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EFFECTIVENESS OF COOLING METHODS IN REDUCING LOSSES DURING CHERRY STORAGE

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ABSTRACT

Efficient use of energy and resources is vital for fostering the sustainable development of our planet and fighting hidden hunger. One way to address this issue is by preserving the quality of raw materials from fruits over a prolonged period. However, fruits have the highest rate of

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ABSTRACT

losses and waste among food products. Incorrect selection of cooling procedures and inappropriate cooling rates can lead to post-harvest quality losses, which in turn will result in loss of product quality and energy. Research into methods capable of minimizing losses and extending the storage life of fruits is essential to determine their effectiveness. The purpose of the research was to evaluate the impact of different cooling methods on the reduction of losses and the extension of the shelf life of cherries. The study involved sweet cherries of different ripening periods (Melitopolska chorna, Krupnoplidna and Valerii Chkalov) and sweet cherries of the Vstriecha variety. The influence of room cooling, forced air cooling, hydrocooling with the addition of lactic and acetic acid, and combined cooling method on cooling rate, weight loss, epiphytic microflora condition, respiratory intensity and heat generation during cherry storage was analyzed. The highest fruit weight losses were observed when using the forced air cooling method, ranging from 1.76 to 1.96%. The combined cooling method for cherries and sour cherries reduced average fruit weight losses by 11.3-22.9 times compared to other methods. When using the combined method, the number of bacteria and fungi on the surface of cherry fruits remained at the same level as before cooling or decreased by 10 to 40% depending on the variety. On the surface of the fruits of the Vstriecha sour cherry variety, the number of bacteria and fungi decreased from 20 to 60% compared to the indicators of the epiphytic microflora before cooling. The proposed combined precooling method is determined to be the most effective in terms of technological indicators and preservation of the quality of cherry and sour cherry fruits. Further studies of the impact of cooling methods on cherry quality will allow the development of mathematical modeling approaches to quantitatively describe precooling processes throughout the entire refrigeration chain for fruit preservation.

Introduction

The efficient use of energy and resources is vital to fostering sustainable development of our planet. Due to the fragility of modern food systems, more and more countries are now prioritizing problems related to the sustainability of food systems. The need to shift towards more sustainable diets and food systems is becoming increasingly clearer. Presently, FAO recommendations include following predominantly plant-based diets, focusing on seasonal and local produce, while also calling for a reduction in food waste (Fischer and Garnet, 2016). These recommendations are based on the fact that plant ingredients are a valuable source of vitamins, minerals, fiber, and other phytonutrients that are important for the prevention of "hidden hunger" (Hutsol et al., 2023). Numerous studies have shown a direct correlation between the consumption of plant products and human health (Fehér et al., 2020). On the other hand, the cultivation of plant products is less harmful to the environment than the production of meat, so increasing the consumption of grains, fruits and vegetables can contribute to the reduction of greenhouse gas emissions (Clune et al., 2017). Given the ever-growing problem of overweight and obesity, fruits and vegetables have a special benefit for the human body, as they have a low calorie content (Arnotti and Bamber, 2019).

However, a significant part of fruit and vegetable production is seasonal and has a relatively short marketing cycle. This leads to an oversaturation of the market during the production season and to large losses and waste. Fruits and vegetables are the main food products most affected by losses and waste (40-50% of their production). Thus, many non-renewable resources are used to produce food that will not be used (Cassani and Gomez-Zavaglia, 2022). Although food production waste can be used in a circular economy, this is still insufficient (Myronycheva et al., 2017). Reducing the loss of fruit and vegetable products can release additional food, reduce the negative impact on the environment, and ensure a more efficient use of valuable resources of the food industry.

Various techniques are used to extend shelf life and reduce product losses: controlled and modified atmospheres, irradiation, antioxidant, and protective coatings (Chockchaisawasdee et al., 2016; Priss et al., 2024; Priss and Kalytka, 2015). However, all listed technologies are used as a supplement to cold storage (Schudel et al., 2023). Refrigeration and refrigerated storage is the most acceptable way to limit cherry spoilage and is a critical step in the post-harvest cold chain to reduce losses and extend shelf life. Precooling is one of the key operations in fruit preservation and is essential to extend its storage life (Duan et al., 2020). It is crucial to conduct precooling as quickly as possible after harvest. According to Ozturk et al. (2017), delaying the precooling of fresh fruit at their field temperature of 35°C for 1 hour can shorten the storage period by approximately 1 day even under optimal storage conditions.

A method widely used to reduce the respiration and respiratory thermogenesis of harvested fruits is precooling (Gao et al., 2019). This method allows to slow down the physiological and biochemical activity of fruits, reduce rotting, and quality decrease. Precooling of fruits and vegetables is based on a strong interaction between modeling, engineering, physiology, and commercial results. Precooling is carried out by various methods: forced air, hydrocooling, cooling with liquid ice, vacuum cooling, and a combination of precooling with treatment with substances of various nature. These methods are based on the principle of rapid heat transfer from fruit products to the cooling medium (Kumar et al., 2023; Lomeiko et al., 2019; Mahajan et al., 2022). In recent years, noticeable progress has been made in the precooling optimization (Jia et al., 2021; Liu et al., 2021a). A study by Yin et al. (2022) highlights the importance of optimizing precooling technology, focusing on fundamental principles of heat and mass exchange between fruit raw materials and the cooling medium.

