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SUBSTANTIATING THE CRITERIA FOR EVALUATING THE QUALITY OF FROZEN SWEET CHERRY FRUITS USING THE METHOD OF MULTI-CRITERIA OPTIMIZATION

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The object of this study is the process of preserving the biochemical and sensory quality parameters in frozen semi-finished sweet cherry products.

The modern food industry requires stable product quality, expanding the range of products, and preserving the nutritional value of raw materials, taking into account seasonality. An important role belongs to frozen fruit raw materials. However, their quality is often unpredictable, making it difficult to ensure stable technological characteristics of the end product. In this context, the scientific substantiation of the criteria for assessing the quality of frozen sweet cherry fruit is of particular relevance. For the current study, the fruits of 33 varieties of sweet cherries of different ripening periods were used. The statistical evaluation of freshly frozen fruits of cherry varieties by a set of parameters and values of the objective function was analyzed.

Using the method of multicriteria optimization, the most suitable sweet cherry varieties for freezing were identified. The best early ripening sweet cherry variety was determined to be Skazka (rank 1) – $\varphi(x5)=4.67$. Optimal for freezing were cherry fruits of medium ripening, the Talisman variety (rank 1) – $\varphi(x5)=3.58$. Based on the values of objective functions, the best for freezing is the late-ripening sweet cherry, the Krupnoplidna variety (rank 1) – $\varphi(x1)=3.43$. On the basis of the research, biochemical and sensory criteria for assessing the quality of frozen semi-finished products of early, medium, and late ripening sweet cherry varieties were devised for their further use in production. The results could be used to improve the criteria for assessing the quality of frozen fruit raw materials within the zero-waste fruit supply chain, which ensures the efficiency and sustainable use of resources for all stakeholders

Keywords: biochemical parameters, sensory parameters, geometric convolution of criteria, grading, waste-free chain

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1. Introduction

In the face of unpredictable events, the issue of food security becomes critical, especially in countries with an increased level of risks caused by natural disasters and military conflicts [1]. Ensuring the sustainability of food systems requires solving the problem of maintaining stable quality, as well as taste and beneficial properties of fruits that serve as raw materials for further processing, in particular by the method of osmotic dehydration [2]. Sweet cherries are one of the most popular fruits used in the confectionery production, in particular candied fruits. The high nutritional value of sweet cherries, which contain vitamins, organic acids, and antioxidants, makes them not only useful but also a tasty component of many desserts. However, to ensure stable quality and preservation of taste and beneficial properties of sweet cherries during their processing into candied fruits, it is necessary to thoroughly control the quality of fruit raw materials [3]. In view of this, the importance of studying sweet cherry varieties characterized by high technological and taste parameters, both for fresh consumption and for further processing is increasing [4]. Important criteria for assessing the quality of fruits are their biochemical indicators, in particular the content of dry soluble substances, sugars, organic acids, vitamins, and polyphenolic compounds [5, 6]. In addition, the physical appearance and taste properties of fruits are decisive factors when choosing sweet cherries for both direct consumption and processing [7, 8]. The stability of functional and technological indicators of fruits is determined by the variability of each of the evaluated criteria [9]. A comprehensive analysis of all fruit characteristics is a key factor in the formation of high-quality fruit raw materials for further processing.

Under current conditions of increased requirements for the quality of food products, ensuring the stability of technological characteristics of semi-finished products is of particular importance. Frozen fruit raw materials, in particular sweet cherries, are widely used in the production of confectionery, candied fruits, yogurts, and other foods. Their quality directly affects the consumer properties of the end product, the economic efficiency of production, and the competitiveness of processing enterprises.

However, current approaches to assessing the quality of frozen fruit raw materials are often fragmentary and do not take into account the entire set of physicochemical, organoleptic, microbiological, and technological parameters. That makes it difficult to take informed decisions when choosing raw materials for long-term storage or use in the food production. Improving the criteria for comprehensive quality assessment will allow for more accurate selection of raw materials with predicted resistance to freezing, for optimizing storage conditions for semi-finished products, reducing losses during processing, as well as ensuring the stability of the properties of end products. Therefore, devising a scientifically sound system for assessing the quality of frozen sweet cherries based on a multi-criteria approach is a relevant task that meets modern challenges in the field of food security, reducing food losses, and implementing the principles of sustainable production.

2. Literature review and problem statement

Production of candied fruits from fresh fruits is a priority area for developing the food industry both in Ukraine and globally. Studies [10, 11] highlight the current trends in this industry, which are focused on improving the quality of products obtained by osmotic dehydration. Sensory, biochemical, and thermophysical characteristics of candied fruits from different types of raw materials were studied. However, the quality indicators of fresh raw materials received for processing were not investigated.

In work [12], the quality of food products with guaranteed added value was considered. The research provided for the determination of physicochemical, microbiological properties, textural and sensory analysis. However, the quality of the input raw materials was not taken into account, which also affects the stability of the quality indicators of the manufactured product. This problem becomes particularly relevant in the context of violation of warranty obligations to ensure food safety due to the deepening of negative trends in the global food system. The worsening situation concerns not only the food system in Ukraine but also global food security, especially in regions affected by russian aggression. Key threats include the theft of crops in the occupied territories, the destruction of arable land in the war zone, and the environmental disaster caused by the explosion of the Kakhovka reservoir [1].

Sweet cherries are a popular semi-finished product in the confectionery industry due to their rich taste, aroma, and attractive physical appearance. They also have nutritional value, as they contain mineral salts, trace elements, pectin, and vitamins [9, 13]. This opens up prospects for expanding the range of uses of sweet cherry semi-finished products for the production of value-added foods. At the same time, there is interest in the year-round use of sweet cherry fruits in the processing cycle for various products. The main unresolved issue is to study the suitability of varieties for freezing their fruits and obtaining high-quality semi-finished products for further processing.

