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Factor-area modelling of sweet cherry and sour cherry quality after hydrocooling treatment

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ABSTRACT

Preserving the quality of fresh fruit during postharvest handling and cooling remains an important challenge for the food industry. This study aimed to evaluate changes in the quality of selected sweet cherry cultivars after hydrocooling, using a mathematical modeling approach to represent quality characteristics digitally and visually. The investigated samples included the sweet cherry cultivars *Valeriy Chkalov*, *Krupnoplidna*, and *Melitopolska Chorna*, as well as the sour cherry cultivar *Vstrecha*, which were subjected to preliminary and slow cooling under convective cooling conditions. Unlike conventional sensory evaluation, which relies primarily on subjective organoleptic assessment, the proposed method integrates multiple quality indicators into a comprehensive quantitative model, providing a more objective and informative evaluation of fruit quality. For all investigated cultivars, only minor changes in the quality growth coefficient and the relative quality decline coefficient were observed after hydrocooling, indicating that the selected quality parameters remained stable following low-temperature treatment. Evaluation based on 10 negative and 5 positive quality characteristics showed that the *Krupnoplidna* cultivar exhibited the most favorable quality profile, with the smallest area of negative factors. In contrast, the *Melitopolska Chorna* cultivar showed the least favorable quality profile, with the highest number of negative parameters and the lowest relative quality growth coefficient. The proposed modeling approach provides an effective tool for the quantitative assessment and comparative analysis of the quality of fruit and berry products after hydrocooling.

Keywords: sweet cherry, sour cherry, hydrocooling, quality parameter, factor area, mathematical modelling, post-harvest treatment

INTRODUCTION

According to the Ukrainian Agricultural Export Association, our country ranks second in the world in gross sweet cherry harvest, producing about 133,000 tons annually **[1]**, and **[2]**. This creates significant potential for the development of innovative areas of its industrial processing - the production of juices, concentrates, candied fruits, dried and frozen products, which expands the possibilities of Ukraine's integration into world markets. Despite their relatively low energy content, fruits play an exceptionally important role in a healthy diet due to their high concentrations of carbohydrates, vitamins, phenolic compounds, organic acids, minerals, phytonutrients, and other nutraceuticals. The content of biologically active substances in fruits can vary by 10–20%, which determines their antioxidant, anti-inflammatory, and immunomodulatory potential and, accordingly, the feasibility of their year-round consumption by the population **[3]**, and **[4]**. Annual losses of fruits in supply chains, amounting to 40–50% of the total production volume, are due to their biological instability, sensitivity to temperature, microbiological and mechanical influences, and seasonal unevenness of logistics flows **[5]**, and **[6]**.

Cooling, as a physical and technological process, is based on the principle of suspended animation and provides prolonged inhibition of enzymatic activity and microbiological changes, thereby extending the shelf life of raw materials and preserving their morphological structure, biochemical profile, functional properties, and sensory characteristics. Among the available cooling methods for delicate fruit raw materials, hydrocooling, which is based on intensive heat exchange between fruits and cold water, is recognized as the most promising. This process provides a rapid decrease in temperature, reduction of mass losses, and reliable stabilization of the organoleptic properties of raw materials **[7]**, and **[8]**. However, hydrocooling creates a moist microenvironment on the fruit surface, which promotes the development of microflora, accelerates spoilage, and necessitates the use of antiseptic treatments **[9]**, **[10]**. and improvement of cold treatment processes during post-harvest ripening of fruits, in particular, when using dilution in the working area **[11]**, and **[12]**. The implementation of scientifically based hydrocooling technology using organic acid solutions can be an effective means of improving the safety of cherries and sour cherries, reducing post-harvest losses, and increasing the economic feasibility of storing raw fruit materials **[13]**, and **[14]**.

In the conditions of modern food production, not only is the regulation of the temperature regime of particular importance, but also a systematic approach to cooling, which includes physical and mathematical modeling of heat and mass transfer, adaptation of regimes to the anatomical and physiological characteristics of the object exposed to artificial cold, and integration with subsequent stages of production of the finished product **[15]**, and **[16]**. Today, there is a noticeable lack of systematic scientific data on the thermodynamic, thermophysical, and mass-transfer characteristics of fruits during cooling, which complicates mathematical modeling and forecasting of quality changes in the logistics chain "field - food product production - consumer" **[17]**, and **[18]**. Preventive actions should be taken to prevent fruit from fungal spoilage and deterioration **[19]**. This complicates the rational design of cooling regimes, taking into account the type of raw material, intended purpose, and further production of the finished product with specified functional properties.

The presented aspects determine the relevance of improving the methods of mathematical modeling of the qualitative state of fruits, using the obtained experimental base, by expanding the set of qualitative parameters, increasing assessment accuracy, and ensuring the objectivity of the examination results.

Despite significant progress in mathematical modeling of cooling processes and fruit product quality, there are still problems with model accuracy, insufficient objectivity in assessment, and practically no comprehensive approach to address them effectively.

However, previous studies have primarily demonstrated the application of the factor-plane modeling method to assess the quality of relatively homogeneous food systems, particularly honey, sausage products, oilseeds, and glycerin. At the same time, the use of this approach for fresh fruit and berry products is insufficiently studied due to the high biological variability of plant raw materials, the complex interplay among physicochemical, structural-mechanical, and organoleptic indicators, and the changes these indicators undergo during post-harvest cooling. Unlike previous studies, this work proposes a methodical approach to the complex mathematical modeling of the quality of sweet and sour cherries after hydrocooling, integrating heterogeneous quality indicators into a single factor-plane model and providing digital and graphical interpretations of the results. This provides a comprehensive quantitative assessment of the quality state of fruits, an objective comparison of varieties, and expands the scope of application of factor-plane modeling for fresh fruit and berry products.

When using the developed mathematical model for product quality, the following scientific hypotheses were put forward. When graphically representing quality models in polar coordinates, the values of the main quality characteristics of fruits outline a flat figure, the area of which identifies the quality space of a given variety of product. Such factor areas can be quantified using dimensionless ratios of the normative and current evaluation characteristics. This interpretation of the quality of the studied product samples is a sufficiently accurate and objective analysis tool.

Therefore, the purpose of the study is to develop and test a methodological approach to factorial-plane mathematical modeling for a comprehensive quantitative assessment of the quality of sweet cherry fruits after hydrocooling, and to conduct a comparative analysis of varieties based on an integrated set of quality indicators.

Scientific Hypothesis

It is hypothesized that the cultivar characteristics of sweet cherry and sour cherry fruits, as well as hydrocooling conditions, have a statistically significant effect on their physicochemical, microbiological, and sensory quality attributes. The integration of these attributes into a factor-area-based mathematical model enables quantitative assessment of fruit quality. It reveals patterns of quality change under varying cooling conditions and subsequent storage.

Objectives

To achieve the research goal, it is necessary to solve the following main tasks:

• to determine the physicochemical, biochemical, microbiological, and mechanical quality characteristics of the sweet cherry cultivars *Valeriy Chkalov*, *Krupnoplidna*, *Melitopolska Chorna*, and the sour cherry cultivar *Vstrecha* after hydrocooling;
• to convert the measured quality characteristics into dimensionless quality indicators based on their reference values;
• to construct and compare factor-area models for each cultivar using the normalized quality indicators;
• to identify the cultivar exhibiting the most favorable integrated quality profile after hydrocooling;
• to evaluate the applicability and limitations of the proposed factor-area modeling approach for the comprehensive quantitative assessment and comparative analysis of fruit quality after hydrocooling.

MATERIAL AND METHODS

Samples

Samples description: The experimental study was conducted using fruits of four commercially cultivated stone fruit cultivars belonging to two species of the genus *Prunus*. The investigated material included three sweet cherry (*Prunus avium* L.) cultivars, *Valeriy Chkalov*, *Krupnoplidna*, and *Melitopolska Chorna*, and one sour cherry (*Prunus cerasus* L.) cultivar, *Vstrecha* (Figure 1).

a) *b)* *c)* *d)*

Figure 1 Samples for testing sweet cherry fruits: a – variety "*Valeriy Chkalov*", b – "*Krupnoplidna*", c – "*Melitopolska Chorna*", d – variety "*Vstrecha*".

The selected cultivars differ in their pomological and quality characteristics and are widely cultivated in Ukraine, making them representative materials for evaluating the influence of postharvest hydrocooling on fruit quality. The fruits of all four cultivars were investigated under identical experimental conditions to enable an objective comparative assessment using the proposed factor-area mathematical modeling approach.

Samples collection: Fruit samples were collected during the 2023 harvesting season from the Research Orchard of Dmytro Motornyi Tavria State Agrotechnological University (Zaporizhzhia region, Ukraine). The experimental material included fruits of three sweet cherry (*Prunus avium* L.) cultivars, *Valeriy Chkalov*, *Krupnoplidna*, and *Melitopolska Chorna*, and one sour cherry (*Prunus cerasus* L.) cultivar, *Vstrecha*. Fruits were harvested at commercial maturity according to the standard harvesting criteria established for each cultivar. Sampling was performed randomly from different trees throughout the orchard to ensure representative fruit samples. Only healthy fruits free from visible mechanical damage, physiological disorders, and symptoms of disease were selected for further investigation. Immediately after harvesting, the samples were transported to the laboratory for subsequent preparation and hydrocooling treatment.

