# CHAPTER 10

# Changes in quality parameters of sweet peppers during low-temperature storage after freezing

Nadiia Zahorko
Igor Dudarev
Valentyna Tkachuk

**Abstract**

Low-temperature storage is a crucial method for extending the shelf life of sweet peppers while aiming to preserve their nutritional and sensory qualities. This study examined the impact of long-term low-temperature storage following freezing on the nutritional value, chemical composition, sensory attributes, and tissue microstructure of sweet pepper fruits. The content of colloidally bound water in sweet peppers significantly decreased from 23.6–26.7% to 9.2–9.4% after 270 days of storage, primarily due to freezing-induced damage, whereas the content of osmotically bound water increased from 66.3–69.0% to 83.3–83.5%. Soluble solids content in pepper fruits remained relatively stable throughout the storage period. Sugar content fluctuated, with some varieties exhibiting decreases of 0.9–6.5% and others increases of 1.4–1.5% after 270 days. Vitamin C and titratable acids declined progressively, with the Sonechko variety showing the greatest reduction in acid content (33.3%). Carotenoid levels in sweet peppers decreased by 17.2–17.8%, most notably at the onset of storage, while phenolic compounds – including anthocyanins, leucoanthocyanins, catechins, and flavonols – increased substantially. Pectin fractions demonstrated dynamic changes: water-soluble pectin initially increased by 41.8–80.9% within the first 10 days but declined by over 51% by day 270; protopectin rose by 101–123.6% after 90 days and remained elevated by 83.1–85.8% at the end of storage. Sensory evaluation revealed that the Atlant and Sonechko varieties retained favourable sensory and nutritional qualities, confirming their suitability for prolonged frozen storage. The freezing method significantly influenced pepper tissue microstructure; cryogenic freezing preserved tissue cohesion by producing small intracellular ice crystals, while cryoprotective solutions such as marinades effectively mitigated freeze-induced damage. These results provide practical insights


DOI: 10.21303/978-9908-9706-2-2.ch10

for the food industry to optimise freezing and storage protocols, thereby enhancing the quality and shelf life of sweet pepper products.

**Keywords**

Sweet pepper, freezing, long-term storage, moisture content, biochemical composition.

## 10.1 Introduction

According to the research data of Ukrainian Research Institute of Nutrition, Biotechnology and Pharmacy, the majority of the Ukrainian population is deficient in vitamins (C, E, $\beta$-carotene, B vitamins, etc.) and minerals (Ca, Mg, Se, etc.), which is one of the causes of premature aging of the human body and the development of many diseases [1].

As reported by the WHO, the daily share of fresh fruit and vegetables in the diet should be 600–800 g. However, the seasonality of agricultural production, the high cost of imported fresh fruit and vegetable products in the markets of Ukraine in winter and spring, the existing traditional methods of their storage do not make it possible to fulfil this task.

Postharvest storage of fruits and vegetables at ambient temperature leads to increased ethylene production, which accelerates ripening, senescence, and spoilage, ultimately resulting in significant quality degradation and economic losses [2]. Fruit and vegetable products lose their nutritional value as early as 2 hours after harvesting, and closer to winter the loss of vitamin C and minerals is 20–30% [3]. In contrast, low-temperature storage effectively reduces the loss of colour, flavour, and texture, thereby slowing down physiological aging and preventing decay. According to S. Mi [4], cold-shock precooling is an effective and environmentally friendly technique for maintaining the postharvest quality of fresh fruits and vegetables.

In addition, the losses of fruit and vegetable products during storage without the use of artificial cold are 15–60% depending on the type of products. Refrigeration technologies for the processing and preservation of food raw materials, semi-finished products, and ready-to-eat foods have become an integral component of global strategies for the storage of current and reserve food supplies. This is supported by international programs of the United Nations (FAO, WHO) and UNESCO (MAB Projects No. 10, 11, 12, 14), which emphasize the importance of food security and stock preservation through the implementation of advanced refrigeration technologies. They have no alternative in storing food stocks [5, 6]. However, storing products sensitive to low temperatures – such as those of tropical and subtropical origin – in a chilled state requires additional protective measures [7]. The criterion for evaluating different preservation methods is the extent to which they maintain the initial quality parameters of the raw materials, as well as the duration over which the method preserves the products with the desired properties. These requirements are best met by low-temperature freezing.

Low-temperature freezing significantly slows down biochemical processes in plant tissues and inhibits the growth of microorganisms that compromise product quality. Although freezing and frozen storage alter the initial mechanical properties of products, they effectively preserve their nutritional value [8]. Freezing of foodstuffs holds significant importance and offers extensive possibilities for preserving taste, appearance, and minimizing biochemical changes in seasonally produced products. This approach facilitates achieving a balanced diet in accordance with scientific recommendations and supports the operation of processing plants during off-season periods. It enables the delivery of frozen products across countries, playing a vital role in international trade, and ensures the provision of various regions with products that may be otherwise unavailable. Furthermore, frozen products are used in a wide range of industrial sectors and support the efficient processing of surplus harvests. This enables their long-term preservation for use during years of reduced agricultural yields, thereby helping to mitigate the impacts of natural disasters. Adopting freezing technology can reduce labour and time costs by up to 30 times in public catering systems and by up to 150 times in households. It also contributes to a 20–40% decrease in raw material losses, enhances microbiological and environmental safety, and reduces energy consumption by 50% compared to the production of sterilized canned foods. Furthermore, freezing permits the use of cost-effective, convenient, and practical packaging, improves product transportability, and facilitates the mechanization of manual labour processes [9–15].