Please note that different methods of cooling have different effects on certain types of fruit. For example, precooling with cold water is recommended for lychees and is not suitable for strawberries, which are prone to rotting. For yellow peaches, precooling in a refrigerator and precooling with cold water are the most effective methods for extending their storage life and preserving quality after harvest. Liu et al. (2021b) established that the combination of precooling with ozone treatment of cherries reduces their intensity of respiration, has a positive effect on the preservation of the appearance of the fruit and its biochemical composition, and slows the softening of the fruits throughout the storage period. Incorrect choice of cooling methods and inappropriate cooling time can lead to post-harvest quality losses, which in turn can result in a loss of product quality and energy.

Cherries (*Prunus avium* L.) and sour cherries (*Prunus cerasus* L.) are popular fruits, attractive not only due to their taste but also due to their claimed valuable properties (Blando and Oomah, 2019; Faienza et al., 2020). However, less than 30-40% of cherries produced annually are eaten fresh; the remaining 60-70% are used in processed form (Picariello et al.,

2016). To increase the share of fresh cherry consumption, new marketing strategies and improved storage technologies are necessary (Dunn et al., 2018).

Cherry fruits harvested have an elevated temperature, increasing metabolic processes and the development of pathogenic microorganisms (Børve and Stensvand, 2019; Villavicencio et al., 2023). Room cooling, forced air tunneling, and hydrocooling are the precooling methods used in the cherry industry for the fresh market (Alonso and Alique, 2006). Each of these methods has its own set of advantages and disadvantages. The disadvantages of the room cooling method include the requirement for a large area, a slower cooling rate compared to other cooling systems, and often resulting in fruit dehydration (Chaves and Zaritzky, 2018). Forced air cooling has a clear advantage over room cooling in terms of cooling time and reduces losses from microbiological damage during storage. However, it is characterized by high weight losses. Hydrocooling is effective due to its low application cost and high energy efficiency compared to forced air cooling. Furthermore, hydrocooling minimizes weight losses. However, during storage, fruits are more prone to rot, and therefore simultaneous use of disinfectants becomes necessary (Ferreira et al., 2009; Sehirli et al., 2020).

A particularly large number of high-quality products with unique characteristics are grown in the conditions of southern Ukraine (Ivanova et al., 2021a; Ivanova et al., 2021b). Melitopol cherries are the gastronomic hallmark of the southern part of the country, contributing to the development of the tourism industry and shaping its economic security (Trusova et al., 2020a). The role of cherries as a tourist magnet in the region can increase the export potential of fruit products, which is especially important for the recovery of the country's economy in the postwar period (Ivanova et al., 2023; Trusova et al., 2020b). Therefore, the application of various precooling methods can be an effective tool for reducing losses and extending the shelf life of cherry fruits. The aim of this research was to establish the most optimal method of precooling for cherry and sour cherry fruits to preserve their quality and extend shelf life.

Materials and Methods

Materials

Sweet and sour cherry fruits at the consumer ripeness stage were selected for research from horticultural farms in the southern steppe zone of Ukraine (46°46'N, 35°17'E). To extend the storage period and preserve the quality of raw fruit material, various methods and precooling regimes were investigated for cherries. The study focused on the following cherry varieties as model samples: Valerii Chkalov (early ripening), Melitopolska chorna (mid-season), Krupnoplidna (late-season), and Vstriecha.

The fruits met the quality standards of the Ukrainian national standard. Immediately after harvest, the fruits were packed in bulk into plastic boxes (600×400×116 mm), with each container holding 10 kg. The physiological and microbiological indicators were analyzed in the laboratories of the Research Institute for Agricultural Technologies and Ecology at the Dmytro Motornyi Tavria State Agrotechnological University (Melitopol).

Precooling procedures

Precooling of fruits was carried out directly after their collection using the following methods: room cooling (RC), forced air cooling (FAC), hydrocooling (HC), and combined cooling (CC).

The conditions for precooling methods are represented by the following options.

Option 1. Cooling of fruits using the traditional room cooling method. Precooling of fruits was carried out with air at a speed of 0.5 $m \cdot s^{-1}$ (air exchange rate of 30 volumes per hour). The temperature in the refrigerated goods storage chambers was maintained at 5±1°C, the relative humidity of the air was at 90±1%.

Option 2. Cooling of fruits by forced air method. The precooling of the fruits was carried out with cold air at a speed of 3.0 $m \cdot s^{-1}$ (air exchange rate of 90 volumes per hour). The temperature in the forced air cooling chambers was 0±1°C, the relative humidity was 90±1%.

Option 3. Hydrocooling of fruits. Cooling was carried out in a stationary pallet hydrocooler MAS-HC-2000-PAL-ST with a capacity of 2 $t \cdot h^{-1}$. The cooling was carried out with ice water (1.0±0.5°C), supplemented with lactic and acetic acids. For swwt cherries, the concentration of lactic acid was 2.16% and the concentration of acetic acid was 1.71% by volume. For sour cherries, the concentration of lactic acid was 2.22% and the concentration of acetic acid was 1.97%.