Sample preparation: After transportation to the laboratory, the fruit samples were sorted, and fruits with visible mechanical damage, physiological defects, or symptoms of disease were excluded. The selected fruits were packed into perforated plastic boxes (10 kg each) and prepared for the cooling treatment. The hydrocooling procedure was carried out as described in the section *Description of the Experiment*. The prepared samples were subsequently used for laboratory analyses.

Number of samples analysed: Each variant of the experiment was performed in 5 replicates, with one replicate corresponding to one box of fruit. The study objects were the fruits of the sweet cherry varieties *"Valeriy Chkalov"*, *"Krupnoplidna"*, and *"Melitopolska Chorna"*, and the sour cherry variety *"Vstrecha"*, which were used as model varieties to evaluate cooling efficiency.

Chemicals

All chemicals used in this study were of analytical grade (grade A, p.d.a.) and supplied by Khimlaborreakt (Ukraine), unless otherwise specified. The following reagents were used: lactic acid (CH_3–CH(OH)–COOH); acetic acid (CH_3COOH); potassium ferric chloride ($K_3[Fe(CN)_6]$); sodium hydroxide (NaOH); hydrochloric acid (HCl); zinc sulfate solution ($ZnSO_4$); sodium tungstate mixture (Na_2WO_4); sulfuric acid (H_2SO_4); sodium carbonate (Na_2CO_3); oxalic acid H_2C2O_4; metaphosphoric acid HPO_3; potassium iodide (KI); hydrogen peroxide H_2O_2; sodium thiosulfate ($Na_2S_2O_3$); phenolphthalein ($C_{20}H_{14}O_4$); distilled water; ethyl alcohol (96%) (C_2H_5OH).

Animals, Plants and Biological Materials

For experimental investigations, the following varieties were used:

Valeriy Chkalov is an early ripening variety. The fruits are large, round-heart-shaped, weighing 7–9 g., with a diameter of 19.3 mm. The average number of fruits in 1 kg of cherries is 125 pieces. The color of the fruit is dark red, almost black. The skin is dense and shiny. The flesh is dark red, with white veins, semi-cartilaginous, and juicy. The taste is wine-sweet. Tasting score – 4.5 points. The fruit's transportability is good.

Melitopolska Chorna is a mid-ripening variety. The fruits ripen in the second decade of June. They have a large, round-oval shape and a dark red, almost black, color. The average weight is 6–8 g., and the diameter is 20.0 mm. The average number of fruits in 1 kg of cherries is 143 pieces. The flesh is dark red, dense, cartilaginous, and juicy. The taste is sweet with a pleasant sourness. Tasting score – 4.8 points. They are noted for their good transportability and universal use.

Krupnoplidna – a late-ripening variety. The fruits ripen in the third decade of June. They are very large, broadly rounded, and dark red. The average weight is 10–12 g. (maximum – 18.2 g). They have a diameter of up to 35 mm. The average number of fruits in 1 kg of cherries is 90 pieces. The skin is thin, dense, and dark red. The flesh is dark red, cartilaginous, and juicy. The taste is sweet and sour. Tasting score – 4.8 points. The fruits of the variety are recommended for universal use, which are noted for their good transportability and suitability for machine harvesting. A variety for both dessert and technological purposes.

Vstrecha is a variety of medium ripening. The fruits ripen in the third decade of June. The fruits are large, one-dimensional, flat-rounded, dark red; average weight – 8.6 g, maximum – 15 g, diameter 17.5 mm. The average number of fruits in 1 kg of cherries is 116 pieces. The flesh is red, tender, juicy, and melting. The taste is sweet and sour. Tasting score – 5.0 points. The fruits have a universal purpose.

Supplier: Scientific Research Garden of TSATU, Zaporizhzhia region, Ukraine.

Instruments

The following laboratory equipment was used in this study: stationary pallet hydrocooler MAS-HC-2000-PAL-ST (manufacturer: Ukrainian engineering company MAS Systems; supplier: LLC "Khimlaborreakt", Ukraine); drying oven (SNOL), muffle furnace (SNOL), mineralizer (Velp Scientifica), steam distillation distiller (Velp Scientifica UDK 129), automatic penetrometer (K95500), pH meter (HI8314 HANNA), thermometer (digital laboratory thermometer TH310 Milwaukee, laboratory scales (AXIS BDM 3), filter paper (SNOL), magnetic stirrer with heating (LMM), burettes (SNOL), flasks with stoppers (SNOL), dispensers and pipettes (SNOL), conical or volumetric flasks (SNOL), centrifuge (SNOL) supplier is LLC "Khimlaborreakt", Ukraine.

Laboratory Methods

The assessment of the functional, technological, and microbiological properties of the cherry samples was conducted in accordance with standard protocols. The selection of sour cherries and sour cherry varieties for research was carried out in accordance with the requirements of ISO 874:1980 **[20]**. The commercial quality of sour cherries was assessed in accordance with the requirements of international standards UNECE FFV-13 “Cherries” **[21]** and UNECE FFV-21 “Sour Cherries” **[22]** in terms of appearance, uniformity, presence of mechanical damage, cracking, disease damage, and compliance with commodity categories. The content of dry soluble substances was determined by the refractometric method in accordance with ISO 2173:2003 **[23]**, the mass concentration of sugars by the ferricyanide method **[24]**, and the titrated acidity by the titrimetric method in accordance with ISO 750:1998 **[25]**. The Folin method was used to determine the total phenolic content (Ciocalteau method **[26]**), and the ascorbic acid content was determined by the 2,6-dichlorophenolindophenol reduction method **[27]**. The average weight of the fruits was determined using electronic laboratory scales. The quantitative composition of epiphytic microflora on the surface of fruits was estimated using serial tenfold dilutions, followed by seeding onto nutrient media and counting colony-forming units in accordance with ISO 4833-1:2013 **[28]**. The respiratory rate was determined by measuring the amount of carbon dioxide released by fruits under hermetic conditions **[29]**, and the heat release rate was calculated using respiratory activity indicators **[29]**. The activities of polyphenol oxidase and peroxidase were determined spectrophotometrically by measuring the rate of oxidation of their respective substrates **[29]**.

Description of the Experiment

Study flow: Cherries and sour cherries were selected for the study based on consumer ripeness, in accordance with ISO 874-1980. The quality of the fruits met the standard requirements set out in UNECE FFV-13 "Cherries". The date of fruit picking was determined by the following indicators: appearance (shape and color, typical for this pomological variety), presence or absence of a stalk, mechanical damage to the skin, damage by pests and fungal diseases, and fruit diameter. Immediately after harvesting, the fruits were packed in bulk in plastic boxes (container size 600×400×116 mm) of 10 kg each. Research on quality indicators was conducted in the laboratories of the Research Institute of Agrotechnology and Ecology at the Tavria State Agrotechnological University named after Dmitry Motorny.

To extend the shelf life of fruit raw materials and preserve their quality, the effect of hydrocooling sweet and sour cherries, combined with the developed protective compositions, was studied. The active ingredients of the protective compositions were lactic and acetic acid. Hydrocooling was carried out using a stationary pallet hydrocooler (MAS-HC-2000-PAL-ST) with a capacity of 2 t/h. Pre-cooling of the fruits was carried out immediately after their collection.

The fruits were cooled in ice water (1.0 ± 0.5 °C) with the addition of organic acid compositions (lactic and acetic). The cooling period for sweet cherries was 18–25 min; for sour cherries, 16 ± 2 min. Until the temperature inside the fruit was 2 ± 0.5 °C (near the stone). According to the research results, 10 complex protective compositions were formed. To study the effectiveness of protective compositions, the following concentrations of lactic and acetic acids were used: 0.01%, 0.25%, 0.50%, 0.75%, 1.00%, 1.25%, 1.50%, 1.75%, and 2.00%. In complex protective compositions, the lactic-to-acetic acid ratio was 1:1.

In the control variant, fruits were hydrocooled without adding organic acids. After cooling, the cherries and sour cherries were stored at 1.5 ± 0.5 °C and 93 ± 1% relative humidity. Fruit products were stored in modernized KH-48 refrigeration chambers equipped with an Eliwell EWDR 902 temperature-control system and Eliwell EWHS 31 relative-humidity sensors. The cooling system of the storage chambers was battery-powered.

The physical storage conditions in the chambers were determined and controlled in accordance with ISO 4833-1:2013. Control audits of sweet and sour cherries during storage were conducted every 10 days; the total storage period was 40 days. Changes in quality indicators during inspections were determined after removal from storage and storage at 15–20 °C.

The temperature inside the fruit was measured using a digital thermometer. The number of fruits with signs of physiological disorders and microbiological diseases was determined by visual inspection 40 days after storage. The percentage of fruits affected by diseases and with signs of physiological disorders was determined. Natural weight losses of fruit raw materials during storage were determined by the method of selecting fixed samples weighing 5 kg. Weighed sweet cherries and sour cherries were placed in labeled nets and then tied. The net number, product name, variety, weight, and date were indicated on the label. Determination of the percentage of natural weight loss of sweet cherry fruits was carried out 40 days after storage.

To assess the impact of combined cooling using a liquid coolant on fruit quality, a set of basic physical and mechanical indicators of sweet cherries and cherries was examined. Determination of these characteristics allows us to assess the response of fruits of different varieties to post-harvest processing and to establish the features of their structure, density, and potential suitability for long-term storage. Analysis of physical and mechanical properties also allows us to predict the resistance of fruits to mechanical loads during transportation and post-harvest handling.