The main aspect in the production of candied fruits is the quality indicators of the finished product, which are regulated by the general technical requirements in accordance with DSTU 6075:2009 “Candied fruits. Technical conditions”. To ensure high quality of the end product, it is necessary to determine the suitability of raw materials for the production of candied fruits. The disadvantages of existing methods of candied fruits production are low biological value and limited functional properties of the product, as well as unsatisfactory organoleptic characteristics. This is due to significant losses of biologically active substances due to prolonged heat treatment at high temperatures, which, in turn, negatively affects the softness of the taste, tenderness of the consistency, and expressiveness of the aroma of the finished product. An option for solving this problem is to find modern methods that could make it possible to reduce the duration of heat treatment of raw materials during the production of candied fruits. An effective technological solution for improving the quality of the end product is the use of osmotic dehydration. This method allows for better preservation of the color, taste, and nutritional value of raw materials [14]. Although osmotic dehydration has been a common strategy for several decades, it has a high potential for further development and improvement. However, the issue of the impact of osmotic dehydration on the quality of the end product depending on the type of raw material remains unaddressed. A comprehensive assessment of the quality of frozen fruits will ensure the selection of the optimal sweet cherry variety, which in turn will reduce the amount of waste during the osmotic dehydration process.

Currently, there is a growing demand for high-quality natural ingredients for the production of functional foods, in particular candied fruits, which can serve as an alternative to confectionery products with a high sugar content. The use of sweet cherry fruits as raw materials for the production of candied fruits is of particular importance due to its attractive organoleptic properties, rich biochemical composition, and high consumer value. However, the suitability of specific varieties for freezing and further technological processing significantly depends on a set of quality characteristics. It has been established [15] that in the process of candied fruits production, many factors related to the properties of the raw materials, technological requirements and quality expectations of consumers should be taken into account. At the same time, it is worth noting that the quality of the end product is closely related to the characteristics of the starting raw materials, primarily the quality of the sweet cherries entering the processing. The authors of [16, 17] highlight the functional and technological properties of sweet cherry fruits as raw materials for the production of candied fruits. It has been established that they are represented by a wide variety of varieties and are characterized by unique properties. Despite a significant number of studies on sweet cherry fruits in terms of their biochemical and sensory characteristics, information on the rational selection of varieties for the production of candied fruits from fresh and frozen raw materials by a balanced set of indicators remains limited. All of the above indicates the importance of scientifically based selection of sweet cherry varieties as a prerequisite for obtaining a quality product and efficient production.

However, analysis of each quality indicator separately does not make it possible to form a set of parameters that determine the best variety. Therefore, to select the optimal variety of fruits that can be recommended for the production of high-quality candied fruits, it is necessary to use a comprehensive assessment. One of the modeling methods based on complex quality indicators is the generalized desirability function proposed by Harrington [18]. In scientific research, it is used to generalize the quality indicators of frozen sweet cherry fruits by various methods and determine the best option [19]. A single comprehensive quality measure can be established from the Harrington desirability function. One key unresolved issue is that the standard form of the desirability function does not take into account correlations or interdependences between criteria since each of them is evaluated independently. As a result, biased ranking of alternatives is likely, especially in the presence of closely related characteristics.

An effective tool for a comprehensive assessment of fruits based on a set of quality indicators is the multi-criteria optimization method. The use of this method makes it possible to take into account not only a set of important indicators but also to reasonably determine the most suitable varieties for freezing and production of semi-finished products for further use [20]. At the same time, issues related to the formation of a set of criteria for assessing frozen sweet cherry fruits of a wide range of varieties with different ripening periods remain insufficiently resolved. In this regard, there is a need for a systematic approach to the selection of varieties that combine technological, biochemical, and organoleptic attractiveness. Work [21] reports the integral methods for a comprehensive assessment of fruits based on a set of generalized indicators. At the same time, a clearly defined set of criteria for assessing frozen fruit raw materials intended for the production of candied fruits has not been proposed. Updating the varietal composition of sweet cherries necessitates a comprehensive assessment of frozen raw materials in order to make a well-founded choice of the optimal variety for further processing.

Issues related to the development of an effective strategy for multi-criteria selection of cherry varieties for recommendations to producers of high-quality raw materials suitable for the manufacture of candied fruits have remained unresolved. This approach involves taking into account several parameters and using analytical methods to make informed decisions. Therefore, assessing the quality of frozen sweet cherries is a multi-faceted task that requires taking into account both biological and technological factors. The use of scientifically sound approaches to the selection of raw materials allows for increased production efficiency and high quality of the end product. Therefore, determining relevant criteria for assessing the quality of frozen sweet cherries using the multi-criteria optimization method is relevant and requires further investigation. This will improve the efficiency of sweet cherry processing, enhance the quality of finished products, and expand opportunities for sustainable production.

3. The aim and objectives of the study

The aim of our study was to establish optimal quality criteria for frozen sweet cherry fruits of different ripening periods based on biochemical, commercial, and organoleptic indicators using the multi-criteria optimization method.

To achieve the goal, the following tasks were set:

– to develop an algorithm for assessing the quality of freshly frozen sweet cherry fruits;

– to determine a ranked series of early-ripening sweet cherry varieties in frozen form;

– to rank freshly frozen fruit raw materials of medium-ripening sweet cherry varieties;

– to establish the priority of freshly frozen fruit raw materials of late-ripening sweet cherry varieties.

4. The study materials and methods

The object of our study is the process of preserving the biochemical and sensory parameters of the quality of frozen cherry fruit raw materials.

Subject of the study: fresh-frozen fruit raw materials of cherry varieties of different ripening periods, criteria for comprehensive quality assessment.