Option 4. Combined method of cooling fruits. Preliminary cooling was carried out in two stages:

Stage 1. The fruits were cooled with ice water (1.0±0.5°C), supplemented with lactic and acetic acids (acid concentrations are the same as in hydrocooling) for 10±2 min at a temperature within the fruit of 4.0±1°C.

Stage 2. The fruits were cooled in forced air cooling chambers with cold air at a speed of 3.0 $m \cdot s^{-1}$ (air exchange rate of 90 volumes per hour) for 30±2 minutes at a temperature of 2.0±0.5°C. The temperature in the forced air cooling chambers was 0±1°C. The relative humidity was 90±1%. The total duration of precooling the fruits using the combined method at a temperature of 2.0±0.5°C was 40±2 min.

The cooling process was carried out in a closed-air circuit. Each cooling option was performed in five repetitions, one box with fruits for each repetition. The fruits were cooled to a temperature inside the fruit (near the stone) of 2.0±0.5°C. The temperature within the fruit was measured with a TM-902 SR digital thermometer with a K-type thermocouple. The thermometer measurement range is from -50°C to 1300°C, and precision of 0.1°C in the temperature range of -50...200°C. The cooled fruits were stored at a temperature of 1.5 ± 0.5°C and a humidity of 93 ± 1% for 30 days.

Physiological and physical indicators

The respiratory intensity was determined by the amount of carbon dioxide released and its absorption by the alkali solution (Wang and Fan, 2019).

Weight loss was determined by fixed sample repetitive weighting throughout the storage period.

The rate of the precooling process was determined according to the formula (1):

$$\vartheta = \tan\alpha = \frac{\Delta t}{\Delta \tau} \quad (1)$$

where:
- ϑ – is the rate of the precooling process, (°C·min^{-1})
- tanα – is the tangent of the angle of inclination of the straight line, or the first derivative equation t=aτ+b;
- Δt – is the difference between the initial and final temperatures of the cooling object, (°C)
- $\Delta\tau$ – is the time difference, (min.)

The intensity of the heat release of fruits during respiration was determined according to formula (2):

$$Q = q_s \cdot RI \quad (2)$$

where:
- q_s – specific heat of respiration;
- RI – respiratory intensity of fruit, (mg CO_2·kg^{-1} per hour)

Specific heat of respiration was determined by calculation based on experimentally obtained data on the amount of carbon dioxide released by fruits during respiration. The process of aerobic respiration of fruits (Castellanos and Herrera, 2015) can be described in a simplified way by Equation 3:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + 2816\ kJ \quad (3)$$

Since the molecular mass of CO_2 is 44, according to the equation of the respiration process, per one molecule of glucose consumed 44·6=264 g of CO_2 will be released. Thus, 264 g of CO_2 will release 2816 kJ of heat, and when 1 g of CO_2 is released, 10.67 kJ of heat will be released. Therefore, the specific heat of respiration q_s will be equal to 10.67 kJ per 1 g.

Analysis of microorganisms

The total number of colony-forming units (CFU) was calculated separately for bacterial and fungal colonies on solid nutrient agar. Paster's method with two types of recipes was used for the determination: 1) for bacteria - fish meal pancreatic hydrolysate -12.0 g, dry peptone -12.0 g, sodium chloride -6.0 g, and microbiological agar 10.0±2.0; 2) for fungi (MPA) – malt extract - 20 g, peptone - 2 g, agar - 20 g. Each medium was sterilized for 20 minutes at 121°C, then Ciprofloxacin 100 ml of 0.2 % solution (in 1 L of water) was added to MPA after cooling to 45.

Fruit washouts were diluted 10^3 times with sterile water and 1 mL was placed in empty Petri dishes in triplicate for each treatment. Approximately 25-30 ml of warm medium (35-40°C) was added to each Petri dish with washing, then gently stirred. The Petri dishes for bacterial determination were incubated at 36°C for 24 hours and for fungi at 24°C for 72 hours. The total number of CFU was calculated for each Petri dish. Images from the optical microscopy examination (Granum 3002) were captured with a magnification of 600 times using a DCM 130E digital camera.

Data analysis

To ensure the reliability and objectivity of research results, variance (ANOVA) and correlation regression methods were used (Schminder et al., 2010). The main statistical values of the experiment were calculated using Statistica software (version 10.0) and Excel. Means and standard deviations were calculated for all data series. The level of significance was established at $p < 0.05$.

Results and Discussion

In the post-harvest period, as a result of natural metabolic processes and under the influence of external factors, fruits lose their weight and original quality. This reduces their value as a food product and their commercial quality. Total losses include weight loss of fruits during transpiration and respiration, as well as losses from damage caused by mechanical, phytopathogenic, and physiological factors. Losses in fruit production due to these factors can reach up to 28%. Of these, 19% were recorded after harvesting at the stage of storage and supply of raw materials to trade networks (Suran et al., 2019).

For the study methods and precooling regimes of sweet and sour cherries, the initial temperature of the raw material was set at the level of 20.0-23.0°C (Fig. 1).