The main physical and mechanical characteristics of the studied varieties of sweet cherries and cherries after processing with a liquid coolant, as determined by experimental studies, are presented in Table 1. The data obtained characterize the varietal features of the fruits and can be used to substantiate rational parameters for post-harvest cooling, storage, and logistical support of fruit products.

Table 1 Quality parameters of cherry and cherry fruits after hydrocooling.

Variety	Before storage	After cooling	
Negative parameters			
Mass loss (mass reduction in %)			
Valeriy Chkalov	0.564	0.5567	For the first 3 days - 1%, for each subsequent day - 0.1%, i.e. 3.7%
Melitopolska Chorna	0.5785	0.5718	
Krupnoplidna	0.5658	0.5589	
Vstrecha (cherry)	0.5891	0.5806	
Respiration intensity, mg CO_2/kg·h			
Valeriy Chkalov	88.384	35.148	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	96.697	34.256	
Krupnoplidna	81.665	30.456	
Vstrecha (cherry)	91.214	38.569	
Heat dissipation intensity, kJ/kg·°C			
Valeriy Chkalov	944.825	375.7321	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	1033.691	366.1966	
Krupnoplidna	872.999	325.5746	
Vstrecha (cherry)	975.078	412.3026	
MAFAnM x10^3, colony-forming units per 1 g of product			
Valeriy Chkalov	21.235	48.958	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	22.259	51.025	
Krupnoplidna	20.894	50.358	
Vstrecha (cherry)	18.547	43.587	
Mushrooms · 10^3, colony-forming units per 1 g of product			
Valeriy Chkalov	6.845	20.589	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	6.125	21.354	
Krupnoplidna	6.058	22.547	
Vstrecha (cherry)	5.784	22.587	
Positive parameters			
Dry soluble content			
Valeriy Chkalov	17.117	16.285	Compare with the initial value. The higher the indicator, the better
Melitopolska Chorna	18.355	17.548	
Krupnoplidna	18.712	17.959	
Vstrecha (cherry)	18.412	17.121	
Sugar content			
Valeriy Chkalov	12.375	11.564	Compare with the initial value. The higher the indicator, the better
Melitopolska Chorna	9.242	8.156	
Krupnoplidna	15.029	13.561	
Vstrecha (cherry)	14.864	13.564	
Titrated acid content			
Valeriy Chkalov	0.715	0.604	Compare with the initial value. The higher the indicator, the better
Melitopolska Chorna	0.916	0.745	
Krupnoplidna	0.873	0.713	
Vstrecha (cherry)	1.425	1.151	
Ascorbic acid content			
Valeriy Chkalov	9.111	7.001	Compare with the initial value. The higher the indicator, the better
Melitopolska Chorna	11.025	8.954	
Krupnoplidna	7.482	5,254	
Vstrecha (cherry)	12.032	9.125	
Phenolic content			
Valeriy Chkalov	200.108	156.125	Compare with the initial value. The higher the indicator, the better
Melitopolska Chorna	257.16	208.125	
Krupnoplidna	279.125	234.456	
Vstrecha (cherry)	206.125	165.254	
Ascorbic acid content			

Polyphenol oxidase activity			
Valeriy Chkalov	7.355	8.567	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	10.156	11.758	
Krupnoplidna	6.025	6.654	
Vstrecha (cherry)	8.125	9.865	
Peroxidase activity			
Valeriy Chkalov	30.125	11.125	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	35.654	8.012	
Krupnoplidna	24.256	7.025	
Vstrecha (cherry)	38.452	16.564	
Indicator of FR/PFO (phenol reductases and polyphenol oxidase)			
Valeriy Chkalov	0.03675515	0.054873	Compare with the initial value. The lower the indicator, the better.
Melitopolska Chorna	0.03949292	0.056495	
Krupnoplidna	0.02158531	0.028381	
Vstrecha (cherry)	0.03941783	0.059696	
Sugar-acid index (CCI)			
Valeriy Chkalov	17.3076923	19.1457	15 – 30 c.o.
Melitopolska Chorna	10.0895197	10.9477	
Krupnoplidna	17.2153494	19.0196	
Vstrecha (cherry)	10.4308772	11.7845	
Sugar-acid index (CCI)			
Valeriy Chkalov	0.75	0.59	Compare with the initial value. The higher the indicator, the better
Melitopolska Chorna	0.99	0.78	
Krupnoplidna	1.12	1.0	
Vstrecha (cherry)	0.69	0.55	

The data in Table 1 are the initial experimental basis for further mathematical modeling. To enable mathematical manipulation of the selected parameters used to assess the quality of fruits with different dimensions, their values are converted to dimensionless units.

Thus, in the mathematical interpretation of the quality of fruit products, their morphological structure, physicochemical properties, and mechanical properties are taken into account. Drawing on experience assessing the quality of honey varieties **[30]**, sausage samples **[31]**, oil varieties **[32]**, and glycerin **[33]**, the evaluation criteria for using such dimensionless complexes were selected (Eqution 1).

$$k_{cn} = \frac{S_i}{S_n} \qquad \varphi_{rdq} = \frac{|S_n - S_i|}{S_n} \cdot 100\% \qquad k_{iq} = \frac{S_n}{S_i} \qquad \varphi_{iq} = \frac{|S_i - S_n|}{S_i} \cdot 100\% \tag{1}$$

when, k_{cn} – quality standards compliance factor; k_{iq} – quality growth rate; φ_{rdq} – relative coefficient of quality decline; φ_{iq} – relative coefficient of quality decline; S_i and S_n – factor areas respectively for the quality characteristics of the sample and regulatory parameters.

Thus, the presented methodology, using experimental and regulatory data, enables a comparative assessment of the qualitative state of the studied fruits, their compliance with regulatory requirements, and the prospects for further production.

Quality Assurance

Number of repeated analyses: All physicochemical, microbiological, and biochemical parameters were determined in triplicate. Experimental data were processed using statistical methods, and the results were presented as mean ± standard deviation (SD).

Number of experiment replication: Four stone fruit varieties (*Valeriy Chkalov*, *Melitopolska Chorna*, *Krupnoplidna* and *Vstrecha*) were used in the study. Five independent replicates were conducted for each variety, with each experimental unit consisting of one fruit box. The total number of experimental units was 20 (n = 20). All analytical determinations were performed in triplicate.

Reference materials: Certified reference materials, standard calibration solutions, and reference control materials specified by the relevant analytical standards were used, where applicable, to verify the performance of laboratory equipment and analytical methods. All measuring instruments were calibrated according to the laboratory's calibration schedule, and the analytical procedures were performed in accordance with the quality assurance requirements of the laboratory's ISO/IEC 17025-accredited management system.

Calibration: Each instrument was calibrated before each experiment, and calibration checks were performed regularly to maintain measurement accuracy.

Laboratory accreditation: The research was conducted at the Ukrainian Laboratory of Quality and Safety of Agro-Industrial Complex Products, which operates in accordance with the management system built in accordance with the requirements of DSTU EN ISO/IEC 17025:2019 (EN ISO/IEC 17025:2017, IDT; ISO/IEC 17025:2017, IDT), which is confirmed by the Certificate of Accreditation of the National Accreditation Agency of Ukraine. Physico-chemical, microbiological, and mechanical studies performed within the framework of this work were carried out in accordance with the laboratory's scope of accreditation, using certified (validated) test methods, calibrated equipment, and measuring instruments, thereby ensuring the traceability, reliability, and reproducibility of the results obtained.

Data Access

The data that support the findings of this study are available from the corresponding author upon reasonable request. The dataset includes experimental measurements of physical-mechanical, physiological-biochemical, microbiological, and commercial quality parameters of sweet and sour cherry fruits, as well as calculated parameters from the factor-area mathematical model used for quality assessment.

Statistical Analysis

The experimental unit was one plastic box (10 kg) of fruit subjected to an individual treatment. Each experimental variant consisted of five independent biological replicates ($n = 5$). Laboratory measurements performed on subsamples from the same experimental unit were treated as technical replicates and averaged before statistical analysis; therefore, only biological replicates were included in the inferential analyses.

Descriptive and inferential statistical methods were used to analyze the experimental data. Data normality was assessed using the Shapiro–Wilk test, while homogeneity of variances was verified using the Levene test. The effects of cultivar and cooling treatment (considered fixed effects) and their interaction were evaluated using a two-way analysis of variance (ANOVA). Relationships among the studied quality indicators were assessed using correlation and regression analyses **[34]**.

The results are presented as mean ± standard deviation (M ± SD). When significant effects were detected, pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test. Differences were considered statistically significant at $p < 0.05$, and exact p-values are reported where appropriate. Statistical analyses were performed using Statistica 10.0 (StatSoft Inc., USA) and Microsoft Excel.

Reporting and transparency statement

The study was conducted on the fruits of four stone fruit varieties (*Valeriy Chkalov*, *Melitopolska Chorna*, Krupnoplidna, and *Vstrecha*). The sample size was determined based on previous studies on post-harvest processing and storage of fruit and berry products, while also accounting for the need to ensure the statistical reliability of the results.

Each experimental variant was represented by five independent biological replicates, where one experimental unit was a separate box of fruits ($n = 20$). All physicochemical, microbiological, and biochemical indicators were determined in three technical replicates.