## 10.2 Nutritional value of fresh sweet peppers

To optimise the frozen product range, it is necessary to select products that are the richest sources of easily digestible carbohydrates, fibre, pectin, vitamins, enzymes, minerals and other beneficial substances. These include sweet pepper. Sweet pepper (*Capsicum annuum L.*) is among the most economically important fruit vegetables, valued for its high nutritional content, appealing flavour, and vibrant colour [16]. However, its relatively short shelf life remains a key limitation in post-harvest handling and distribution. Its fruits contain up to 5% sugar (on raw matter), 1.5% protein, 0.95% fat, 0.5% potassium salts, 0.13% sodium, 0.16% iron (iron salts contribute to the increase of haemoglobin in the blood) and others. Specific pleasant flavour of pepper is determined by the presence of essential oils in it, the concentration of which ranges from 0.1–1.25% per dry matter.

The main advantage of pepper is that it provides a large group of vitamins. In terms of vitamin C content, it surpasses all other vegetable plants and, depending on variety, growing conditions and degree of maturity, contains an average of 100–400 mg per 100 g of raw matter.

The presence of vitamin P (140–170 mg per 100 g) in peppers enhances the biological effect of vitamin C by delaying oxidation and promoting full absorption. P-active substances are flavonols (85%), catechins (10%), anthocyanins (6%). Their content reaches a maximum at the beginning of fruit ripening, then decreases. Pepper fruits contain carotene (1.7–2.0 mg/100 g), B vitamins (thiamine 0.09–0.2 mg/100 g, riboflavin 0.02–0.1 mg/100 g), folic acid (0.1–0.17 mg/100 g), nicotinic acid (0.5–0.6 mg/100 g). It is enough 20–50 g of fresh peppers to meet the daily requirement of vitamin C and P.

Due to its nutritional value, peppers are widely grown on all continents of the globe. It is grown both in the open ground and in greenhouses. In Ukraine, sweet pepper is grown in greenhouses in limited quantities, because its yield due to biological features is much lower (8–10 kg/m$^2$) than cucumber (24–30 kg/m$^2$). Its production is primarily carried out on farms, totalling approximately 100 thousand tonnes per year, with around 19 thousand tonnes produced annually in the Zaporizhzhia region. The yield ranges from 200 to 460 cwt/ha, depending on the variety and agricultural practices [15, 17].

### 10.3 Characteristics of sweet pepper varieties

Pepper is one of the leading vegetable crops in Ukraine. It plays a crucial role as a raw material base for the canning industry and is widely used for consumption in both fresh and canned forms. Its rich chemical composition and harmonious flavour make it ideal for use in dietary and medical nutrition.

Pepper is an annual plant (it can be perennial in the tropics). The stem is short or medium-long. The flower is oviparous. The fruit is a 2–4 nested berry, depending on the variety it can have a shape – rounded, flattened, egg-like, spherical, cube-shaped, cone-shaped, cylindrical, pyramidal.

Pepper colour depends on ripeness and variety: in the phase of technical maturity, it can be light green, dark green, milky white, yellow, or violet-green. In the phase of biological maturity (seed), it changes to red, orange-red, dark red, yellow, or orange. Seeds of pepper are yellowish-white, flat-rounded. The root system of pepper plants is highly branched. The characteristics of sweet pepper varieties are listed below [18, 19]:

**1. The Lastivka variety** was developed by the Moldavian Research Institute of Irrigated Agriculture and Vegetable Growing. It is a medium-ripening variety, with a period from sprouting to the first harvest at the stage of technical ripeness lasting 89–118 days, and up to 128–132 days for biological ripeness. The plant has a semi-spreading bush of medium height (42–53 cm). Fruits are cone-shaped, slightly oval, smooth, medium-sized, and weigh between 40–60 g. The pulp is sweet, with a thickness of 6–8 mm. The colour of the fruit at technical maturity is light green, while at biological maturity it is dark red. The yield is 223–487 cwt/ha.

**2. The Aivenho variety** was developed by PE "Agrosvit" and is a medium-ripening type. The vegetation period until the first harvest is 110–118 days. The plant forms a stem-type, semi-branched bush with a height of 53–68 cm. Fruits are cone-shaped, slightly ribbed, smooth, and medium to large in size, weighing between 75 and 98 grams. The pulp is sweet and 6–8 mm thick. The fruit is light green at technical maturity and turns red at biological maturity. The yield ranges from 230 to 520 cwt/ha.