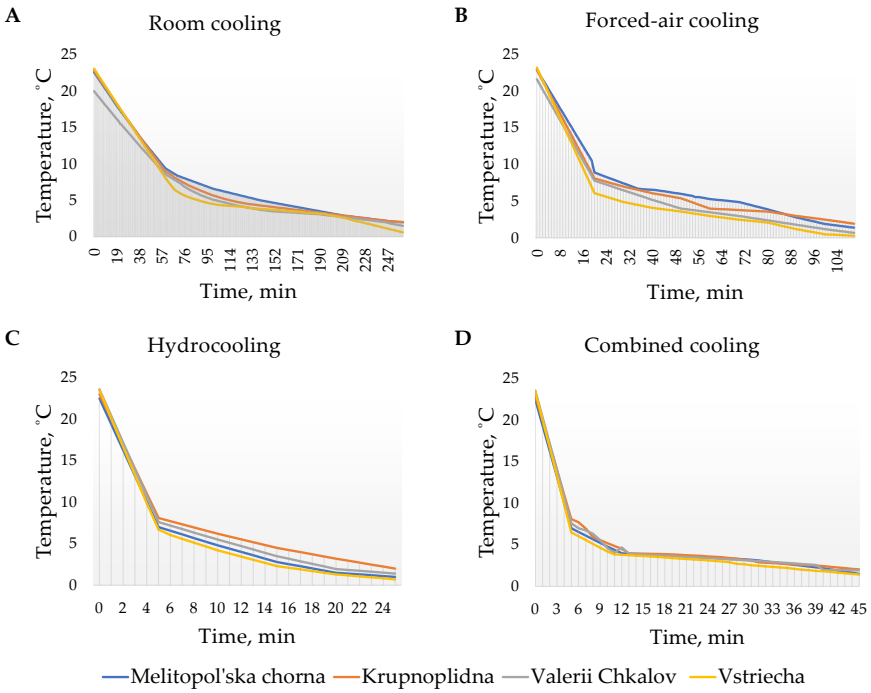

Figure 1. Thermogram of room cooling (A), forced air cooling (B), hydrocooling (C), and combined cooling (D) of sweet cherry and sour cherry fruits

The entire process of temperature reduction in RC can be divided into two periods. The first period lasts up to 60 minutes (Fig. 1A) and is characterized by an intense decrease in temperature. From the 61st minute of cooling, the second period of free-temperature reduction begins. This period lasts until the final necessary temperature is established in the fruits (2±0.1°C). The time of precooling of sweet cherry fruits to a temperature of 2°C by the RC method was 245-260 min, and of sour cherry fruits – 225 min. This is significantly less than described in other studies (Thompson, 2016). However, the fruit species, the final and initial cooling temperatures will be significant factors, and the cooling rate will vary (Saquet et al., 2016).

The FAC of fruits in the forced air cooling chambers occurred at a faster rate compared to the RC (Fig. 1B). The time required for the cooling from a temperature of 21.5-23.5°C to a temperature of 2±0.1°C for cherry fruits was: Valerii Chkalov variety – 86 min, Melitopolska chorna variety – 99 min, and Krupnoplidna variety – 109. For the sour cherry fruits of Vstriecha variety, precooling by forced air method took 81 min.

Based on the analysis of the thermogram of HC with ice water containing lactic and acetic acids, a temperature reduction dynamic, similar to that of RC and FAC, was observed (Fig. 1C). The total duration of the precooling process at a temperature of 2±0.1°C ranged from 18 to 25 minutes for sweet cherry fruits, while for sour cherry fruits it was 16 minutes. In the study by Shen et al. (2024) sweet cherries (*Prunus avium* L., 'Black Pearl') were cooled to 6.1°C at the core of the fruit within 0.5 hours using an ice slurry (Shen et al., 2024). As mentioned above, the cooling time depends on the initial temperature of the cherries, as well as their species and variety specificity.

In (Fig. 1D), the duration of the process was extended compared to HC. Cherries were cooled for 40-44 minutes, depending on the variety, sour cherries were cooled for 36 minutes. The cooling rate of cherry fruits within the first 60 minutes varied between -0.190°C·min^{-1} for the Valerii Chkalov variety and -0.230°C·min^{-1}for the Krupnoplidna variety (Tab. 1).

Table 1.
Rate of the cooling process of the sweet and sour cherry fruit varieties

Time of cooling, (min.)	Rate, ϑ, (°C·min^{-1})			
	Valerii Chkalov	Melitopolska chorna	Krupno-plidna	Vstriecha
Room cooling				
0-60 min	-0.190	-0.220	-0.230	-0.250
From the 61st minute until the internal fruit temperature reached 2.0±0.5°C	-0.036	-0.037	-0.035	-0.038
Forced-air cooling				
0-20 min	-0.690	-0.650	-0.740	-0.855

Time of cooling, (min.)	Rate, ϑ, (°C·min^{-1})			
	Valerii Chkalov	Melitopolska chorna	Krupno-plidna	Vstriecha
From the 21st minute until the internal fruit temperature reached 2.0±0.5°C	-0.087	-0.100	-0.068	-0.067
Hydrocooling				
0-5 min	-3.2	-3.1	-2.98	-3.4
From the sixth minute until the internal fruit temperature reached 2.0±0.5°C	-0.377	-0.383	-0.305	-0.400
Combined cooling				
0-10 min	-1.781	-1.542	-1.463	-1.786
From the 11th minute until the internal fruit temperature reached 2.0±0.5°C	-0.069	-0.067	-0.060	0.071

The cooling of the sour cherry Vstriecha fruits using the RC method was faster compared to that of the sweet cherry fruits. During the initial 0-60 minutes of cooling, the cooling rate for cherry fruits was -0.250°C·min^{-1}, and the temperature inside the cherry fruit decreased to 8.1-9.4°C (Fig. 1A). Subsequently, in the second stage of cooling (starting from the 61-minute mark) to the final target temperature of 2±0.1°C, the temperature decrease rate ranged from -0.035 to -0.038°C·min^{-1}, regardless of the species and varietal characteristics of the fruits.