Research hypothesis: one of the possible ways to assess the quality of fruit raw materials is to use the multi-criteria optimization method. For a comprehensive assessment of the quality of cherry fruit raw materials, it is advisable to use such criteria as the amount of juice loss immediately after freezing, the concentration of dry soluble substances; sugars, titrated acids, vitamin C, and the sum of phenolic substances and the sensory profile. It is assumed that a comprehensive assessment of the quality of fresh-frozen fruit raw materials according to these criteria could make it possible to rank sweet cherry varieties of different ripening periods to select the best one for freezing. It is also expected to improve the criteria for comprehensive assessment of the quality of frozen fruit raw materials. This, in turn, will contribute to the optimization of the storage processes of semi-finished sweet cherry products and the production of end products while maintaining stable technological characteristics.

33 varieties of sweet cherry were selected for our study, divided into 3 groups:

– Group 1 – early ripening varieties – Svit Erliz, Merchant, Bigaro Burlat, Rubinova rannya, Valeriy Chkalov, Kazka (control), Zabuta;

– Group 2 – mid-ripening varieties – Kordia, Octavia, Vinka, Pervystok, Temp, Ulyublenytsya Turovtseva, Talisman, Dilemma, Melitopolskaya black (control), Orion, Chervneva rannya, Dachnitsa, Prostir;

– Group 3 – late ripening varieties – Karina, Regina, Mirage, Krupnoplodna (control), Udivitelna, Zodiac, Surprise, Kolkhoznitsa, Kosmichna, Prazdnichna, Anons, Temporion, Meotida.

The sweet cherries were selected for the study in the state of consumer ripeness according to DSTU ISO 874-2002. The quality of the fruits met the standard requirements for sweet cherries according to DSTU 8153:2015. The date of fruit harvest was determined by the following indicators: physical appearance (shape and color typical for a certain pomological variety), presence or absence of a stalk, mechanical damage to the peel, damage by pests and fungal diseases, fruit diameter. Immediately after harvest, the fruits were packed in bulk in plastic boxes (container size $600 \times 400 \times 116$ mm), 10 kg each.

During the removal process, the sweet cherry fruits were simultaneously sorted by quality. Fruits for freezing must be developed, whole, fresh, clean, not affected by pests, diseases, and meet the requirements for the first commercial grade in appearance and size according to DSTU 4837-2007.

The collected and sorted sweet cherries were transported to the laboratory where they were technologically prepared for freezing. It included the following stages: inspection, sorting, calibration, washing, removal of excess moisture. Freezing was carried out in bulk in polyethylene bags with a capacity of 0.5 kg at a temperature of minus 30°C ± 1°C. Freezing was considered complete when the temperature in the center of the fruit reached minus 18°C ± 1°C. The study of the functional and technological indicators of each variety of sweet cherry semi-finished products was carried out on freshly frozen samples. Defrosting of the fruits was carried out in the open air at room temperature of 24–25°C.

The study on the quality indicators of frozen sweet cherries of varieties of three ripening periods was carried out in laboratories at the Scientific Research Institute of Agrotechnology and Ecology, the Tavria State Agrotechnological University named after Dmitry Motorny (Melitopol, Ukraine).

Experimental data collection was performed during 2008–2019. Determination of chemical composition components and organoleptic indicators was performed immediately after freezing according to standard methodologies [22].

The amount of cell sap loss – by determining the difference in fruit weight before and after defrosting.

The content of dry soluble substances was determined using a refractometer. The method is based on determining the mass fraction of dry soluble substances by refractive index. The refractive index of the analyzed solution was measured at a temperature of (20.0 ± 0.5)°C on an ABBE AR12 refractometer.

Mass concentration of sugars was determined by the ferricyanide method. This method is based on the ability of reducing monosaccharides to reduce potassium ferricyanide – K3[Fe(CN)6] (red blood salt) in an alkaline medium to potassium ferric cyanide (ferrocyanide) – $K_4[Fe(CN)_6]$ (yellow blood salt). Methylene blue was used as an indicator. When potassium ferricyanide is reduced, a change in the color of the solution from blue to colorless or light yellow is observed. The amount of sucrose was determined by first converting it to invert sugar.

The content of titrated acids was determined by the titrimetric method. The method involves neutralizing the organic acids contained in the product under study with a 0.1 N alkali solution. Titration is carried out until the solution transitions from an acidic to an alkaline medium. This transition is visually recorded by the appearance of a pink color of the solution in the presence of the phenolphthalein indicator. The accuracy of the method is ±0.5%.

The content of phenolic substances was determined using the Folin-Denis reagent. The method is based on the complexation reaction of polyphenols with the Folin-Denis reagent, as a result of which colored compounds are formed, which make it possible to determine the optical density. To calculate the content of polyphenols in sweet cherry fruits, a standard, rutin, was used.

The content of ascorbic acid was determined by the iodometric method using the Tillmans reagent. The method is based on the reducing properties of ascorbic acid. Under the influence of ascorbic acid, the solution of the indicator 2,6-dichlorophenolindophenol, which has a blue color, is reduced to a colorless compound.

The overall sensory assessment of frozen sweet cherry fruits was carried out on a 9-point scale.

5. Results of quality assessment of frozen sweet cherry fruits of different ripening periods according to optimal criteria

5. 1. Development of an algorithm for assessing the quality of freshly frozen sweet cherry fruits

The optimal choice of a sweet cherry variety for freezing and production of semi-finished products with high characteristics involves a comparative analysis of the properties of each variety. Sweet cherry fruits, as raw materials, have numerous parameters that significantly affect the quality of finished products. Key factors include chemical composition, physical characteristics, and organoleptic properties. Given the variability of values for the criteria under different production conditions, the choice of the best variety is possible only with an integrated approach. In this context, it is advisable to apply the multi-criteria optimization method, which takes into account the relationship between the quality indicators of sweet cherries and their permissible values. The essence of the method is to use a decision-making mechanism based on predetermined criteria. This allows us to exclude the influence of units of measurement, as well as the size of the intervals of permissible values of each of the criteria on the final selection of the variety (objective function) [22].