**3. The Atlant variety** is a high-potential, medium-ripening type. The period from seedling emergence to the first harvest at technical ripeness is 90–120 days, and up to 132–136 days at biological ripeness. The plant forms a stem-type bush with a height of 55–70 cm. Fruits are cone-shaped, ribbed, large, and weigh between 120 and 150 grams. The pulp is sweet and 5–7 mm thick. The fruit is green at technical maturity and dark red at biological maturity. The yield ranges from 235 to 530 cwt/ha.

**4. The Antei variety**, developed by PE "Agrosvit", is a medium-ripening type. The vegetation period until the first harvest is 105–128 days. The plant forms a stem-type bush with a height of 70–90 cm. Fruits are cone-shaped with pronounced ribbing, very large, and weigh between 130 and 180 grams. The pulp is sweet and 4–7 mm thick. The fruit is green at technical maturity and dark red at biological maturity. The yield ranges from 270 to 540 cwt/ha.

**5. The Sonechko variety** is a medium-ripening type. The period from sprouting to technical ripeness is 110–120 days, and up to 140–150 days to reach biological ripeness. The plant is compact and stunted, with a height of 30–40 cm. Fruits are rounded, smooth, and non-ribbed; they are green at the stage of technical ripeness and turn orange-yellow at biological ripeness. The average fruit weight is 70–100 grams, with a flesh thickness of 6–8 mm. The yield ranges from 240 to 470 cwt/ha.

## 10.4 Tissue microstructure of sweet peppers after freezing

The effect of different freezing methods on the microstructure of pepper fruits was investigated using the following approaches:

– cryogenic environment: freezing in liquid nitrogen at –273°C and in liquid nitrogen vapour at –170°C;

– air environment: freezing in the air of a refrigeration chamber at –24°C with natural air circulation;

– liquid environment: freezing in a marinade, using plastic cups with a capacity of 0.250 $dm^3$.

To assess the damaging effect of ice on the cellular structure of tissues, histological studies were conducted on pepper fruits before and after freezing in different environments.

In **Fig. 10.1, *a, b***, the tissues of fresh sweet pepper fruits are shown. The cells in the longitudinal section appear more elongated and closely packed, with minimal intercellular spaces. In the transverse section, the cells appear more rounded, with the sides of the cell walls being 1.5–2.0 times smaller compared to the longitudinal section. The intercellular spaces are larger and more pronounced, and the cell walls remain undistorted.

Freezing in liquid nitrogen and nitrogen vapour resulted in a more cohesive cell structure, as small ice crystals formed inside the cells before noticeable dehydration of the cells occurred (**Fig. 10.1, *c, d***). When frozen in liquid nitrogen, the cells of various tissues, including the pulp, do not separate. While they maintain a healthy appearance, some areas show visible damage to the cell walls. Even with cryogenic freezing, a more precise selection of the freezing parameters is necessary, which calls for more advanced equipment.

However, it is known that application of ultrahigh freezing rates leads to irreversible changes in protein structures of the cell, as well as deterioration of the quality of frozen products due to the appearance of large cracks on the fruit surface (when freezing in liquid nitrogen **Fig. 10.1, *a***) and many microcracks (when freezing in nitrogen vapour **Fig. 10.1, *b***). This phenomenon occurs as a result of high internal stresses in the tissues, loss of plastic properties of the surface layers and expansion of the frozen inner layers of the product. The size of cracks also depends on the type and size of the frozen product. The larger the product and the higher the freezing rate, the greater the internal stresses, resulting in larger cracks.

**Fig. 10.1, *d*** clearly shows the structure of cells frozen using the traditional method in the air environment of the refrigerating chamber. Unlike the cells of fresh fruit, they have acquired an angular shape, likely due to the pressure exerted by ice crystals formed in the intercellular spaces. Significant ruptures in the cell membranes of the fruit pulp, along with the formation of folds in the protoplasm and mechanical damage, are visible. According to S. Schudel et al. [21], the freezing of plant tissues with high moisture content frequently results in the formation of ice crystals that disrupt cellular structures. This damage contributes to drip loss and decreased tissue firmness, ultimately compromising the overall quality of the thawed product.