Randomization during the distribution of fruits among experimental variants was implemented by randomly selecting samples from the total batch of fruits for each variety. Blinding was not used during the experiment or in the analysis of the results, since the study did not involve subjective evaluation that could affect the results. All selected samples and obtained experimental data were included in the statistical analysis. No samples or measurement results were excluded from the study.

All methods, experimental conditions, and approaches to statistical data processing are presented with sufficient detail to ensure reproducibility of the results by other researchers.

RESULTS AND DISCUSSION

One of the key stages in assessing the effectiveness of post-harvest fruit processing is a comprehensive analysis of indicators that characterize their quality, nutritional value, and suitability for further storage. Since the studied indicators have different physical natures, units of measurement, and directions of influence on the product's overall condition, to enable their comparison and integral assessment, the experimental data were reduced to a dimensionless form.

Based on the results of experimental studies, all determined quality indicators of sweet cherry fruits were classified into two groups: positive parameters, the increase in the values of which indicates an improvement in product quality (content of dry soluble substances, sugars, phenolic compounds, ascorbic acid, marketable yield, etc.), and negative parameters, the increase in which indicates a deterioration in the consumer properties of the fruits (respiration intensity, heat release, development of epiphytic microflora, loss of marketable quality, etc.).

To ensure correct comparison of heterogeneous indicators, their absolute values were transformed into dimensionless criteria by normalization relative to the normative or reference values of the corresponding indicators. This approach allowed us to exclude the influence of the quantity's dimensionality. It enabled a more comprehensive assessment of the effectiveness of the applied cooling regimes and of post-harvest fruit processing.

In the first stage of the research, the main physical-mechanical, physiological-biochemical, microbiological, and commodity characteristics of the studied varieties of sweet cherries and cherries treated with a liquid coolant were determined. The results obtained served as the basis for calculating dimensionless quality criteria and forming an integral assessment of the fruits' condition.

Calculation of the qualitative characteristics of the studied fruits and their evaluation criteria in dimensionless units

Using the above methods of normalization and calculation of quality criteria, dimensionless parameters for assessing the condition of fruits of the *Valeriy Chkalov* variety of sweet cherry were determined; the results are given in Table 2.

Table 2 Quality parameters of the fruits of cherries of the *Valeriy Chkalov* variety after a slow cooling process.

	Indicator	Regulatory data		Characteristics of a qualitative state	
		R_n	R, con. un	$\overline{R_i}$	R_i, con. un
	Evaluation by negative parameters				
1	Mass loss, %	1.0	1.0	1.0	1.0
2	Breathing intensity, mg CO_2/kg·h	88.384	1.0	30.125	0.341
3	Heat dissipation intensity, kJ/kg·°C	944.825	1.0	322.036	0.341
4	MAFAnM x10^3, CUO/g	21.235	1.0	10.254	0.483
5	Mushrooms x10^3, CUO/g	6.845	1.0	2.224	0.325
6	Polyphenol oxidase activity	7.355	1.0	6.754	0.918
7	Peroxidase activity	30.125	1.0	32.012	1.063
8	Phenolic compounds/polyphenol oxidase	0.0368	1.0	0.03375	0.917
9	Sugar-acid index	17.308	1.0	17.3063	0.999
10	Firmness of fruit pulp	0.75	1.0	0.70	0.933
	Assessment by positive parameters				
1	Dry soluble content, %	17.117	1.0	17.111	0.999
2	Sugar content, %	12.375	1.0	12.374	0.999
3	Titrated acid content, %	0.715	1.0	0.715	1.0
4	Ascorbic acid content, %	9.111	1.0	9.001	0.988
5	Phenolic content, %	200.11	1.0	200.1	0.999

Note:
Rn – the value of the normalized parameter in physical units; R = 1 μm. un. – normalized indicator in conventional units;
$\overline{R_i}$ – average value of the evaluated parameter in physical units; Ri – the current parameters presented in con. un.

Obtaining mathematical algorithms for determining the magnitude of factor areas in dimensionless units

Experimentally determined qualitative characteristics of the studied fruit products were laid out on semi-diagonals using polar coordinate systems (Figure 1). Then, the geometric visualization of the model of the qualitative state of a specific product sample, based on negative parameters, was obtained as an irregular 10-gon with area S_i, highlighted in blue. The factor normative area S_n is presented in the form of a regular 10-gon, since its semi-diagonals are equal to units. The normative factor area for the 10-factor space was determined as for the corresponding area of a regular polygon (Equation 2).

$$S_n = \frac{mR^2 \sin^2\left(\frac{180}{m}\right)}{tg\left(\frac{180}{m}\right)} = mR^2 \sin\left(\frac{180}{m}\right) \cdot \cos\left(\frac{180}{m}\right) = 0{,}5mR^2 \sin\left(\frac{360}{m}\right) = 5 \sin 36° = 2{,}939\ \mathrm{com.un}^2 \quad (2)$$

where *m = 10* – the number of estimated parameters is equal to the number of angles of the polygon.

As a result of algebraic evaluation of the obtained geometric figures (Figure 1), the following mathematical algorithm was derived for the 10 – factor space of negative quality parameters (Equation 3):

$$S_{10}=0,5sin\alpha[R_1 \cdot R_2+R_2 \cdot R_3+R_3 \cdot R_4+R_4 \cdot R_5+R_5 \cdot R_6+R_6 \cdot R_7+R_8 \cdot R_7+R_8 \cdot R_9+R_9 \cdot R_{10}+R_{10}R_1] \quad (3)$$

where R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8, R_9, R_{10} – experimental values of the corresponding qualitative characteristics of fruit products; α – the central angle between the sides of the polygon is: for 10 – square α = 36°

Construction of geometric models of the quality state of the studied varieties of fruit products

Using the aforementioned method for constructing a geometric model, we obtained a geometric interpretation of the quality-state model for the sweet cherry variety "*Valeriy Chkalov*" (Figure 2).

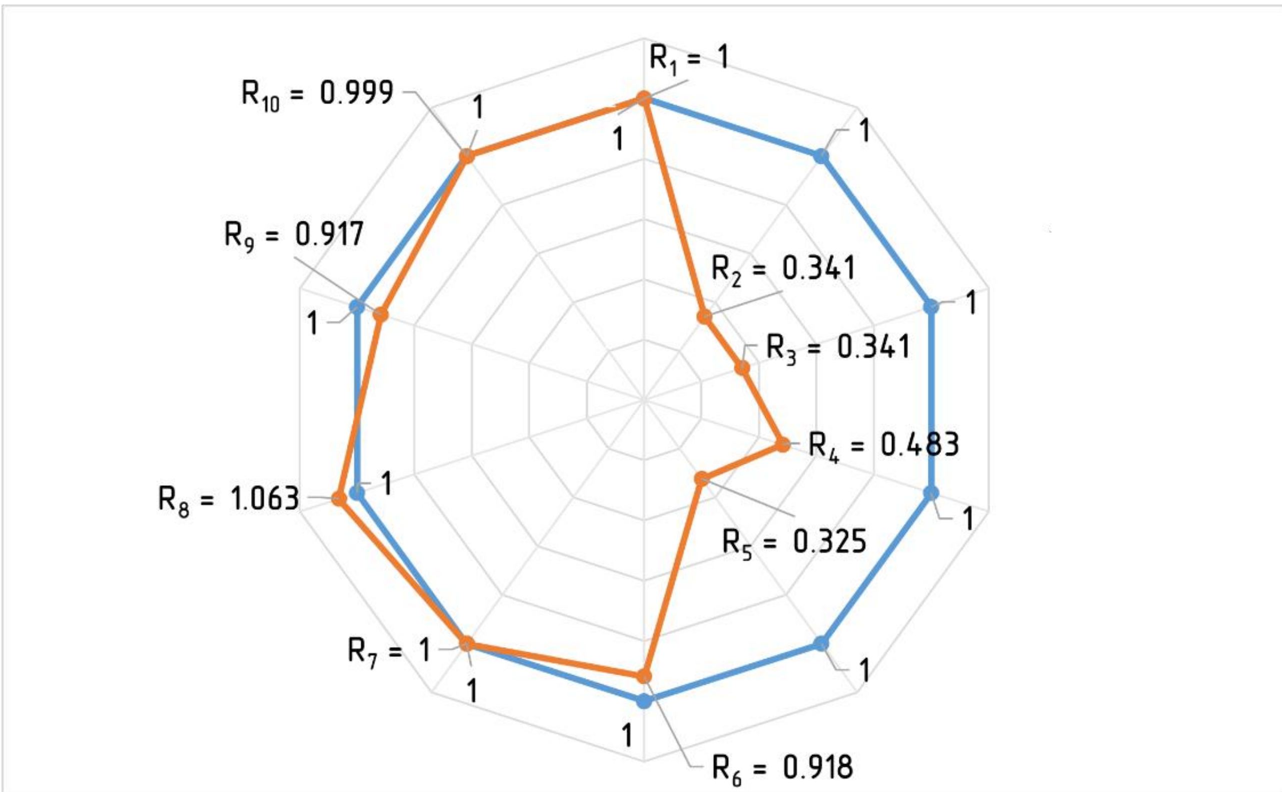

Figure 2 Quality model based on negative parameters of sweet cherry of the *"Valeriy Chkalov"* variety for the hydrocooling process before storage.

The given models of the normative state and the studied sweet cherry variety indicate that in the process of slow cooling for this fruit, the positive is almost 50% lower than the normative state in terms of the intensity of respiration and heat release; the negative can be attributed to the excess of almost 25% of peroxidase activity. The potential for growth in technological parameters in this process, given the characteristics, was 20.08%.