To scientifically substantiate the optimal selection of a sweet cherry variety suitable for freezing and the production of semi-finished products, an algorithm was built using the multi-criteria optimization method, consisting of the following main stages:

1. Formulation of the optimization task. At this stage, key criteria and their significance for obtaining a high-quality end product are determined. The main criteria Aj selected were the physical, biochemical, and organoleptic indicators of frozen sweet cherry fruits of different ripening periods (early, medium, and late). The following indicators were determined: the amount of juice loss (A_1), the content of dry soluble substances (A_2), sugars (A_3), titrated acids (A_4), ascorbic acid (A_5), the total content of phenolic compounds (A_6). The average sensory assessment of fruits was estimated (A_7).

2. Normalization of criteria. This was carried out in order to eliminate the influence of the units of measurement of

physical-biochemical and sensory criteria of frozen fruits of different varieties, which makes it possible to convert their values into dimensionless quantities $\left(f_j \rightarrow \hat{f}_j\right)$.

Before carrying out the normalization operation, it is necessary to establish:

– the maximum $\left(f_j^+\right)$ and minimum $\left(f_j^-\right)$ value of the j-th criterion of the studied varieties (x_i);

– the optimal value of the jth criterion was determined by the following rule;

– if the evaluation criterion (f_j) tends to the minimum value, then

$$\left(f_j^{opt} \rightarrow \min\right), mo = f_j^{opt} = f_j^-;$$

– if the evaluation criterion (f_j) tends to the maximum value, then

$$\left(f_j^{opt} \rightarrow \min\right), mo = f_j^{opt} = f_j^+.$$

The trend for the optimal value of the jth criterion $\left(f_j^{opt}\min; f_j^{opt}\max\right)$ is taken into account when choosing formula (1) for carrying out the normalization operation

$$\hat{f}_j\left(x_i\right)=\begin{cases}\dfrac{\left(f_j\left(x_i\right)-f_j^-\right)}{\left(f_j^+-f_j^-\right)}, \text{if } f_j^{opt} \rightarrow \max,\\[2ex] \dfrac{\left(f_j^+-f_j\left(x_i\right)\right)}{\left(f_j^+-f_j^-\right)}, \text{if } f_j^{opt} \rightarrow \min,\end{cases} \quad (1)$$

$\hat{f}_j\left(x_i\right)$ – value of the j-th criterion in normalized form for the i-th variety;

$f_j\left(x_i\right)$ – value of the j-th criterion for the i-th variety in the corresponding units of measurement;

f_j^+, f_j^- – range of permissible values of the j-th criterion of compared varieties.

3. Calculation of values for the objective function. After the normalization operation, the values of objective function (φ) are calculated for each variety (x_i) according to formula (2)

$$\phi\left(x_i\right)=\sum^n\left|\hat{f}_j\left(x_i\right)-\hat{f}_j\left(x^i\right)\right| \rightarrow \min, \quad (2)$$

where $0 \le \hat{f}_j\left(x_i\right) \le 1$,

$\hat{f}_j\left(x^i\right)=1$,

$\varphi(x_i)$ is the objective function of the i-th variety;

n – number of criteria;

$\hat{f}_j\left(x_i\right)$ – value of the j-th criterion in normalized form for the i-th variety;

$\hat{f}_j\left(x^i\right)$ – value of the j-th criterion in normalized form for the ideal variety;

x^i – ideal variety (with optimal values of criteria).

Proving $\hat{f}_j\left(x^i\right)=1$.

If $f_j^{opt} \rightarrow \max$, then, according to formula (2), the value of the j-th criterion in normalized form for the ideal variety for verification can be calculated from formula (3)

$$\hat{f}_j\left(x^i\right)=\frac{f_j\left(x^i\right)-f_j^-}{f_j^+-f_j^-}, as\ f_j\left(x^i\right)=f_j^{opt}=f_j^+. \quad (3)$$

If $f_j^{opt} \rightarrow \min$, then, according to formula (2), the value of the j-th criterion in normalized form for the ideal variety for testing can be calculated from formula (4)

$$\hat{f}_j\left(x^i\right)=\frac{f_j^+-f_j\left(x^i\right)}{f_j^+-f_j^-}, as\ f_j\left(x^i\right)=f_j^{opt}=f_j^-. \quad (4)$$

4. Analysis of the results. The choice of the best variety is determined by the conditions for maximum approximation of its objective function to the objective function of the ideal variety, which is equal to zero

$$\phi\left(x^i\right)=\sum^n\left|\hat{f}_j\left(x^i\right)-\hat{f}_j\left(x^i\right)\right|=\sum^n\left|1-1\right|=0. \quad (5)$$

Therefore, the smaller the value of the objective function for the variety in the range of values for the criteria of the studied varieties, the higher its suitability for freezing and further processing of the resulting semi-finished products.

5. 2. Results of objective functions for the ranked series of early ripening sweet cherry varieties in frozen form

To scientifically substantiate the choice of the optimal sweet cherry variety suitable for freezing and production of semi-finished products by the method of multi-criteria optimization, calculations were carried out based on the developed algorithm. Analysis of values of the objective functions allowed us to establish a ranked series of early ripening sweet cherry varieties (Tables 1, 2).

Among the studied group of early ripening varieties, the Valeriy Chkalov variety (rank 1), φ(x2)=1.22, was optimal according to the studied parameters (Table 2).