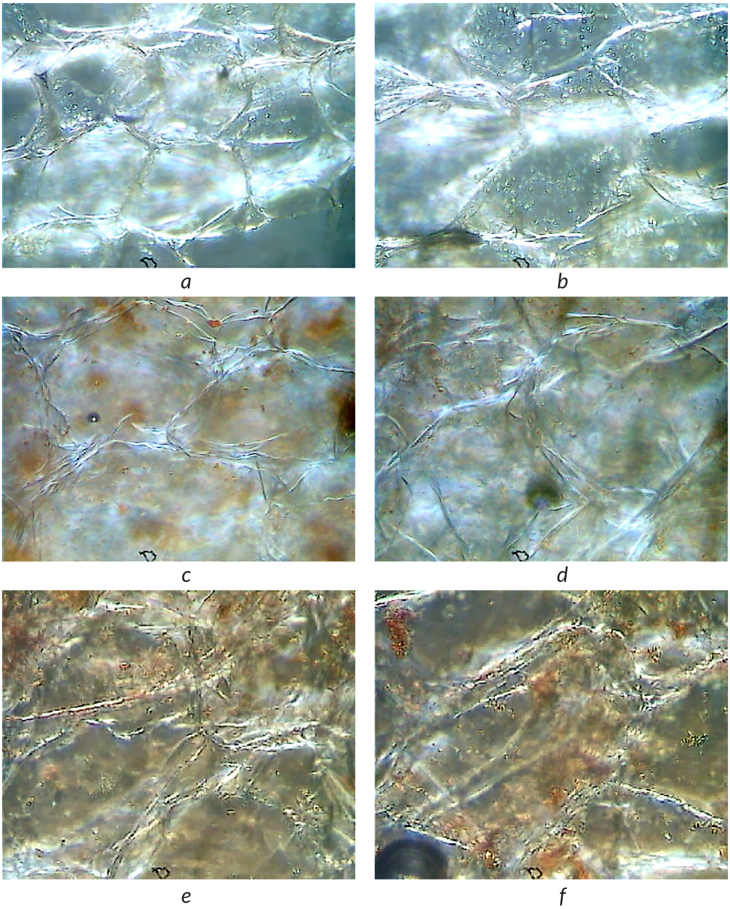
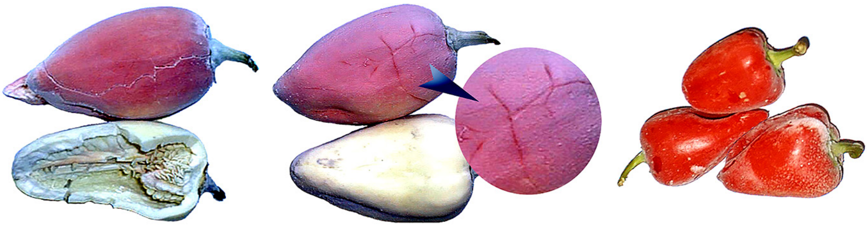



**Fig. 10.1** Tissue microstructure of sweet pepper (Atlant variety): *a* – fresh – cross section; *b* – fresh – longitudinal section; *c* – frozen in liquid nitrogen; *d* – frozen in nitrogen vapour; *e* – frozen in bulk in a freezer; *f* – frozen dry in an air environment – defrosted

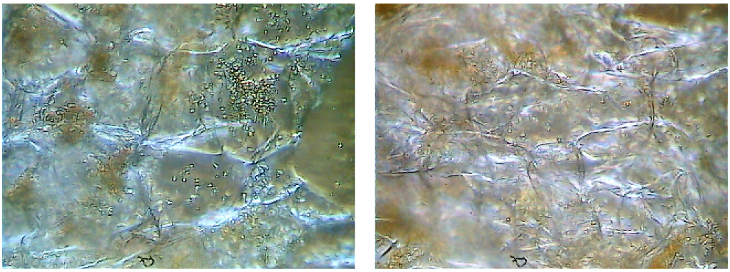
In **Fig. 10.1**, ***e*** the tissue microstructure of sweet pepper samples frozen in bulk in a freezer is presented, while in **Fig. 10.1, *f***, the sample frozen dry in an air environment and then defrosted is shown. **Fig. 10.2** illustrates the appearance of sweet peppers frozen using different techniques. Fruit frozen at a moderate rate had the best quality characteristics (**Fig. 10.2**, ***c***).



*a* *b* *c*

**Fig. 10.2** Frozen pepper fruits in: *a* – liquid nitrogen; *b* – nitrogen vapour; *c* – air environment of the refrigerating chamber

There is very little information in the published papers regarding the effect of freezing on the tissue structure of fruits and vegetables frozen in solutions containing substances with cryoprotective effect. The microstructure of the pepper fruit parenchyma, frozen in a marinade, is similar to the structure of fruits frozen using the cryogenic method (**Fig. 10.3**).



*a* *b*

**Fig. 10.3** Microstructure of pepper tissues frozen in marinade: *a* – Atlant variety; *b* – Sonechko variety

A comparative study of histological sections of peppers frozen using different methods showed that those frozen in a marinade produced a higher-quality product, with maximum restoration of cell shape, volume, and water content.

## 10.5 Quality parameters of sweet peppers during storage at low temperatures

The study of the chemical composition and sensory properties of sweet peppers was conducted on fruits frozen in the air environment of a freezing chamber at −24 ± 2°C (relative humidity 90–95%, air velocity 2.5–3.0 m/s) until their core temperature reached −20 ± 2°C, followed by storage for 270 days at −20 ± 2°C.

### 10.5.1 Content of water in sweet peppers during low-temperature storage

In plant tissues, water constitutes 70–95% of the raw mass. Even a slight reduction in the water content of pepper fruits leads to a noticeable loss of their natural freshness and firmness, thereby diminishing overall quality, shelf life, and market value [22].

According to the existing classification, two forms of water are distinguished: free water and bound water. Bound water is further subdivided into osmotically bound water, which is bound to ions (partially proteins and polysaccharides) and plays an important role in osmotic pressure in plant cells, and colloidally bound water, which is located inside colloidal systems, on the surface of colloids, and between them.