The positive characteristics of the sweet cherry variety "*Valeriy Chkalov*" during hydrocooling did not change significantly after intensive cooling (Figure 3), indicating a satisfactory outcome of this low-temperature treatment. The prospects for growth in technological indicators of this sweet cherry processing process amounted to only 0.62% according to the given characteristics of the fruits (Table 2).

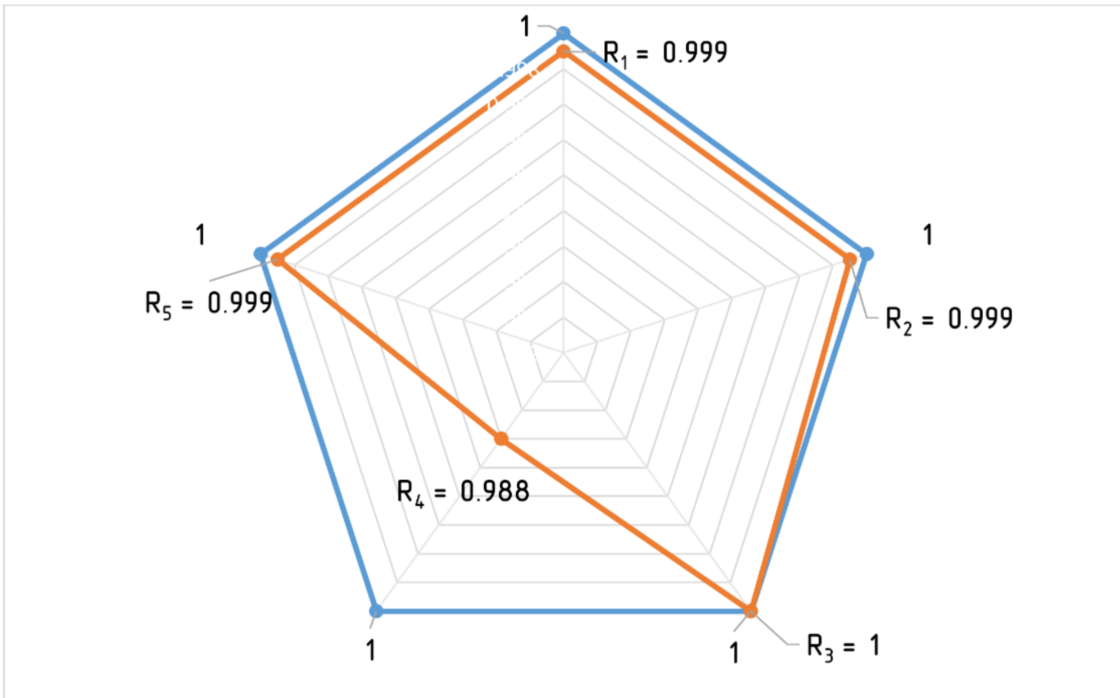

Figure 3 Quality model based on positive parameters of sweet cherry of the *"Valeriy Chkalov"* variety for the hydrocooling process before storage.

As a result of algebraic evaluation of the obtained geometric figures (Figure 2), the following mathematical algorithm was derived for the 5-factor space of positive quality parameters:

$$S_{05}=0,5\sin\alpha\cdot[R_1\cdot R_2+R_2\cdot R_3+R_3\cdot R_4+R_4\cdot R_5+R_5\cdot R_1] \quad (4)$$

where the central angle for the represented pentagon is $\alpha = 72^0$.

Similar results in assessing quality according to positive characteristics were also observed for the studied varieties of sweet cherry, "*Melitopolska Chorna*" and "*Krupnoplidna*", and sour cherry, "*Vstrecha*".

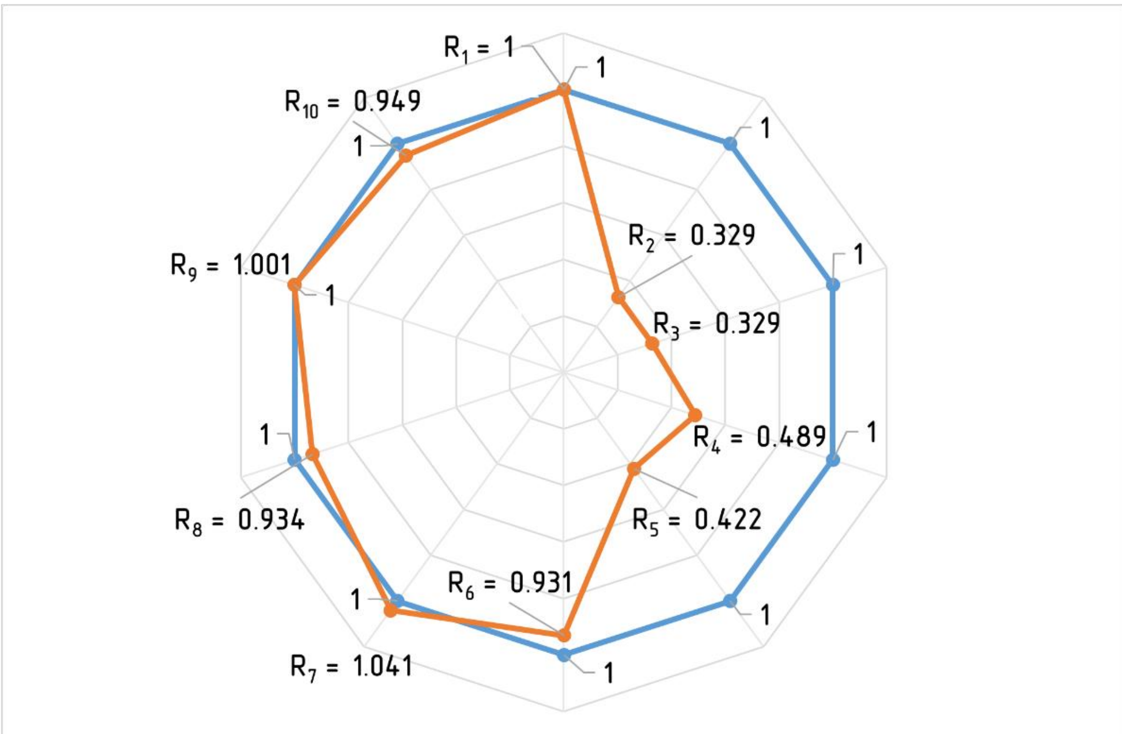

Figure 4 Quality model based on negative parameters of the sweet cherry variety "*Melitopolska Chorna*" for the hydrocooling process before storage.

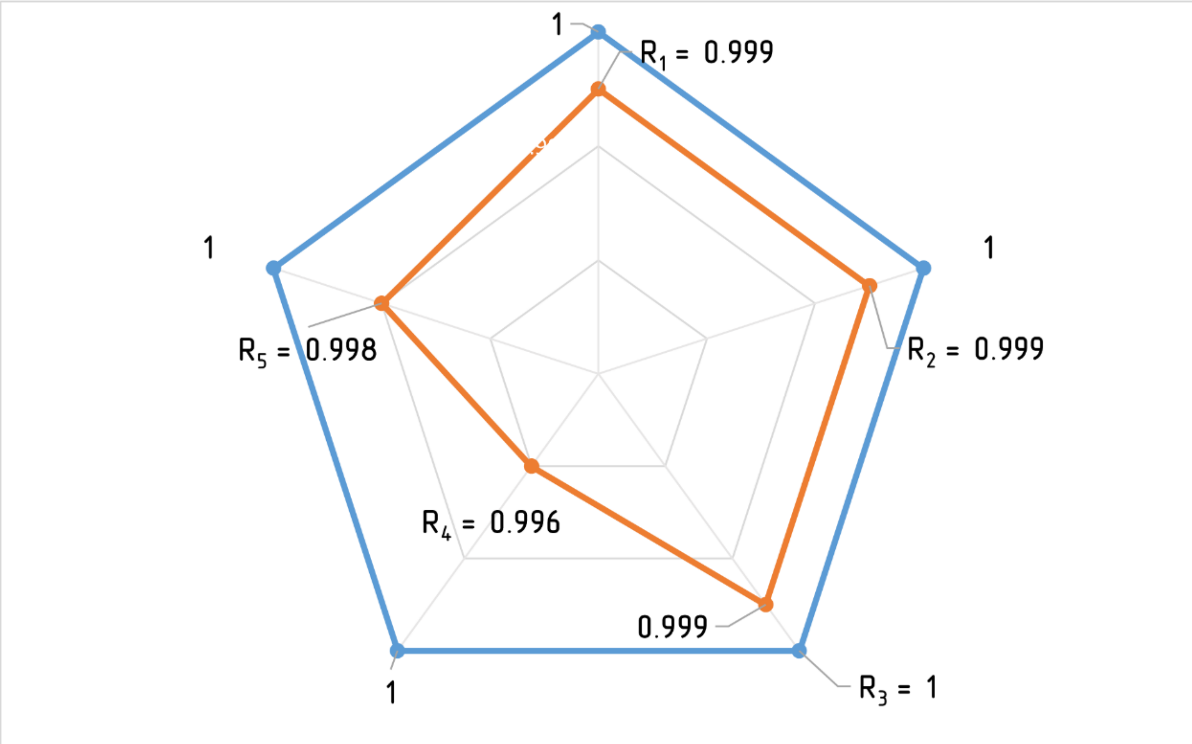

Figure 5 Quality model based on positive parameters of the sweet cherry variety "*Melitopolska Chorna*" for the hydrocooling process before storage.