Table 1

Functional and technological indicators of early ripening sweet cherry fruits for calculating objective functions $\varphi(x_1)...\varphi(x_7)$ when choosing the optimal variety of frozen raw materials

Alternative, X_i	Variety	Criterion, Aj						
		Amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (%), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg per 100 g), A_5	Vitamin C, (mg per 100 g), A_6	Sensory evaluation, (score), A_7
		f_1	f_2	f_3	f_4	f_5	f_6	f_7
X_1	Rubinova rannya	15.50	16.80	12.30	0.38	175.27	6.92	7.70
X_2	Valeriy Chkalov	15.90	16.50	12.60	0.53	194.07	7.13	8.90
X_3	Svit Erliz	16.10	16.20	12.90	0.53	155.63	7.26	8.20
X_4	Merchant	19.70	14.00	10.60	0.37	157.24	6.90	7.70
X_5	Kazka – control	15.40	14.80	11.60	0.49	203.17	7.36	9.00
X_6	Biharo Burlat	19.10	13.50	11.10	0.47	160.78	6.84	7.80
X_7	Zabuta	16.00	14.90	12.50	0.53	196.54	7.31	7.90

Table 2

Results of determining the objective functions $\varphi(x_1)...\varphi(x_7)$ when choosing the optimal variety of early ripening sweet cherry in frozen form

Alternative, X_i	Variety	Criterion, Aj							Value of objective function, $\phi(x_i)$	Rank
		Amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (%), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg per 100 g), A_5	Vitamin C, (mg per 100 g), A_6	Sensory evaluation, (score), A_7		
		$\hat{f}_1$	$\hat{f}_2$	$\hat{f}_3$	$\hat{f}_4$	$\hat{f}_5$	$\hat{f}_6$	$\hat{f}_7$		
X_1	Rubinova rannya	0.89	0.88	0.96	0.23	0.40	0.38	0.28	2.99	5
X_2	Valeriy Chkalov	0.81	0.81	1.09	0.81	0.80	0.52	0.94	1.22	1
X_3	Svit Erliz	0.77	0.74	1.22	0.81	–0.02	0.61	0.56	2.32	4
X_4	Merchant	0.09	0.23	0.22	0.19	0.01	0.37	0.28	5.60	7
X_5	Kazka – control	0.91	0.42	0.65	0.65	0.99	0.67	1.00	1.71	2
X_6	Biharo Burlat	0.21	0.12	0.43	0.58	0.09	0.33	0.33	4.91	6
X_7	Zabuta	0.79	0.44	1.04	0.81	0.85	0.64	0.39	2.04	3
f_j^-		14,90	13.00	10.10	0.32	156.66	6.34	7.20	–	–
f_j^+		20,20	17.30	12.40	0.58	203.67	7.86	9.00	–	–
f_j^{opt}		19.7 (max	17.3 (max)	12.4 (max)	0.58 (max)	203.67 (max)	7.86 (max)	9 (max)	–	–

The Valery Chkalov 1st rank variety with the minimum value of the objective function in terms of quality parameters is the best compared to the control variety Kazka of early ripening period. Therefore, it is advisable to form a set of suitability criteria for the studied group of varieties based on the quality indicators of fruits of the 1st rank varieties of the Valery Chkalov variety. Based on this, a balanced set of initial biochemical, marketable, and organoleptic criteria has been devised for the group of early ripening varieties, which makes it possible to scientifically predict their greatest value. This set includes the initial concentration of the following physical-biochemical indicators: the amount of juice loss immediately after freezing is no more than 16%; the initial concentration of dry soluble substances is 16.50%; sugars – 12.60%; titrated acids – 0.53%; vitamin C – 7.13 mg/100 g; the amount of phenolic substances – 194.07 mg/100 g; sensory score – 8.9 points.

5. 3. Results of objective functions for a ranked series of sweet cherry varieties of medium ripening period in frozen form

Based on our analysis of values for objective functions, a ranking of freshly frozen fruit raw materials of sweet cherry varieties of medium ripening period was constructed (Tables 3, 4).

Table 3

Functional and technological indicators of medium-ripening sweet cherry fruits for calculating objective functions $\varphi(x_1)...\varphi(x_{13})$ when choosing the optimal variety of frozen raw materials

Alternative, X_i	Variety	Criterion, Aj						
		Amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (%), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg per 100 g), A_5	Vitamin C, (mg per 100 g), A_6	Sensory evaluation, (score), A_7
		f_1	f_2	f_3	f_4	f_5	f_6	f_7
X_1	Vinca	15.40	16.80	12.20	0.72	172.51	8.08	9.00
X_2	Pervistok	16.90	16.70	12.40	0.65	171.05	9.05	8.30
X_3	Temp	15.00	17.40	13.20	0.67	173.74	8.07	8.40
X_4	Ulyublenytsya Turovtseva	19.20	15.30	10.80	0.68	226.85	9.02	8.00
X_5	Talisman	13.20	18.50	14.60	1.00	216.60	10.48	8.90
X_6	Dilema	14.70	17.80	12.90	0.65	185.79	10.94	8.50
X_7	Melitopol's'ka chorna – control	14.50	17.20	11.20	0.62	227.08	10.11	8.50
X_8	Kordiy	10.70	16.60	13.80	0.74	239.47	10.63	8.40
X_9	Oktaviya	15.90	16.30	13.80	0.63	203.33	9.25	8.70
X_{10}	Orion	13.40	17.60	13.40	0.59	210.54	10.46	8.60
X_{11}	Chervneva rannya	18.20	17.30	11.00	0.66	179.57	5.95	7.70
X_{12}	Dachnytsya	16.70	18.50	15.60	0.63	128.70	6.32	8.80
X_{13}	Prostir	16.90	15.70	12.70	0.70	240.24	7.73	8.60

Table 4

Results of determining the objective functions $\varphi(x_1)...\varphi(x_{13})$ when choosing the optimal variety of sweet cherry of medium ripening period in frozen form