Free water is located in the intercellular spaces of the product and acts as a solvent for mineral substances. At temperatures below the cryoscopic temperature, it freezes into ice. As free water freezes, the concentration of salts in the unfrozen intercellular solution increases, causing a shift of its cryoscopic temperature to lower values. Bound water freezes at lower temperatures than free water.

The experiments revealed the dynamics of total moisture content, colloidally bound water, and osmotically bound water in sweet pepper frozen in bulk, measured before freezing and after 10, 90, 180, and 270 days of storage. Two sweet pepper varieties, Atlant and Sonechko, were used in the study. The results are presented in **Table 10.1**.

The content of colloidally bound water in fresh fruits was 26.7% in the Atlant variety and 23.6% in the Sonechko variety (**Table 10.1**). After 10 days of storage, it decreased to 19.1% and 13.8%, respectively, and by the end of the storage period (270 days), it further declined to 9.4% in the Atlant variety and 9.22% in the Sonechko variety. Thus, after 10 days of storage, the colloidally bound water content in the Atlant variety decreased by 28.5% compared to its initial level in fresh fruits, while in the Sonechko variety it decreased by 41.5% (**Table 10.1**). A similar trend was observed throughout the storage period. After 180 days of storage, the water content decreased by 44.6% in the Atlant variety and by 48.2% in the Sonechko variety compared to the initial level. After 270 days of storage, the decrease was 64.8% and 60.9%, respectively.

**Table 10.1 Water content in sweet peppers during low-temperature storage**

| Sweet pepper variety | Storage period, days | Total water content (moisture), % | Colloidally bound water content, % | Osmotically bound water content, % |
|---|---|---|---|---|
| Atlant | Fresh | 93.00 ± 0.01 | 26.70 ± 0.00 | 66.30 ± 0.00 |
| | 10* | 92.99 ± 0.48 | 19.10 ± 0.36 | 73.89 ± 0.46 |
| | 180* | 92.95 ± 0.39 | 14.80 ± 0.57 | 78.15 ± 0.38 |
| | 270* | 92.89 ± 0.34 | 9.40 ± 0.76 | 83.49 ± 0.32 |
| | $HCP_{0.5}$ | 0.45 | 9.11 | 9.04 |
| Sonechko | Fresh | 92.60 ± 0.00 | 23.60 ± 0.00 | 69.00 ± 0.06 |
| | 10* | 92.59 ± 0.43 | 13.80 ± 0.30 | 78.79 ± 0.15 |
| | 180* | 92.53 ± 0.24 | 12.23 ± 0.21 | 80.30 ± 0.60 |
| | 270* | 92.47 ± 0.38 | 9.22 ± 0.22 | 83.25 ± 0.30 |
| | $HCP_{0.5}$ | 0.41 | 7.75 | 7.25 |

*Note: * after freezing*

The content of osmotically bound water also changed during freezing and low-temperature storage (**Table 10.1**). The content of osmotically bound water in the fruits of the Atlant variety was 66.3% before freezing and 83.49% at the end of storage (270 days). In the Sonechko variety, it was 69.0% before freezing and 83.25% at the end of storage. Thus, after 10 days of storage, its content increased relative to the initial level by 11.4% in the Atlant variety and by 14.2% in the Sonechko variety. By the end of the storage period (270 days), the increase reached 25.9% and 20.7%, respectively.

The reduction in colloidally bound water is primarily caused by the destructive effects of low temperatures during the freezing process. Under these external influences, gels convert into sols, and partially vice versa. As a result, the amount of osmotically absorbed water increases, although not in direct correlation with the decrease in colloidally bound water. In the fruits of both varieties, the total moisture content changes only slightly during freezing and storage. A slower decline in moisture content during the storage of pepper fruits was also reported by E. R. Bayogan et al. [23].

### 10.5.2 Sensory properties of sweet peppers during low-temperature storage

Sensory evaluation is the most significant method of determining the quality of both fresh and frozen products. In this case, the taste, aroma, colour, shape, consistency, packaging, labelling, and weight of the product are assessed.

Sensory evaluation of fresh and frozen pepper fruits was conducted after defrosting, until the temperature reached 2°C. Sweet peppers were evaluated both fresh and after 90, 180, and 270 days of storage. The sensory evaluation of sweet pepper samples was conducted by a group of specially trained experts. The 5-point hedonic scale (5 – like extremely, 4 – like moderately; 3 – neither like nor dislike, 2 – dislike moderately; 1 – dislike extremely) was used. An average score was calculated from the evaluation results to characterize the comprehensive sensory attributes of the pepper.

**Table 10.2** shows that the Atlant and Sonechko varieties demonstrated the best performance both fresh and frozen. When fresh, they received scores of 5.0 and 4.98 points, respectively. The fruits of the Atlant variety were large in size, had a vibrant dark red colour, and featured a pulp thickness of 6 mm. The fruits of the Sonechko variety were orange-yellow in colour, had an equally attractive appearance, and a pulp thickness of 7 mm.