In the case of FAC, the rate of temperature decrease in cherry fruits during the first 20 minutes ranged from -0.65 to -0.74°C·min^{-1} (Tab. 1), while for cherry fruits it was -0.855°C·min^{-1}. However, in the second stage of cooling, the rate slowed significantly. For cherry varieties, this rate ranged from -0.068 to -0.1°C·min^{-1}. Among the varieties tested, the FAC cooling rate for Vstriecha cherry fruits was the lowest (-0.067°C·min^{-1}). The kinetics of the FAC method remained consistent across the tested fruit species and varietal characteristics. Forced air cooling included two brief stages: in the first stage, the temperature dropped to 6-9°C in 20 minutes, followed by a slower second stage, bringing the internal fruit temperature to 2±0.5°C within 75-112 minutes.

The first stage of the HC process with ice water, supplemented with lactic and acetic acids, lasted 5 minutes, during which the internal temperature of the fruit dropped to 6.7-8.1°C. The initial 5-minute cooling rate for cherries treated with ice water and lactic and acetic acids ranged from -2.98°C·min^{-1} (Krupnoplidna variety) to -3.2°C·min^{-1} (Valerii Chkalov variety). The highest cooling rate was observed in sour cherry fruits (-3.4°C·min^{-1}). The second stage of HC precooling showed a slowing in temperature reduction, with the cooling rate for cherry fruits ranging from -0.305 to -0.383°C·min^{-1}, and for sour cherry fruits, -0.4°C·min^{-1}.

Therefore, the cooling rate of cherry fruits during hydrocooling with lactic and acetic acids exceeded that of FAC 4.5 times and that of RC 11.7 times. For the Vstriecha cherry variety, the HC cooling rate was 5 and 14.6 times higher compared to the FAC and RC methods, respectively. Furthermore, the rate of temperature decrease for fruits during FAC exceeded that during RC 2.5 times for sweet cherries and 2.8 times for sour cherries.

The cooling rate directly influences the intensity of oxidation reduction processes in fruits and affects their subsequent transport and storage capabilities. During storage, respiration is the primary oxidation reduction process, where oxygen is consumed and carbon dioxide and heat energy is released. Part of this energy supports internal processes, while the remainder is released as heat into the environment, adding a heat load and considerably slowing the cooling process (Liu et al., 2021b). Precooling reduces the intensity of respiration of fruits and, consequently, respiratory thermogenesis. Indicators of respiratory intensity and heat release in fruit materials before and after cooling are presented in Table 2.

Table 2.
Intensity of respiration and thermogenesis in sweet and sour cherry fruits during cooling

Cooling method	Respiratory intensity, ($mgCO_2kg^{-1}\cdot h^{-1}$)		Intensity of heat release, ($kJ\cdot kg^{-1}\cdot °C$)	
	before cooling	after cooling	before cooling	after cooling
Valerii Chkalov				
RC	88,38±0.78	49.92±1.85	943.02	532.65
FAC		40.12±0.76		428.08
HC		30.13±0.59		321.49
CC		30.90±1.43		329.70
LCD_{05}		1.76		
Melitopolska chorna				
RC	96.70±1.32	54.83±1.18	1031.79	585.04
FAC		48.51±1.35		517.60
HC		31.85±1.19		339.84
CC		32.06±0.49		342.08
LCD_{05}		1.1		
Krupnoplidna				
RC	81.67±0.43	46.15±0.57	871.42	492.42
FAC		37.86±0.41		403.97
HC		24.36±1.20		259.92
CC		25.13±0.71		268.14
LCD_{05}		0.96		
Vstriecha				
RC	91.21±1.23	46.81±0.73	973.21	499.46
FAC		32.40±1.52		345.71
HC		25.45±0.67		271.55
CC		27.64±1.42		294.92
LCD_{05}		1.92		

The intensity of the respiration of the cherry fruits immediately after harvest was relatively high, ranging from 81.67 to 96.70 mg CO_2 $kg^{-1} \cdot h^{-1}$. The lowest respiratory rate was observed in the Krupnoplidna cherry variety, while the highest was recorded in the Melitopolska chorna variety. This rate is more than double that reported by Alique et al. (2003). Toivonen and Hampson (2017) measured the respiration rate of nine cherry varieties at 0, 5, and 10°C, finding similar rates in most varieties at 0°C but considerable variation at 5 and 10°C (Toivonen and Hampson, 2017). Abiotic factors also impact respiratory activity (Priss et al., 2017). Esti et al. (2002) studied the effect of cooling on the quality characteristics of two cherry varieties, Sciazza and Ferrovia, after 15 days of storage at 1°C and 95% relative humidity. The Ferrovia variety exhibited higher respiratory activity than the Sciazza variety (Esti et al., 2002).