Alternative, X_i	Variety	Criterion, *Aj*							Value of objective function, $\phi(x_i)$	Rank
		Amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (%), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg per 100 g), A_5	Vitamin C, (mg per 100 g), A_6	Sensory evaluation, (score), A_7		
		$\hat{f}_1$	$\hat{f}_2$	$\hat{f}_3$	$\hat{f}_4$	$\hat{f}_5$	$\hat{f}_6$	$\hat{f}_7$		
X_1	Vinca	0.39	0.42	0.33	0.79	0.39	0.43	1.00	2.25	7
X_2	Pervistok	0.21	0.39	0.36	0.50	0.38	0.61	0.61	2.93	11
X_3	Temp	0.44	0.58	0.50	0.58	0.40	0.42	0.67	2.41	9
X_4	Ulyublenytsya Turovtseva	-0.06	0.03	0.09	0.63	0.88	0.60	0.44	3.40	12
X_5	Talisman	0.65	0.87	0.74	1.96	0.79	0.88	0.94	0.82	2
X_6	Dilema	0.47	0.68	0.45	0.50	0.51	0.96	0.72	1.70	4
X_7	Melitopol's'ka chorna – control	0.49	0.53	0.16	0.38	0.88	0.81	0.72	2.04	5
X_8	Kordiy	0.94	0.37	0.60	0.88	0.99	0.91	0.67	0.65	1
X_9	Oktaviya	0.33	0.29	0.60	0.42	0.67	0.65	0.83	2.21	6
X_{10}	Orion	0.62	0.63	0.53	0.25	0.73	0.87	0.78	1.58	3
X_{11}	Chervneva rannya	0.06	0.55	0.12	0.54	0.46	0.02	0.28	3.97	13
X_{12}	Dachnytsya	0.24	0.87	0.91	0.42	0.00	0.09	0.89	2.58	10
X_{13}	Prostir	0.21	0.13	0.41	0.71	1.00	0.36	0.78	2.40	8
f_j^-		10,20	15.20	10.30	0.53	128.20	5.82	7.20	–	–
f_j^+		18,70	19.00	16.10	0.77	240.74	11.13	9.00	–	–
f_j^{opt}		19,2 (max)	19 (max	16.1 (max)	0.77 (max)	240.74 (max)	11.13 (max)	9 (min)	–	–

According to the results of multi-criteria analysis, within the studied group of varieties of medium maturity, the best in terms of balance of indicators were the frozen fruits of the Cordia variety (rank 1) — $\varphi(x8)$=0.65 (Table 4).

The Cordia rank 1 variety with the minimum value of the objective function in terms of quality indicators is better compared to the control variety Melitopol black of medium ripening. Analysis of the data on the basis of which the objective function was formed allowed us to identify a set of commodity, biochemical, and organoleptic indicators for fruits of medium ripening. It was established that the initial concentration of physical-biochemical indicators was at the following level: the amount of juice loss immediately after freezing is up to 10.7%; the initial concentration of dry soluble substances is 16.60%; sugars – 13.80%; titrated acids – 0.74%; vitamin C – 10.63 mg/100 g; the amount of phenolic substances is 239.47 mg/100 g; sensory assessment is 8.4 points.

5. 4. Results of objective functions for the ranked series of late-ripening sweet cherry varieties in frozen form

As a result of our analysis of values for the objective functions, the priority of fresh-frozen fruit raw materials of late-ripening sweet cherry varieties was established by the level of compliance with the specified criteria. The analysis of values for the objective functions made it possible to form a ranked series of semi-finished products from the fruits of late-ripening sweet cherry varieties with a balanced set of quality indicators (Tables 5, 6).

Table 5

Functional and technological indicators of late-ripening sweet cherry fruits for calculating objective functions $\varphi(x_1)...\varphi(x_{13})$ when choosing the optimal variety of frozen raw materials

Alternative, X_i	Variety	Criterion, *Aj*						
		Amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (%), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg per 100 g), A_5	Vitamin C, (mg per 100 g), A_6	Sensory evaluation, (score), A_7
		f_1	f_2	f_3	f_4	f_5	f_6	f_7
1	2	3	4	5	6	7	8	9
X_1	Krupnoplidna– control	11.60	18.50	14.40	0.67	245.79	7.74	9.00

Continuation of Table 1

1	2	3	4	5	6	7	8	9
X_2	Karina	12.20	18.20	12.50	0.64	252.17	8.33	8.40
X_3	Rehina	13.90	17.10	11.90	0.57	273.11	7.29	8.10
X_4	Mirazh	11.50	18.20	13.90	0.70	209.73	10.67	8.40
X_5	Udivityel'na	11.60	18.60	13.00	0.70	288.55	7.58	8.90
X_6	Zodiak	13.20	17.00	13.10	0.72	272.95	9.60	8.70
X_7	Syurpryz	14.70	17.90	13.40	0.63	238.34	8.10	8.70
X_8	Kolkhoznytsya	13.50	17.80	12.60	0.63	238.84	7.85	8.00
X_9	Kosmichna	15.10	17.70	13.60	0.66	246.87	8.95	8.80
X_{10}	Prazdnichna	12.40	16.80	12.70	0.61	225.34	10.25	8.40
X_{11}	Anons	13.90	17.60	12.40	0.71	195.04	8.20	8.50
X_{12}	Temporion	11.40	18.30	12.80	0.69	202.06	7.72	8.50
X_{13}	Meotida	11.00	18.40	14.10	0.66	256.49	8.03	8.80

Table 6

Results of determining the objective functions $\varphi(x1)...\varphi(x13)$ when choosing the optimal variety of sweet cherry of late ripening period in frozen form