**Table 10.2 Mean scores of sensory properties of sweet peppers**

| Sweet pepper variety | Storage period, days | | | | |
|---|---|---|---|---|---|
| | Fresh | 10 | 90 | 180 | 270 |
| Atlant | 5.00 | 4.44 | 4.52 | 4.60 | 4.42 |
| Sonechko | 4.98 | 4.36 | 4.44 | 4.54 | 4.38 |
| Antei | 4.86 | 4.16 | 4.16 | 4.12 | 4.24 |
| Aivenho | 4.84 | 4.26 | 4.18 | 4.18 | 4.26 |
| Lastivka | 4.98 | 4.36 | 4.02 | 4.34 | 4.38 |

The Atlant, Sonechko, and Lastivka varieties received high sensory scores in their fresh form – 5.00, 4.98, and 4.98, respectively (**Table 10.2**). These same varieties also received the highest ratings after 10 days of storage, with average scores of 4.44, 4.36, and 4.36, respectively. A slight change in fruit colour, softening of consistency, partial loss of aroma and flavour were noted. Similar, but more pronounced, changes were observed in the fruits of other varieties after 10 days of storage: Aivenho scored 4.26, and Atlant scored 4.16. After 270 days of storage, the sensory properties of sweet peppers were evaluated as follows: Atlant – 4.42, Sonechko – 4.38, Lastivka – 4.38, Aivenho – 4.26, and Antei – 4.24.

As shown by the tasting evaluation results, changes in fruit consistency began to deteriorate immediately after freezing and continued through the first half of the storage period. This was due to water recrystallization in the fruit tissues, which led to the destruction of cell membranes and moisture loss during thawing. By the end of the storage period, this process had diminished, and the pulp consistency developed a more stable structure. According to the results of the sensory analysis, the Atlant and Sonechko varieties stood out most prominently in terms of colour, aroma, and flavour.

### 10.5.3 The effect of low-temperature storage on the chemical composition of sweet peppers

The freezing process significantly alters the biochemical characteristics of succulent plant products. Natural changes occur in the content of soluble solids, sugars, acids, vitamin C, polyphenols, carotenoids, aromatic compounds, and other chemical components. All sweet pepper varieties studied exhibited changes in soluble solids content during the freezing process (**Table 10.3**).

**Table 10.3 Content of soluble solids in sweet peppers during storage, %**

| Sweet pepper variety | Storage period, days | | | | | |
|---|---|---|---|---|---|---|
| | Fresh | 10 | 90 | 180 | 270 | $HCP_{0.5}$ |
| Atlant | 6.10 | 6.32 | 6.18 | 6.10 | 6.00 | 0.38 |
| Antei | 5.90 | 6.08 | 6.10 | 6.00 | 6.00 | 0.38 |
| Lastivka | 5.76 | 5.80 | 5.80 | 5.74 | 5.70 | 0.56 |
| Aivenho | 5.92 | 6.00 | 6.04 | 6.01 | 6.00 | 0.42 |
| Sonechko | 7.40 | 7.51 | 7.50 | 7.44 | 7.41 | 0.50 |

During the first 10 days of low-temperature storage, the soluble solids content increased in all varieties compared to fresh peppers, specifically by 3.6% in the Atlant variety, 3.1% in Antei, 0.7% in Lastivka, 1.4% in Aivenho, and 1.5% in Sonechko (**Table 10.3**). These changes were caused by water crystallization within the parenchyma cells, leading to an increased concentration of dry matter. For comparison, during storage of peppers at a temperature of 10.61 ± 0.04°C and relative humidity of 99.48 ± 0.31%, the soluble solids content also increased over an 8-day period, from an initial value of 6.04 to 7.20°Brix on the eighth day [24].

After 90 days of storage, the soluble solids content of peppers remained almost unchanged, decreasing by only 2.2% in the Atlant variety and by 0.1% in the Sonechko variety compared to the levels after 10 days of storage. During the same period, the soluble solids content in the Antei and Aivenho varieties increased by 0.3% and 0.7%, respectively. In the Lastivka variety, the amount of soluble solids remained at the same level as after 10 days of storage. After 270 days of storage, compared to fresh peppers, the soluble solids content in the peppers of the Atlant and Lastivka varieties decreased by 1.6% and 1.0%, respectively. In contrast, the soluble solids content increased in the Antei, Aivenho, and Sonechko varieties of peppers by 1.7%, 1.4%, and 0.1%, respectively.

Similar to the changes in soluble solids content, the sugar content in all pepper varieties increased after 10 days of storage (**Table 10.4**). In the Atlant and Aivenho varieties, the sugar content increased by 2.3% after 10 days of storage compared to fresh peppers. In the Sonechko, Lastivka, and Antei varieties, the increase was 2.2%, 1.4%, and 0.8%, respectively. By the end of the storage period, the sugar content compared to the initial level in fresh peppers decreased in the Atlant, Antei, and Sonechko varieties by 6.5%, 2.2%, and 0.9%, respectively. Meanwhile, in the Lastivka and Aivenho varieties, the sugar content increased by 1.4% and 1.5%, respectively.