The high intensity of respiration in fruits corresponded to the high intensity of heat release. Before cooling, the highest heat release intensity was recorded in the Melitopolska chorna variety (1031.79 $kJ \cdot kg^{-1} \cdot °C^{-1}$), while the lowest was in the Krupnoplidna variety (871.42 $kJ \cdot kg^{-1} \cdot °C^{-1}$). After precooling with various methods, reductions in respiration and heat release intensity were observed across all species and varietal characteristics. The highest respiratory intensity (46.15–54.83 mg CO_2 $kg^{-1} \cdot h^{-1}$) and heat release (492.42–585.04 $kJ \cdot kg^{-1} \cdot °C^{-1}$) in sweet and sour cherry fruits were observed under the room cooling method. Both the HC and CC methods reduced the intensity of respiration and heat release by 1.7 to 1.9 times compared to room cooling.

Studies by Alique et al. (2005) demonstrate the intensity of respiratory metabolism in the Ambrunés cherry variety of the Picotas group under different pretreatments, including heat treatment at 50°C for 2 minutes, hydrocooling, and normal cooling. Hydrocooling was associated with lower respiratory activity, slowed aging, extended the storage period, and reduced quality loss (Alique et al., 2005). The rate of reduction in respiratory intensity was lowest with the room cooling method (Tab. 3).

Table 3.
The rate of decrease in respiratory intensity of fruits depending on the cooling method

Fruit variety	Rate, ϑ, ($mgCO_2kg^{-1} \cdot h^{-1} \cdot min$)			
	RC	FAC	HC	CC
Valerii Chkalov	-1.60	-2.01	-2.43	-2.40
Melitopolska chorna	-1.75	-2.01	-2.70	-2.69
Krupnoplidna	-1.48	-1.83	-2.39	-2.36
Vstriecha	-1.85	-2.45	-2.74	-2.65
Mean value	-1.67	-2.08	-2.57	-2.53

During HC and CC, the rate of decrease in respiratory intensity was the highest.
The crucial influence of the precooling method on the change in the rate of fruit respiratory intensity was confirmed by the results of the two-factor variance analysis (Fig. 2).

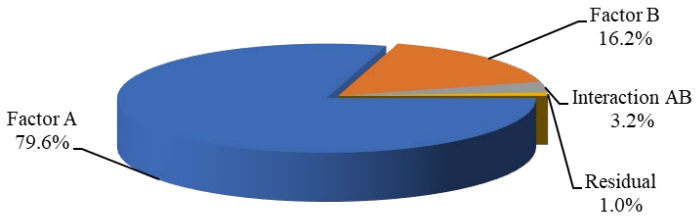

Figure 2. Influence of factors on changes in respiratory intensity, %: factor A – precooling method, factor B – variety, AB – interaction of factors A and B, residual – other factors

The influence of factor A (precooling method) is dominant with a share of influence of 79.6%. The influence of factor B and the interaction of factors AB is 16.2% and 3.2%, respectively. Therefore, utilizing the HC and CC approaches contributes to the fastest decrease in the intensity of respiration, which, in turn, inhibits thermogenesis in plant cells, contributes to stabilization of temperature conditions during transportation and further storage, and significantly reduces the heat load on the equipment.

The most important indicator that characterizes changes in fruit quality after precooling and during storage is weight loss (Tab. 4).

Table 4.
Weight loss during fruit precooling with different methods

Fruit variety	Weight loss, (%)			
	RC	FAC	HC	CC
Valerii Chkalov	1.09±0.08	1.81±0.01	-	0.09±0.02
Melitopolska chorna	0.74±0.05	1.76±0.04	-	0.07±0.01
Krupnoplidna	0.71±0.01	1.96±0.04	-	0.08±0.01
Vstriecha	0.61±0.001	1.78±0.04	-	0.08±0.003
Mean value	0.9±0.04	1.83±0.03	-	0.08±0.01
LCD_{05}	0.07	0.04		0.01

The highest weight loss in both sweet and sour cherries was observed with the forced air cooling (FAC) method, averaging approximately 1.83%. Among the varieties, the Krupnoplidna cherry exhibited the greatest weight loss at 1.96%, while the Melitopolska chorna variety had the lowest at 1.76%. With room cooling, weight loss in all cherry varieties was, on average, 2.03 times lower than with FAC. This finding suggests that the high intensity of air movement in FAC accelerates the cooling process, but also intensifies respiration inhibition, contributing to increased weight loss.

In particular, no fruit mass loss was observed during hydrocooling (HC), likely due to water uptake (Alique et al., 2003). Other researchers have reported similar findings: weight

losses in the Cordia and Regina cherry varieties were reduced after 10 minutes of hydrocooling at 0.9°C. After 15 days of storage at 1°C with 85-95% humidity, these fruits maintained high firmness and lower weight loss compared to control fruits without prior hydrocooling (Ristić et al., 2021). Hydrocooling appears to be the most effective method for inhibiting the respiratory process, reducing thermogenesis, and completely eliminating weight loss. However, this method leaves droplet moisture on the surface of the fruit after the cooling process. For fruits treated with the combined cooling method, the average weight loss was 0.08%, with values ranging from 0.07% (Melitopolska chorna variety) to 0.09% (Valerii Chkalov variety). This weight loss was 11.3 times lower than with room cooling and 22.9 times lower than with FAC. The impact of the precooling method on quantitative weight loss of fruits was confirmed by the results of a two-factor variance analysis (Fig. 3).