After hydrocooling of the sweet cherry variety "*Melitopolska Chorna*", only peroxidase activity exceeded the initial value by 1% (Figure 4); the remaining characteristics were lower than the initial values. The intensity of respiration and heat release, the number of fungi, and the number of mesophilic-aerobic and facultative-anaerobic microorganisms were all less than 50% of the initial values (Figure 5), indicating the effectiveness of this low-temperature treatment. The potential for growth in technological parameters in this process, given the characteristics, was 44.02%.

Positive characteristics practically did not change after liquid cooling of the sweet cherry "*Melitopolska Chorna*" (Figure 5). The growth prospects for the technological indicators of this sweet cherry processing process were only 0.38%.

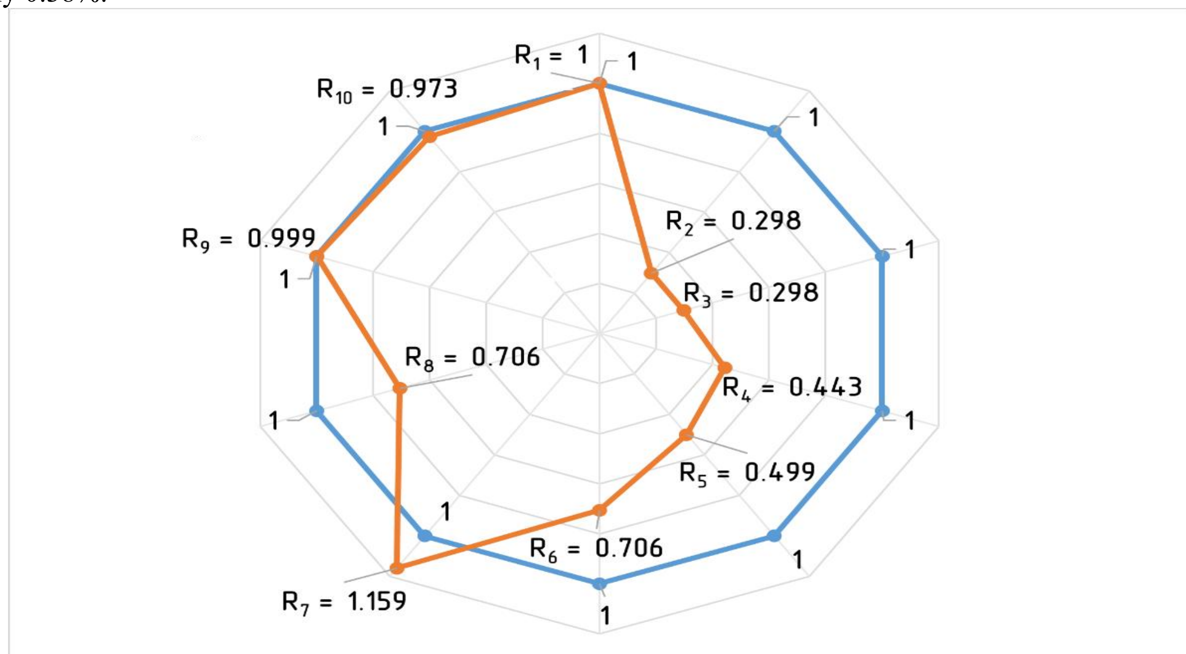

Figure 6 Model of the quality state of the cherry variety "*Krupnoplidna*" for the hydrocooling process before storage.

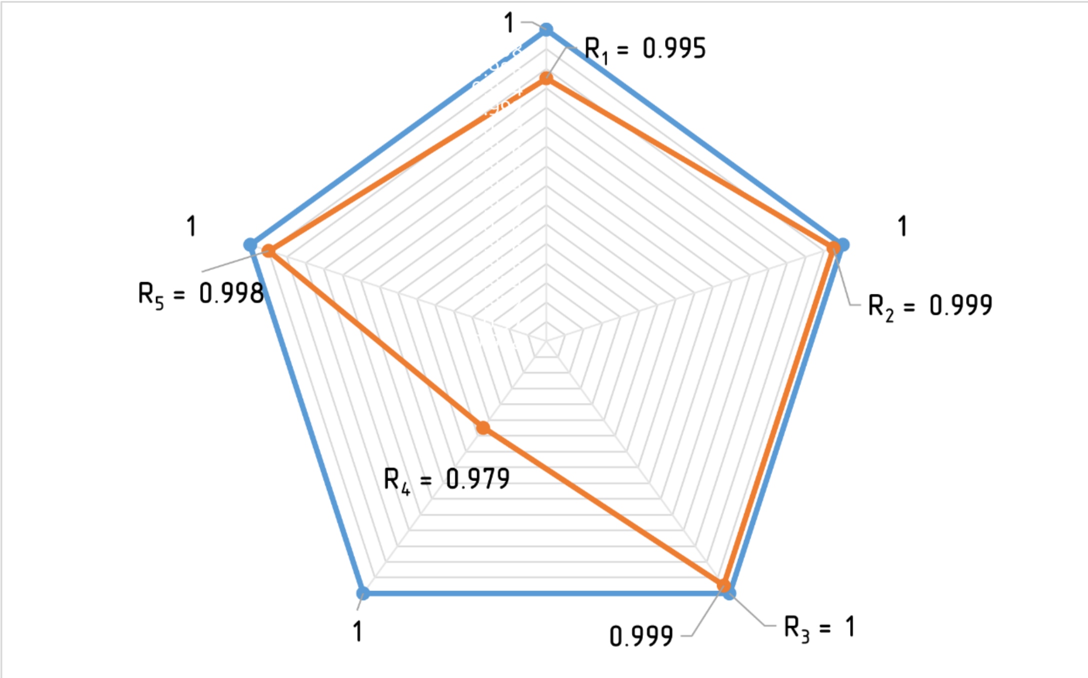

Figure 7 Quality model based on positive parameters of the cherry variety "*Krupnoplidna*" for the hydrocooling process before storage.

The positive characteristics of the "*Krupnoplidna*" variety of cherries practically did not change after the liquid cooling process (Figure 6), which indicates a satisfactory result of this low-temperature effect - 99% of the initial state. The prospects for improving the technological indicators of this cherry-processing process (Figure 7) were only 1.19%, given the fruits' characteristics.

A detailed analysis of the results showed that liquid cooling enables the maximum preservation of not only the organoleptic indicators but also the chemical composition of sweet cherry fruits. In particular, the contents of sugars, titrated acids, and phenolic substances remained stable throughout the storage period, and antioxidant activity decreased by only 0.5–0.8% relative to the initial values. The preservation of the fruits' structural and mechanical properties, particularly the elasticity and density of the pulp, also indicates the effectiveness of this processing method, which ensures high marketable quality of sweet cherries of the "*Krupnoplidna*" variety during subsequent storage.

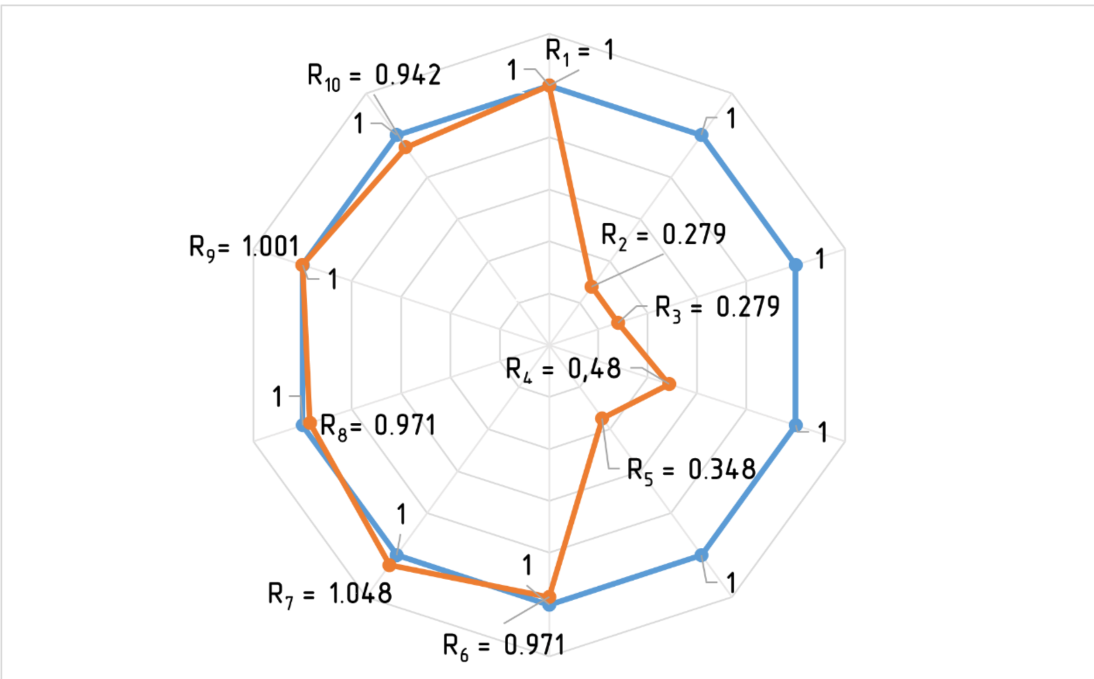

Figure 8 Model of the quality state of cherries of the "*Vstrecha*" variety for the process of hydrocooling by negative parameters before storage.