**Table 10.4 Content of sugar in sweet peppers during storage, %**

| Sweet pepper variety | Storage period, days | | | | | |
|---|---|---|---|---|---|---|
| | Fresh | 10 | 90 | 180 | 270 | $HCP_{0.5}$ |
| Atlant | 4.31 | 4.41 | 4.40 | 4.37 | 4.03 | 0.33 |
| Antei | 3.58 | 3.61 | 3.64 | 3.50 | 3.50 | 0.29 |
| Lastivka | 3.60 | 3.65 | 3.70 | 3.70 | 3.65 | 0.26 |
| Aivenho | 3.43 | 3.51 | 3.56 | 3.50 | 3.48 | 0.20 |
| Sonechko | 5.43 | 5.55 | 5.60 | 5.33 | 5.38 | 0.22 |

The content of organic acids in pepper fruits is relatively low and does not significantly influence their flavour. However, the amount of these acids is important for assessing the nutritional value of the fruits. In fresh fruits of all five varieties, the titratable acid content ranged from 0.19% to 0.27% (**Table 10.5**).

After 10 days of low-temperature storage, a decrease in titratable acid content was observed in all pepper varieties, ranging from 4.8% to 26.1% (**Table 10.5**).

However, in the Antei variety, this indicator increased by 5.3%. After 270 days of storage, a decrease in titratable acid content was recorded in all varieties, with the most significant reductions observed in the Atlant and Sonechko varieties – by 20.8% and 33.3%, respectively. For comparison, T. V. R. Rao et al. [25] found that the titratable acidity of pepper fruits decreased during 18 days of storage at both 10°C and 25°C.

**Table 10.5 Content of titratable acid in sweet peppers during storage, %**

| Sweet pepper variety | Storage period, days | | | | | |
|---|---|---|---|---|---|---|
| | Fresh | 10 | 90 | 180 | 270 | $HCP_{0.5}$ |
| Atlant | 0.24 | 0.21 | 0.21 | 0.20 | 0.19 | 0.04 |
| Antei | 0.19 | 0.20 | 0.20 | 0.20 | 0.18 | 0.04 |
| Lastivka | 0.21 | 0.20 | 0.18 | 0.19 | 0.19 | 0.04 |
| Aivenho | 0.23 | 0.17 | 0.21 | 0.20 | 0.19 | 0.01 |
| Sonechko | 0.27 | 0.24 | 0.20 | 0.20 | 0.18 | 0.05 |

Sweet pepper fruits are among the vegetables richest in vitamin C content (**Table 10.6**). The highest amount of vitamin C is accumulated in fruits at the stage of biological maturity [19], while in overripe fruits, the ascorbic acid content decreases. In fruits at the technical maturity stage, the vitamin C content is 40–50% lower than in those at biological maturity.

**Table 10.6 Content of vitamin C in sweet peppers during storage, mg/100 g**

| Sweet pepper variety | Storage period, days | | | | | |
|---|---|---|---|---|---|---|
| | Fresh | 10 | 90 | 180 | 270 | $HCP_{0.5}$ |
| Atlant | 220.10 | 201.90 | 190.50 | 179.10 | 167.00 | 0.77 |
| Antei | 189.51 | 156.40 | 145.00 | 136.00 | 127.40 | 0.38 |
| Lastivka | 162.80 | 141.32 | 136.00 | 119.43 | 108.36 | 0.20 |
| Aivenho | 187.01 | 163.31 | 151.83 | 138.00 | 129.65 | 0.41 |
| Sonechko | 214.00 | 195.80 | 188.84 | 178.41 | 157.65 | 0.71 |

According to the results, the ascorbic acid content in all five varieties of fresh peppers was high, ranging from 162.8 to 220.0 mg/100 g (**Table 10.6**). The highest vitamin C content was found in the Atlant and Sonechko varieties, with values of 220.10 and 214.00 mg/100 g, respectively. Throughout the entire storage period, a decrease in vitamin C content was observed. After 270 days of low-temperature storage, the vitamin C content had decreased by 24.1% to 33.4%, ranging from

108.36 to 167.00 mg/100 g. For comparison, during storage of peppers at a temperature of 10.61 ± 0.04°C and relative humidity of 99.48 ± 0.31%, the ascorbic acid content initially decreased from 1.055 to 1.023 g/kg FW by the fourth day of storage, and then increased to 1.074 g/kg FW by the eighth day [24].

The transformation of ascorbic acid in frozen fruits involves its oxidation to dehydroascorbic acid, and subsequently to 2.3-diketogulonic acid. The first compound remains physiologically active, while the latter is not effective from a nutritional standpoint. Despite the loss of ascorbic acid in pepper fruits during low-temperature storage, the residual content remains high. Compared to many other vegetables – even when fresh – the vitamin C content in sweet peppers is several times greater. This highlights the unique value of storing nutrient-rich vegetable crops like sweet pepper at low temperatures to preserve their high nutritional quality.

Humans cannot synthesise carotenoids and therefore depend entirely on their intake from food sources. Of the approximately 600 carotenoids currently identified, only around 50 exhibit vitamin A activity and are classified as provitamin A carotenoids. These compounds are present as pigments in foods such as red peppers, carrots, and pumpkins. $\beta$-carotene is considered the most effective provitamin A carotenoid. Moreover, $\beta$-carotene serves not only as a source of vitamin A but also fulfils important biological functions [20].