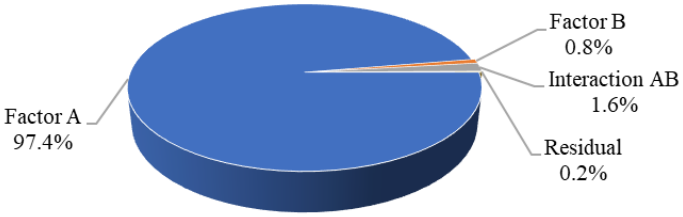

Figure 3. Impact of factors on fruit weight loss, %: factor A – precooling method, factor B – fruit variety, AB – interaction of factors A and B, residual – other factors

The influence of factor A (precooling method) on fruit weight loss is dominant, accounting for 97.4%, while the combined influence of fruit variety (factor B), the interaction between factors (AB) and other random factors is negligible, with a combined share not exceeding 1.6%.

The primary cause of the loss of fresh produce during sales is rotting due to microorganisms (Prusky, 2011). During the storage period, cherry fruits exhibit the development of epiphytic microflora, which can reduce the commercial quality of the raw product. The growth of epiphytic microflora on the surface of the fruit surface over a 30-day storage period was found to depend on the precooling method applied (Tab. 5).

Before cooling, the average number of fungi and bacteria on the fruit surface was $6.20 \cdot 10^3$ CFU·g^{-1} and $20.73 \cdot 10^3$ CFU·g^{-1}, respectively. The lowest counts of fungi ($5.78 \cdot 10^3$ CFU·g^{-1}) and bacteria ($18.55 \cdot 10^3$ CFU·g^{-1}) were found on the surface of the Vstriecha cherry fruits, while the highest fungal count was observed in the Valerii Chkalov cherry fruits ($6.85 \cdot 10^3$ CFU·g^{-1}) and the highest bacterial count in Melitopolska chorna cherries ($22.26 \cdot 10^3$ CFU·g^{-1}). After 30 days of storage under RC, FAC, and HC conditions, the number of bacteria and fungi on the fruit surface increased by 1.4 to 2.3 times and 2.0 to 3.3 times, respectively, depending on the species and the variety.

Table 5.
Quantitative composition of epiphytic microflora on the surface of fruits depending on the precooling method (30 days of storage).

Group of micro-orga-nisms	Quantity of microorganisms $\times 10^3$, (CFU·g^{-1})					
	Before coo-ling	RC	FAC	HC	CC	LCD_{05}
Valerii Chkalov						
Bacteria	21.24±0.85	32.55±2.20	31.25±0.87	48.96±1.043	20.35±1.27	1.68
Fungi	6.85±0.05	15.07±0.15	16.25±0.84	20.59±0.635	4.25±0.58	0.75
Melitopolska chorna						
Bacteria	22.26±0.85	33.46±1.40	33.09±1.76	51.03±1.18	19.25±1.86	2.12
Fungi	6.13±0.07	14.65±1.03	15.25±0.47	21.35±1.26	4.528±0.53	1.0
Krupnoplidna						
Bacteria	20.89±1.27	30.26±0.74	29.25±1.47	50.36±0.74	21.56±0.37	1.14
Fungi	6.06±0.73	16.46±2.25	17.26±0.95	22.547±1.80	5.49±0.77	1.82
Vstriecha						
Bacteria	18.55±2.22	27.65±0.68	25.49±0.80	43.59±2.15	15.65±1.27	2.29
Fungi	5.78±0.88	12.55±0.89	11.50±0.89	22.59±0.98	3.66±0.67	1.22
Mean value						
Bacteria	20.73±1.30	30.98±1.25	29.77±1.23	48.48±1.28	19.20±1.19	-
Fungi	6.20±0.43	14.68±1.07	15.06±0.79	21.77±1.17	4.48±0.64	-

Georgian researchers have explored cherry storage methods to minimize the development of infectious disease pathogens in fruits. Their comparative study of three cherry varieties stored for up to 42 days at 0-1ºC found that the Cordia variety exhibited the highest resistance to microbial damage (Jgenti et al., 2022).

Initially, HC facilitated a reduction in surface microflora. However, during extended storage, the droplet moisture on the surface of the fruit promoted bacterial and fungal growth, leading to intensive development of pathogenic microflora on the surfaces of the moist fruits. After 30 days of storage after precooling with HC, the highest fungal count was observed in the Vstriecha variety ($22.59 \cdot 10^3$ CFU·g^{-1}), and the highest bacterial count in Melitopolska chorna cherries ($51.03 \cdot 10^3$ CFU·g^{-1}).