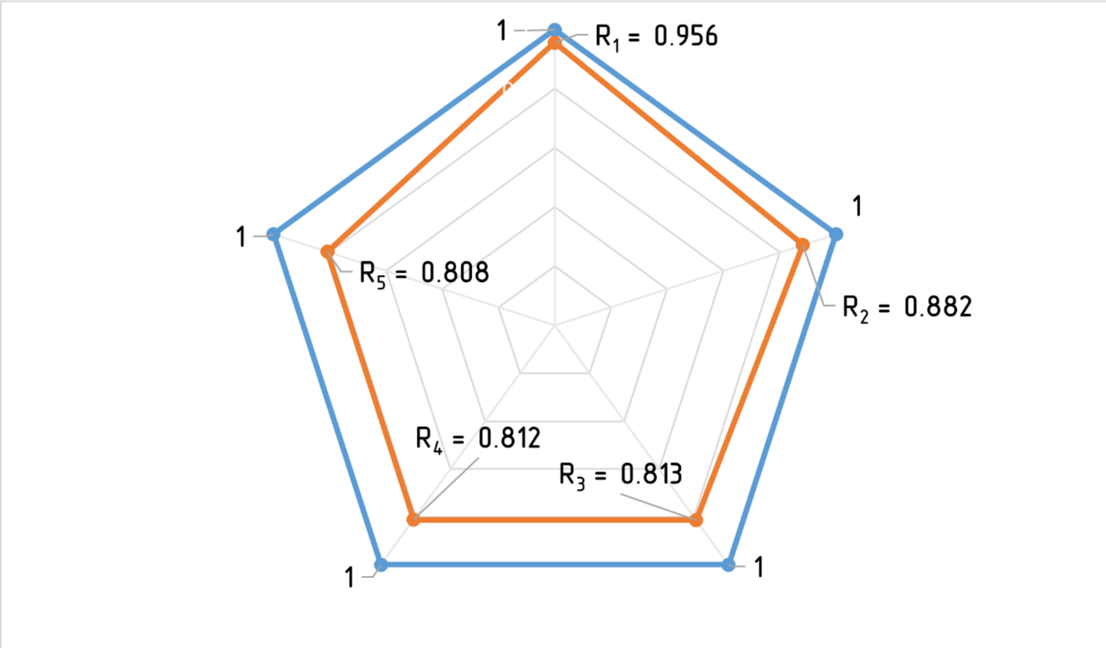

Figure 9 Model of the quality state of cherries of the "*Vstrecha*" variety for the hydrocooling process according to positive parameters before storage.

The model assessment (Figure 8) revealed that only one of the negative characteristics of the cherry variety "*Krupnoplidna*" after the liquid cooling process became less than or equal to its initial value, indicating the effectiveness of the low-temperature effect used. It can also be noted that the intensities of respiration, heat release, mass loss, and peroxidase activity were less than 50% of the initial state. The potential for growth in technological parameters in this process, according to the given characteristics, was 49.73%.

It is also worth noting that the intensity of respiration and heat release, as well as the numbers of fungi and mesophilic-aerobic and facultative-anaerobic microorganisms, were less than 50% of the initial state in the cherry variety "*Vstrecha*" (Figure 9). The potential for growth in technological parameters in this process, given the characteristics, was 44.48%.

Analysis of the results of mathematical modeling

Using the results of mathematical modeling with the factorial area method, the necessary criteria for assessing the quality state were determined and are given in Table 3.

Table 3 Quality parameters of sweet cherry and sour cherry fruits after the hydrocooling process.

Variety of fruit products		Factorial area		Characteristics of the qualitative condition of fruit			
		S_{neg}, con.un^2	S_{pos}, con.un^2	k_{iq}	k_{cn}	φ_{rdq}, %	φ_{iq}, %
Cherry varieties							
1	**Valeriy Chkalov**	1.63	2.36	0.99	0.55	44.89	0.62
2	**Melitopolska Chorna**	1.65	2.37	1.0	0.56	44.2	0.38
3	**Krupnoplidna**	1.48	2.35	0.99	0.5	49.73	1.19
Cherry variety							
4	**Vstrecha**	1.64	2.37	0.99	0.56	44.48	0.5

Note: S_{neg} – factorial area estimated by negative parameters; S_{pos} – factorial area estimated by positive parameters.

Based on the data in Table 3, a comparative graphical analysis of changes in the quality assessment criteria for the studied samples of sweet cherries and sour cherries of the "*Vstrecha*" variety was conducted (Figure 10).

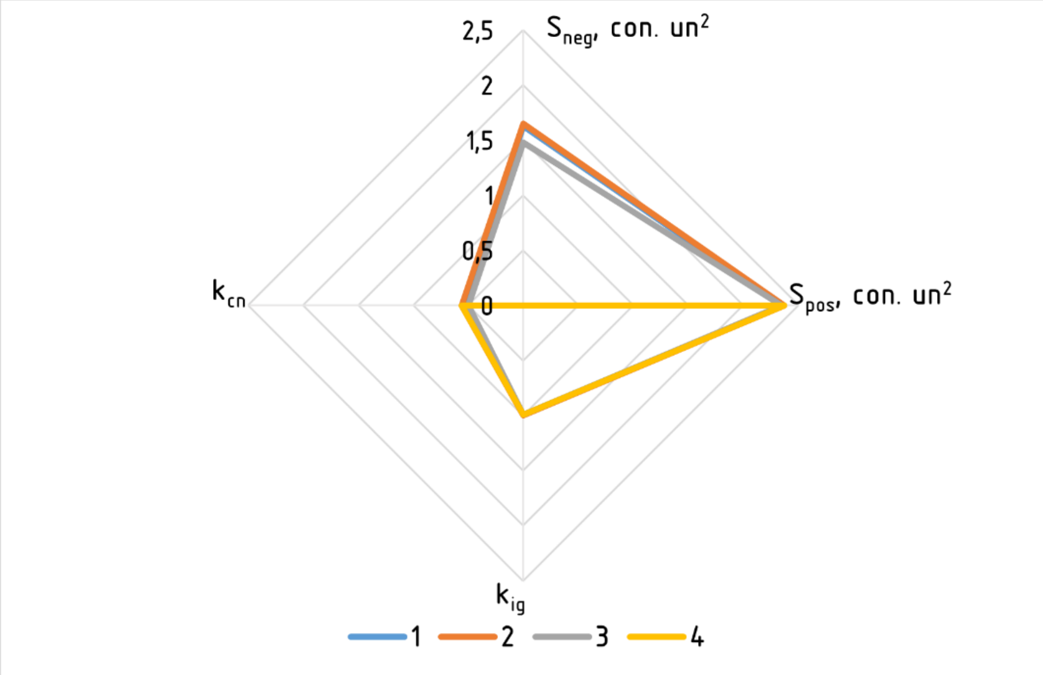

Figure 10 Comparative analysis of changes in the quality assessment criteria of the studied sweet cherry and sour cherry samples.
Note: 1 – *Valeriy Chkalov*, 2 – *Melitopolska Chorna*, 3 – *Krupnoplidna*, 4 – *Vstrecha*.

For all studied varieties of fruit products, after cooling with a liquid coolant, a slight change in the quality growth coefficients k_{iq} and φ_{iq} (Figure 10) was observed, provided that the selected regulatory quality parameters for the coefficient k_{cn} were met. The value of the relative quality decline coefficient φ_{rdq} also varied slightly among the studied varieties, indicating that quality characteristics remained constant after hydrocooling. The minimum negative factor area was observed in the sweet cherry "*Krupnoplidna*", potentially increasing this variety's stability during further storage.

The growth of global consumption of fresh fruits and vegetables is accompanied by increased requirements for their quality, safety, and shelf life **[35]**, and **[36]**. Cherries are a valuable source of phenolic compounds, ascorbic acid, and other bioactive components, but after harvest, they quickly lose their marketable and functional properties due to intensified physiological, biochemical, and microbiological processes **[37]**, and **[38]**. This necessitates the use of methods that enable a comprehensive assessment of changes in fruit quality after harvest.

The results obtained confirmed the feasibility of using the factor-area method for an integrated assessment of fruit quality after hydrocooling. Unlike traditional analyses of individual physicochemical or microbiological indicators, the proposed approach integrates physicochemical, physiological-biochemical, microbiological, and commodity characteristics into a single assessment system, providing a more complete picture of changes in product quality.

The division of indicators into positive and negative is based on their biological significance. Positive indicators include indicators whose preservation indicates high nutritional, biological, and consumer value of the fruit (content of dry soluble substances, sugars, titrated acids, phenolic compounds, ascorbic acid, and sugar-acid index). Negative indicators were defined as those whose increases indicate the intensification of degradation processes or a decrease in product safety, in particular, mass loss, respiration intensity, heat release, the development of mesophilic microflora, fungi, and polyphenol oxidase activity. This approach provides a biologically sound interpretation of integral quality criteria.

After hydrocooling, all studied varieties were characterized by a high level of preservation of positive indicators. The values for the area of positive factors (S_{pos}) were 2.35–2.37 con. un², the quality gain coefficient (k_{iq}) was 0.99–1.00, and the coefficient of prospective quality improvement ($\varphi_{iq)}$ did not exceed 1.19%. This indicates minimal losses of dry soluble substances, sugars, phenolic compounds, and ascorbic acid after hydrocooling.

