature and time was studied under different pressure modes of the sublimation process (Figure 6-7).

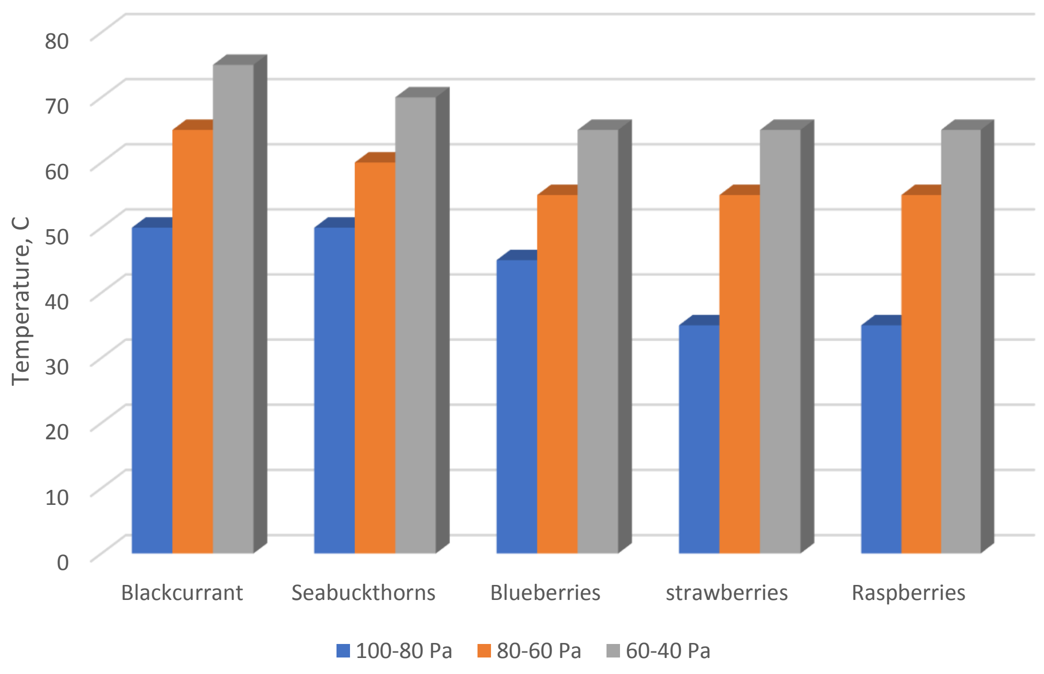

Figure 6. Change in freeze drying temperature, depending on the vacuum

Figure 6 shows that the optimum temperature for the sublimation of berries is observed when the pressure in the chamber ranges from 100-80 Pa. In Figure 7, the sublimation time decreases as the pressure decreases to 60-40 Pa. Lowering the operating pressure in the sublimation chamber tightens the operating conditions of vacuum pumps and results high energy costs, which consequently leads to equipment wear.

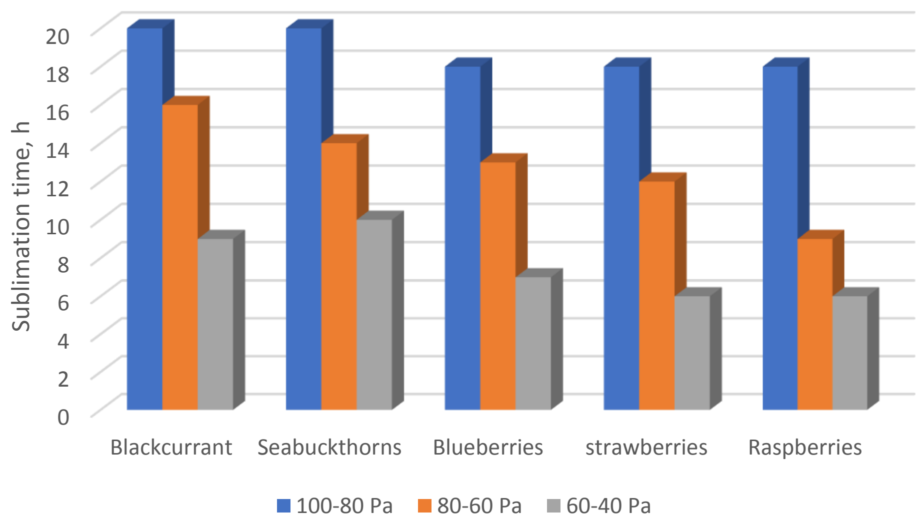

Figure 7. Change in freeze-drying time, depending on the parameters of evacuation

As a result of the research, it was concluded that pressure reduction negatively affects the quality of the finished product. The pressure of 100-80 Pa is optimal, at which the organoleptic characteristics of the berries are preserved, and due to the low humidity, the berries can be stored for a long time.