Alternative, X_i	Variety	Criterion, Aj							Value of objective function, $\phi(x_i)$	Rank
		Amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (%), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg per 100 g), A_5	Vitamin C, (mg per 100 g), A_6	Sensory evaluation, (score), A_7		
		$\widehat{f}_1$	$\widehat{f}_2$	$\widehat{f}_3$	$\widehat{f}_4$	$\widehat{f}_5$	$\widehat{f}_6$	$\widehat{f}_7$		
X_1	Krupnoplidna–control	0.78	0.79	0.86	0.60	0.54	0.26	1.00	1.17	2
X_2	Karina	0.67	0.68	0.31	0.48	0.61	0.40	0.57	2.28	7
X_3	Rehina	0.33	0.29	0.14	0.20	0.83	0.15	0.36	3.70	13
X_4	Mirazh	0.80	0.68	0.71	0.72	0.16	0.98	0.57	1.37	4
X_5	Udivityel'na	0.78	0.82	0.46	0.72	0.99	0.22	0.93	1.07	1
X_6	Zodiak	0.47	0.25	0.49	0.80	0.83	0.72	0.79	1.66	5
X_7	Syurpryz	0.18	0.57	0.57	0.44	0.46	0.35	0.79	2.64	9
X_8	Kolkhoznytsya	0.41	0.54	0.34	0.44	0.47	0.29	0.29	3.23	12
X_9	Kosmichna	0.10	0.50	0.63	0.56	0.55	0.56	0.86	2.25	6
X_{10}	Prazdnichna	0.63	0.18	0.37	0.36	0.33	0.88	0.57	2.69	10
X_{11}	Anons	0.33	0.46	0.29	0.76	0.01	0.37	0.64	3.14	11
X_{12}	Temporion	0.82	0.71	0.40	0.68	0.08	0.25	0.64	2.41	8
X_{13}	Meotida	0.90	0.75	0.77	0.56	0.66	0.33	0.86	1.17	3
f_j^-		10,50	16.30	11.40	0.52	194.54	6.69	7.60	–	–
f_j^+		15,60	19.10	14.90	0.77	289.05	10.75	9.00	–	–
f_j^{opt}		14,7 (max)	19.1 (max	14.9 (max)	0.77 (max)	289.05 (max)	10.75 (max)	9.0 (min)	–	–

The Udivitelna 1 rank variety with the minimum value of the objective function in terms of quality parameters is the best compared to the control variety Krupnoplodna of late ripening. Among the samples of fresh-frozen late-ripening sweet cherry fruits, the best variety according to the set of optimal criteria was determined to be the Udivitelna variety (rank 1) – $\varphi(x_5)$=1.07. Our analysis of the data that formed the basis for the formation of the objective function allowed us to determine the set of physical-biochemical and organoleptic criteria for fruits of late-ripening varieties immediately after freezing. In fresh-frozen sweet cherry fruits, the amount of juice loss immediately after freezing is 11.6%, the initial concentration of dry soluble substances is 18.60%; sugars – 13.00%; titrated acids – 0.70%; vitamin C – 7.58 mg/100 g; the amount of phenolic substances was 288.55 mg/100 g, the sensory assessment was at the level of 8.9 points.

6. Discussion of results based on determining the criteria for assessing the quality of frozen sweet cherry fruits

National characteristics of the population shape the need of society for a certain set of fruit crops in the consumer basket [23]. Sweet cherry (*Prunus avium L.*) is a real fruit brand of the southern region of Ukraine. It opens the fruit season and is distinguished by a balanced biochemical composition [24]. This nutritious fruit is a source of polyphenols and has a high antioxidant potential [25, 26]. At the same time, sweet cherry fruits are perishable products, have a short harvesting period and a limited period of fresh consumption [27]. In view of this, to ensure a prolonged period of consumption of sweet cherries in processed form with optimal quality characteristics, a methodology for selecting sweet cherry varieties for the production of candied fruits with the best quality parameters has been proposed. Candied fruits with useful ingredients can be used as an energy delicacy and a healthy product. It has been established that saccharification of fruit causes a decrease in water activity as a result of osmotic dehydration and contributes to the extension of fruit storage periods [28].

A comprehensive assessment of the quality of fruit raw materials makes it possible not only to improve the quality of the end product but also optimize production processes and reduce losses at the processing stage. Taking into account the trends towards healthy eating and the use of natural ingredients, it also remains relevant to study the influence of variety on the preservation of biologically active substances in frozen raw materials.

The use of a modified algorithm for evaluating fresh-frozen fruits using the multi-criteria optimization method makes it possible to identify the best early, medium, and late ripening sweet cherry varieties that are most suitable for use in frozen form and further processing. Similar studies have been conducted to assess the quality of frozen cherry fruits, in particular, the influence of quality indicators and the limits of the intervals of permissible values for determining the most suitable cherry fruits for freezing were established [20]. The multi-criteria optimization mechanism made it possible to select evaluation criteria for fruits taking into account the species and varietal characteristics of crops and their further use.

As part of the research on the quality of frozen early ripening sweet cherry fruits, the fruits of the Valery Chkalov variety were identified according to biochemical, sensory, and statistical characteristics (Table 1). This variety demonstrated the best results according to the objective functions, receiving the maximum values, $\varphi(x_2)$=1.22.

Of particular value are studies that analyze the influence of technological parameters on the quality of finished products – for example, candied fruits from frozen sweet cherries, where the important criteria are the preservation of shape, color, taste, and bioactive substances. This allowed us to form the basis for determining a set of commodity, biochemical, and organoleptic criteria for the quality of early-ripening fruits suitable for the production of candied fruits. As a result of our analysis of the quality of fresh semi-finished products from medium-ripening sweet cherries according to a set of quality characteristics, it was found that the Cordia variety (rank 1) has the maximum value of the objective function $\varphi(x_8)$=0.65 (Table 4). This makes it the basis for forming quality criteria for medium-ripening fruits suitable for the production of candied fruits.