In modern studies, CFD modeling and other mathematical approaches are widely used to evaluate cooling processes **[39]**, and **[40]**. Such models effectively describe heat and mass transfer processes but do not allow for a comprehensive assessment of changes in the physiological, biochemical, and microbiological characteristics of fruits. In contrast, the factor-area method integrates indicators of different natures, regardless of their dimensionality, and provides not only an overall quality indicator but also a graphical visualization of each indicator's contribution to the overall result. This distinguishes it from traditional multivariate methods, such as principal component analysis (PCA), cluster or discriminant analysis, which allow classification of objects but do not provide a single, integrated criterion **[41]**, and **[42]**. Similarly, the Harrington desirability function provides a generalized indicator, but does not reflect the contribution of individual characteristics to the formation of the final score **[43]**.

Analysis of negative indicators showed that after hydrocooling, the intensity of respiration and heat release significantly decreased in all studied varieties, and for the varieties "*Melitopolska Chorna*", "*Krupnoplidna*" and "*Vstrecha*" these indicators were less than 50% of the initial level. The results obtained are consistent with data from other authors, who associate rapid cooling with a decrease in cellular respiration intensity, inhibition of enzymatic processes, and slowing of the physiological aging of fruits **[44]**, **[45],** and **[46]**. Rapid removal of field heat reduces the duration of fruit exposure to the zone of high metabolic activity, thereby reducing moisture loss and preserving their marketable properties.

After hydrocooling, an improvement in the fruits' microbiological state was also observed. For most of the studied varieties, the numbers of mesophilic aerobic and facultative anaerobic microorganisms, as well as microscopic fungi, were lower than the initial values, consistent with the results of other studies **[47]**, **[48]**, and **[49]**. However, the observed effect cannot be explained solely by low temperature. In the proposed technology, the cooling medium contained lactic and acetic acids, which, in addition to their sanitary and preventive functions, suppressed the development of surface microflora by lowering the medium's pH and inhibiting microbial metabolic activity. Thus, the improvement in microbiological indicators is most likely due to the synergistic effect of rapid cooling and organic acids. Comparative analysis of integral indicators showed that the best results after hydrocooling were demonstrated by the variety "*Krupnoplidna*", which was characterized by the smallest area of negative factors (S_{neg} = 1.48 con. un^2) and the largest coefficient of reduction of negative impact (φ_{rdq} = 49.73%). This is probably due to the biological characteristics of the variety, in particular, higher tissue density, better integrity of integumentary structures, and lower intensity of post-harvest metabolism. For the varieties "*Valeriy Chkalov*", "*Melitopolska Chorna*" and "*Vstrecha*", the integral indicators were close, indicating a similar response of the fruits to hydrocooling conditions.

At the same time, the results obtained do not allow us to quantitatively distinguish the contribution of individual factors to the formation of the final effect. The observed changes are likely the result of a combination of rapid temperature decreases, the use of organic acids, and the fruit's varietal characteristics. To confirm this assumption, it is advisable to conduct a factorial experiment with individual cooling options, without acid treatment, and at varying organic acid concentrations.

The practical value of the proposed method lies in its potential for operational assessment of post-harvest cooling effectiveness, comparison of different technological modes, and selection of varieties most suitable for long-term storage. Since the model is based on an integrated assessment of quality indicators, it can be adapted to both laboratory studies and commercial hydrocooling systems, provided a standardized set of indicators is used.

However, the model requires further validation across a larger number of varieties, under different soil and climatic conditions, and in different production systems. It is also advisable to compare the integral indicators with the actual storage duration, sensory characteristics, and post-harvest losses, which will allow for assessing their prognostic value.

The advantages of the developed approach are the assessment's complexity, the ability to integrate indicators of different natures, the simplicity of the mathematical implementation, and the clarity of the graphical interpretation of the results. At the same time, the model's accuracy depends on the correct choice of indicators and their normative values, and it does not describe the mechanisms underlying the physiological and biochemical processes that underlie fruit degradation. Therefore, it is advisable to consider it as a tool for comprehensive assessment that complements, rather than replaces, physiological and kinetic models of post-harvest changes.

Thus, the results of the study confirm that hydrocooling is an effective means of preserving cherry quality, and the factor-area method provides a comprehensive, integrated assessment of their condition, taking into account physiological, biochemical, microbiological, and commodity indicators. Unlike traditional statistical methods, the proposed approach not only integrates heterogeneous indicators into a single criterion but also provides a visual interpretation of these indicators, making it a promising tool for assessing the effectiveness of post-harvest cooling technologies and optimizing storage conditions for fruit and berry products.

Limitations

The present study has several limitations that should be considered when interpreting the results. First, the proposed factor-area modeling method was validated using only four cultivars of sweet and sour cherries. Although these cultivars differed in their biological and technological characteristics, additional studies involving a wider range of fruit species, cultivars, and growing conditions are required to confirm the broader applicability of the proposed approach.

Second, the experiments were performed under controlled hydrocooling conditions using a liquid coolant supplemented with lactic and acetic acids. Consequently, the observed effects reflect the combined influence of rapid cooling, organic acid treatment, and varietal characteristics. Because the experimental design did not include untreated fruit or a water-only hydrocooling control, the individual contribution of each factor could not be quantified.

Third, the developed mathematical model was based on a predefined set of 10 negative and 5 positive quality indicators. Although these parameters comprehensively describe the quality of the studied fruits, incorporating additional physiological, biochemical, microbiological, or mechanical indicators may further improve the model's robustness and predictive performance.

Another limitation is that fruit quality was evaluated immediately after hydrocooling and during the initial stage of postharvest handling. Therefore, the predictive ability of the proposed model for long-term storage remains unverified and requires validation under extended storage conditions.

Furthermore, the proposed model has not yet been validated using an independent experimental dataset. Validation using data obtained in different production seasons, orchards, laboratories, or commercial storage facilities would increase confidence in the robustness and generalizability of the modeling approach.

Although several physicochemical and biochemical parameters associated with fruit quality were evaluated, a comprehensive sensory assessment, including trained panelists or consumer testing, was not conducted. Therefore, the relationship between the calculated integral quality indices and consumer perception requires further investigation.

Finally, although microbiological indicators were determined, the initial microbiological status of the harvested fruits before treatment was characterized only with respect to the parameters analyzed. Additional information on the natural microbiota composition and field-related microbial variability would improve the interpretation of microbiological changes following hydrocooling.

Future research should include long-term storage experiments, untreated and water-only hydrocooling controls, a broader range of cultivars and fruit species, independent validation datasets, comprehensive sensory evaluation, and industrial-scale verification to assess further the robustness, predictive capability, and practical applicability of the proposed methodology.

CONCLUSION

As a result of the research, a method for mathematical modeling of the qualitative state of sweet and sour cherry fruits, based on factor areas, was developed and tested, providing a comprehensive assessment of products using a set of 10 negative and 5 positive quality indicators. The proposed approach integrates physico-mechanical, physiological-biochemical, microbiological, and commodity characteristics into a single evaluation system, enabling comparison of the qualitative state of fruits after post-harvest processing.

It was experimentally established that hydrocooling of fruits of the sweet cherry varieties "*Valeriy Chkalov*", "*Melitopolska Chorna*", "Krupnoplidna", and the sour cherry variety "*Vstrecha*" helps preserve their main physico-chemical indicators. The area of positive factors (Spos) ranged from 2.35–2.37 com. un2, and the quality gain coefficient (k_{iq}) was 0.99–1.00, indicating a high level of preservation of the nutritional and biological value of fruits after hydrocooling.

The use of a liquid coolant was accompanied by a decrease in negative quality indicators, in particular, the intensity of respiration, heat release, and development of microflora. For most of the varieties studied, these indicators decreased by more than 50% relative to the initial state. The values of the coefficient of compliance with regulatory parameters (k_{cn}) were 0.50–0.56, and the coefficient of reduction of negative impact (φ_{rdq}) was 44.20–49.73%, which confirms the effectiveness of the applied hydrocooling technology under the conditions of the experiment.

According to the results of the integral assessment, the best quality indicators after hydrocooling were established for the cherry variety "Krupnoplodna", which was characterized by the smallest area of negative factors (S_{neg} = 1.48 com. un^2) and the largest value of the coefficient of reduction of negative impact (φ_{rdq} = 49.73%). In contrast, the variety "*Melitopolska Chorna*" had the largest area of negative factors (S_{neg} = 1.65 com. un^2) and the smallest φ_{rdq} value (44.20%), indicating its lower resistance to post-harvest changes among the studied varieties.

The results obtained indicate that the factor-area method is a promising tool for a comprehensive assessment of the effectiveness of post-harvest fruit cooling technologies. However, it should be noted that the proposed approach was tested only on four varieties of sweet cherry and sour cherry under controlled hydrocooling conditions. Therefore, its applicability for predicting quality changes during long-term storage, as well as for other varieties, crops, and industrial conditions, requires further experimental validation.

The practical significance of the study lies in the potential of the proposed approach to comprehensively assess the effectiveness of post-harvest cooling technologies and to select varieties suitable for storage. Further research should validate the model under long-term storage conditions, expand the list of varieties studied, and conduct production testing in industrial hydrocooling systems.

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