Conclusion. As a result of research, it was revealed that as pressure of sublimator decreases, the temperature on the shelves increases, which, in turn, has a negative impact on the quality of the final product. Additionally, experimental evidence reveals that lower pressure in the sublimator results in a shorter drying time for the berries.

According to the conducted research, the optimal parameters of freeze-drying of black currant berries, blueberries, strawberries, raspberries and sea buckthorn will be selected. In further research, it is planned to continue mathematical modeling of the physio-chemical properties of freeze-dried berries.

Acknowledgement.

This study «Development of technology to ensure the safety of the quality of agricultural raw materials and processed products in order to reduce losses during various storage methods» [IRN: BR10765062] was funded by the Ministry of Agriculture of the Republic of Kazakhstan.

References

1. Crane, J.H. (2017). This document was developed using information compiled ruing the National Mango Board-sponsored 2015-2017 research project, Mango Cultivar Evaluation Project-Phase 1.
2. Bustos, M.C., Rocha-Parra, D., Sampedro, I., de Pascual-Teresa, S., & León, A.E. (2018). The influence of different air-drying conditions on bioactive compounds and antioxidant activity of berries. Journal of Agricultural and Food Chemistry, 66(11), 2714-2723.
3. Piecko, J., Konopacka, D., Mieszczakowska-Frąc, M., & Kruczyńska, D. (2017). The effectiveness of vacuum-microwave drying methods in the preservation of Amelanchier berries (Amelanchier canadensis L. Medik.). International Journal of Food Engineering, 13(6).
4. D.I. Onwude, N. Hashim, K. Abdan, R. Janius, and G. Chen, “Numerical modeling of radiative heat

and mass transfer for sweet potato during drying, ”Journal of Food Processing & Preservation. – Vol. 42. – No. 10. – Pp. 1-14, 2018.

5. A. Calín-Sánchez, L. Lipan, M. Cano-Lamadrid et al., “Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs,” Foods. – Vol. 9. – No. 9. – Pp. 1-27, 2020.
6. Fissore, D., Pisano, R., & Barresi, A. (Eds.). (2019). Freeze Drying of Pharmaceutical Products. CRC Press.
7. Punthi, F., Yudhistira, B., Gavahian, M., Chang, C.K., Cheng, K.C., Hou, C.Y., & Hsieh, C.W. (2022). Pulsed electric field- assisted drying: A review of its underlying mechanisms, applications, and role in fresh produce plant- based food preservation. Comprehensive Reviews in Food Science and Food Safety, 21(6), 5109-5130.
8. Shkarupa, I.L., Khmelnitsky, A.K., & Shkarupa, M.I. (2013). CERAMIC HIGH-TEMPERATURE FAST NEUTRON REACTOR. SCIENCE AND WORLD, 58.
9. Sadowska, K., Andrzejewska, J., & Klóska, Ł. (2017). Influence of freezing, lyophilisation and air-drying on the total monomeric anthocyanins, vitamin C and antioxidant capacity of selected berries. International Journal of Food Science & Technology, 52(5), 1246-1251.
10. Harguindeguy, M.; Fissore, D. On the effects of freeze-drying processes on the nutritional properties of foodstuff: A review. Dry. Technol. 2019, 1-23. [Google Scholar] [CrossRef]].
11. Akter, F., Muhury, R., Sultana, A., & Deb, U.K. (2022). A Comprehensive Review of Mathematical Modeling for Drying Processes of Fruits and Vegetables. International Journal of Food Science, 2022.
12. Ndisanze, M.A., & Koca, I. (2022). Dehydration and rehydration kinetics modeling in the phytochemical, aroma, and antioxidant capacity of tree tomato fruit dried with microwaves and freeze driers: a comparative study. Processes, 10(8), 1437.
13. M. Sahoo, S. Titikshya, P. Aradwad, V. Kumar, and S.N. Naik, “Study of the drying behaviour and color kinetics of convective drying of yam (Dioscorea hispida) slices,” Industrial Crops and Products, vol. 176, article 114258, 2022.
14. F.H. Cosme-De Vera, A.N. Soriano, N.P. Dugos, and R.V.C. Rubi, “A comprehensive review on the drying kinetics of common tubers,” Applied Science and Engineering Progress, vol. 14, no. 2, pp. 146-155, 2021.
15. John, I., Pola, J., Muthukumar, K., Thanabalan, M., & Appusamy, A. (2022). Production of bioethanol from sweet lime peel via a statistically optimized simultaneous saccharification and fermentation process using isolated enzymes. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(1), 1327-1335.