The fruits of late-ripening sweet cherries of the Udivitelna variety demonstrate the minimum value of the objective function, $\varphi(x_5)$=1.07 (Table 6). The qualitative characteristics of this variety serve as the basis for the formation of quality criteria for late-ripening fruit raw materials used for freezing and further production of candied fruits.

The applied statistical approaches are fully consistent with the calculations by other researchers who also determine the minimum values when selecting fruit crops for similar purposes [29]. Our research results show that the quality of sweet cherry fruit raw materials depends on the characteristics of the variety. This conclusion is confirmed by the data reported by other scientists [30]. It was found that the sensory and chemical properties of dried fruits differed significantly depending on the cherry variety. Optimization of the selection of quality fruits is a key problem for producers and scientists who are looking for universal methodologies and approaches to the selection of raw materials, taking into account improved quality criteria for further processing. The efforts of the world community are aimed at assessing the effectiveness of various methods of raw material analysis and determining the criteria for its quality. Therefore, it is important to expand the criteria for assessing the quality of cherries that affect the end product indicators. In addition, it is advisable to establish the limits of permissible parameters for fruit raw materials to be processed in order to integrate these products into a waste-free production chain.

The use of a multi-criteria approach makes it possible to integrate quantitative and qualitative data, optimize the process of selecting raw materials, and ensure stable quality of finished products. This is especially relevant in the production of semi-finished products from frozen sweet cherries, where it is important to achieve a balance between preserving organoleptic properties, nutritional value, and technological efficiency of processing. Thus, the combination of classical analytical methods of quality control with multi-criteria approaches forms a modern scientific basis for the rational use of fruit raw materials in the food industry.

Among the limitations of this study, it is worth noting that for frozen semi-finished sweet cherry products there are no clear regulatory indicators for the quality of raw materials for the production of candied fruits. This complicates the selection of reference criteria for a comprehensive assessment of fruit raw materials. In addition, organoleptic properties, such as taste, aroma, and attractiveness of appearance after freezing, are difficult to quantitatively formalize. This complicates the integration of such data into formal multi-criteria models.

The main disadvantages also include the limited sample size, which limits the statistical significance of the results. In addition, the varietal characteristics of sweet cherries were not taken into account, as well as the ripening periods of fruits of varieties of foreign origin that were introduced in different regions. The practical significance of the results relates to optimizing fruit selection methods taking into account a more detailed criterion gradation that can be adapted to different regions. In addition, an important direction is to expand the range of sweet cherry varieties, which will allow for a deeper study on the set of quality criteria for raw materials for further processing into candied fruits. This, in turn, will ensure a more accurate interpretation of the results.

The future development of our research is aimed at improving the methods for selecting fruit raw materials, in particular by expanding the assessment criteria and taking into account various factors that can affect the quality of sweet cherry fruits for the production of candied fruits. In particular, further research may focus on optimizing the parameters of raw material selection for different climatic and soil conditions, which will make it possible to more accurately adapt recommendations for different regions. It is expected that the standardization of parameters for assessing the quality of fruit raw materials will contribute to preserving the quality of the end product, as well as valorization of the entire supply chain.

Further research should be directed at expanding the varietal range of sweet cherries, which will make it possible to improve the system of multi-criteria quality assessment, including biochemical, sensory, and technological indicators. It is promising to study the influence of various processing and storage techniques on the stability of fruit properties, which will contribute to the optimization of technological regimes. Integration of multi-criteria optimization into other stages of production will ensure effective quality management and will become the basis for devising waste-free, economically and environmentally effective technologies.

7. Conclusions

1. Using a modified multi-criteria optimization method, an algorithm for evaluating fresh-frozen fruits of sweet cherry varieties of three ripening periods has been constructed. Evaluation criteria for fresh-frozen fruit raw materials have been proposed. It was shown that the smaller the value of the objective function of the variety in the range of values of the criteria of the studied varieties, the higher its suitability for freezing and further processing of the resulting semi-finished products.

2. Among the early-ripening sweet cherry varieties, the most suitable for freezing was the variety Valeriy Chkalov, which ranked 1st with the minimum value of the objective function, $\varphi(x_2)$=1.22. Optimal criteria have been established for varieties of this group: juice loss after freezing is no more than 16%, content of dry soluble substances – 16.50%, sugars – 12.60%, titrated acids – 0.53%, vitamin C – 7.13 mg/100 g, phenolic substances – 194.07 mg/100 g, sensory assessment – 8.9 points.

3. Among the varieties of sweet cherry of medium maturity, the best in terms of quality set was determined to be the variety Kordiya with rank 1 and the minimum value of the objective function, $\varphi(x_8)$=0.65. The optimal indicators of this variety: juice loss after freezing is up to 10.7%, dry soluble substances – 16.60%, sugars – 13.80%, titrated acids – 0.74%, vitamin C – 10.63 mg/100 g, phenolic substances – 239.47 mg/100 g, sensory assessment – 8.4 points.

4. Among the varieties of sweet cherry of late maturity, the best in terms of quality complex was determined to be the variety Udivitelna with rank 1 and the value of the objective function of $\varphi(x_8)$=1.07. Optimal indicators: juice loss – 11.6%, dry soluble substances – 18.60%, sugars – 13.00%, titrated acids – 0.70%, vitamin C – 7.58 mg/100 g, phenolic substances – 288.55 mg/100 g, sensory assessment – 8.9 points. The use of the multi-criteria optimization method for assessing the quality of sweet cherry fruits can be used as a practical tool at processing enterprises for the purpose of informed selection of raw materials, optimization of freezing processes, reduction of technological losses, and improvement of the quality of finished foods.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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