The positive impact of hydrocooling on the microbiological and aromatic stability of Ambrunes cherries was shown by Serradilla et al. (2010). Sehirli et al. (2020) found that sodium hypochlorite and peracetic acid treatment in a hydrocooling system effectively prevents postharvest diseases in cherries during storage and transportation. Suran et al. (2019) demonstrated the efficacy of specialized treatments in preventing brown fruit rot in cherries and highlighted the ongoing need to develop storage methods to reduce microbiological spoilage.

Using a combined preliminary cooling method for cherries led to a reduction in epiphytic microflora on the surfaces of sweet and sour cherries after 30 days of storage. For some varieties, the counts of bacteria and fungal on the surface of the cherry remained at precooling

levels or decreased by 10-40%, depending on the variety. For Vstriecha cherries, the number of bacteria and fungi decreased by 20-60% compared to precooling levels.

Conclusions

1. When using the room cooling method, the respiratory intensity decrease rate in cherry fruits was low, although the weight loss of the fruit was, on average, two times lower than with forced air cooling. The number of microorganisms on the surface of the fruit was similar for both methods. Forced air cooling led to the highest weight loss of fruits, but slowed respiratory processes more effectively than room cooling.
2. Hydrocooling achieved the shortest time to cool fruits to 2±0.1°C, taking only 16 to 25 minutes depending on the variety. Both the hydrocooling and the combined cooling method reduced respiration and heat release intensity compared to air-based cooling methods, and water cooling also minimized weight loss. However, hydrocooling left droplets of moisture on the surface of the fruit, which stimulated the growth of phytopathogenic microflora during extended storage. After 30 days of storage, the highest levels of fungi (20.59–22.59·10^3 CFU·g^{-1}) and bacteria (43.59–51.03·10^3 CFU·g^{-1}) were found on the surfaces of cherry fruits.
3. The combined cooling method reduced average fruit weight loss by factors of 11.3 and 22.9 compared to room cooling and forced air cooling, respectively. The rate of decrease in respiratory intensity was higher than with air methods and almost equal to that of hydrocooling. This combined method also helped reduce the levels of bacteria and fungi on the fruit surface compared to the levels of the initial epiphytic microflora. Therefore, the proposed combined precooling method is the most effective in terms of technological indicators and in preserving the quality of sweet and sour cherries.
4. Selecting the appropriate precooling method can prevent fruit loss during storage and long-distance transportation within the cold chain, contributing to the efficient use of energy resources.

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SKUTECZNOŚĆ METOD CHŁODZENIA W KONTEKŚCIE OGRANICZANIA STRAT PODCZAS PRZECHOWYWANIA CZEREŚNI I WIŚNI

Streszczenie. Efektywne wykorzystanie energii i zasobów ma kluczowe znaczenie dla wspierania zrównoważonego rozwoju i zwalczania ukrytego głodu. Jednym ze sposobów rozwiązania tego problemu jest zachowanie jakości surowców owocowych przez dłuższy czas. Jednak owoce są najbardziej narażoną na straty produkcyjne grupą żywności oraz najczęściej marnotrawioną. Nieprawidłowy dobór procedur chłodzenia i nieodpowiednie tempo procesu mogą prowadzić do utraty jakości owoców po zbiorach. To z kolei spowoduje utratę jakości produktu i straty energii. Celem badań była ocena wpływu różnych metod chłodzenia na zmniejszenie strat i wydłużenie okresu przechowywania czereśni. Badaniami objęto czereśnie o różnym okresie dojrzewania (Melitopolska chorna, Krupnoplidna i Valerii Chkalov) oraz wiśnie odmiany Vstriecha. Przeanalizowano wpływ chłodzenia w chłodni, chłodzenia dynamicznego („wymuszonego") powietrzem, hydrochłodzenia z dodatkiem kwasu mlekowego i octowego oraz metody łączonej na szybkość chłodzenia, utratę masy, stan mikroflory epifitycznej, intensywność oddychania i wytwarzanie ciepła podczas przechowywania czereśni i wiśni. Najwyższe straty masy owoców zaobserwowano przy zastosowaniu metody chłodzenia dynamicznego, w zakresie od 1,76 do 1,96%. Metoda łączona chłodzenia czereśni i wiśni zmniejszyła średnie straty masy owoców o 11,3-22,9 razy w porównaniu z innymi metodami. Podczas stosowania metody łączonej liczba bakterii i grzybów na powierzchni owoców wiśni pozostała na tym samym poziomie co przed chłodzeniem lub

zmniejszyła się o 10 do 40% w zależności od odmiany. Na powierzchni owoców wiśni odmiany Vstriecha liczba bakterii i grzybów zmniejszyła się od 20 do 60% w porównaniu ze wskaźnikami mikroflory epifitycznej przed chłodzeniem. Zaproponowana kombinowana metoda chłodzenia wstępnego została uznana za optymalną pod względem wskaźników technologicznych i zachowania jakości owoców wiśni i czereśni. Dalsze badania wpływu metod chłodzenia na jakość wiśni i czereśni pozwolą na opracowanie metod modelowania matematycznego w celu ilościowego opisu procesów wstępnego chłodzenia w całym łańcuchu chłodniczym procesu przechowywania owoców.

Słowa kluczowe: trwałość przechowalnicza, czereśnia, wiśnia, wstępne chłodzenie, szybkość chłodzenia, utrata masy, mikroflora epifityczna, termogeneza respiracyjna, ciepło właściwe respiracji