The carotenoid content in sweet pepper fruits of the two varieties, Atlant and Sonechko, during low-temperature storage is shown in **Table 10.7**. In fresh sweet pepper fruits, the carotenoid content was 22.5 ± 0.50 mg/100 g for the Atlant variety and 15.60 ± 0.14 mg/100 g for the Sonechko variety. During storage, the carotenoid content in both varieties decreased. After 270 days of storage, the content had declined by 17.2% and 17.8% for the Atlant and Sonechko varieties, respectively. Notably, a significant reduction was already observed after just 10 days of storage, with decreases of 13.8% for the Atlant variety and 16.5% for the Sonechko variety compared to the fresh samples. Thus, the most intensive loss of carotenoids in pepper fruits occurs during the initial stage of storage.

Phenolic compound content plays a crucial role in determining sweet pepper quality. Many of these phenolics, primarily belonging to the flavonoid group, exhibit notable biological activity, particularly P-vitamin (vitamin P) effects, which are most pronounced when combined with ascorbic acid. Sweet peppers are classified among vegetables with a high content of vitamin P.

Freezing of sweet pepper fruits resulted in an overall increase in the content of the analysed phenolic compounds (**Table 10.7**). In fresh sweet pepper fruits of the Atlant and Sonechko varieties, the anthocyanin content was 1.06 ± 0.15 mg/100 g and 1.10 ± 0.08 mg/100 g, respectively. In the Atlant variety, anthocyanin levels increased significantly during storage, reaching 1.76 ± 0.17 mg/100 g after 90 days – a 66.0% increase compared to fresh samples. Following this peak, a gradual decline was observed, with the content decreasing to 1.53 ± 0.08 mg/100 g after 270 days of storage. Nevertheless, despite the decreasing trend after 90 days, the anthocyanin content after 270 days remained 44.3% higher than that in the fresh Atlant samples. In the Sonechko variety, the trend in anthocyanin content during storage was similar. After 90 days of storage, the anthocyanin content increased by 115% compared to the fresh samples, reaching 2.36 ± 0.07 mg/100 g. This was followed by a slight decrease, with the content measuring 2.32 ± 0.11 mg/100 g after 270 days of storage. Overall, low-temperature storage led to a substantial increase in anthocyanin content in sweet pepper samples.

Leucoanthocyanins are another type of flavonoid compound found in plants. Leucoanthocyanins were found in equal amounts in the fresh fruits of the Atlant and Sonechko pepper varieties, each containing 52.2 mg/100 g (**Table 10.7**). Throughout the entire period of low-temperature storage, their content increased. After 10 days of storage, the leucoanthocyanin content increased by 9.8% in the Atlant variety (red fruits) and by 1.0% in the Sonechko variety (orange-yellow fruits). As storage progressed, a marked increase in leucoanthocyanin content was recorded, reaching 99.70 ± 0.41 mg/100 g in the Atlant variety and 96.80 ± 0.07 mg/100 g in Sonechko by day 90. These values correspond to an increase of 91.0% in Atlant variety and 85.4% in Sonechko variety, compared to the fresh fruits. Thereafter, the leucoanthocyanin content continued to rise, although at a slower rate. After 270 days of storage, the content reached 100.80 ± 0.12 mg/100 g in Atlant variety and 109.50 ± 0.19 mg/100 g in Sonechko variety.

Catechins are a class of flavonoids, commonly found in a variety of fruits and vegetables, and are associated with numerous beneficial health effects. In fresh fruits of sweet pepper varieties Atlant and Sonechko, their content was 56.00 ± 0.25 mg/100 g and 55.60 ± 0.32 mg/100 g, respectively **(Table 10.7**). During low-temperature storage following freezing, the catechin content increased, reaching 136.8 ± 0.14 mg/100 g for Atlant and 135.3 ± 0.25 mg/100 g for Sonechko by day 270. Thus, over the 270-day storage period, the catechin content in the pepper fruits of Atlant and Sonechko varieties increased by 144.3% and 143.3%, respectively. The most pronounced increase in catechin content occurred between days 10 and 180 of storage.

Flavonols are a subclass of flavonoids, characterised by their yellow or yellow-green colour, and contribute to the overall pigmentation of many fruits and vegetables. The flavonol content in fresh fruits of sweet pepper varieties Atlant and Sonechko was 32.00 ± 0.48 mg/100 g and 35.00 ± 0.14 mg/100 g, respectively (**Table 10.7**). During low-temperature storage following freezing, their (flavonols) content increased. Within the first ten days of storage, the flavonol content in the pepper samples increased by 5–9% compared to fresh fruits, with an increase of 8.1% for Atlant and 5.7% for Sonechko. During the subsequent storage period, a more pronounced increase in flavonol content was observed. After 270 days of storage, the flavonol content in the pepper fruits ranged from 95.80 to 101.30 mg/100 g. Therefore, over the duration of prolonged low-temperature storage (270 days), the flavonol content increased by 189.4–199.4% compared to the levels in fresh fruits.

The total flavonoid content in sweet peppers increased throughout the entire low-temperature storage period and, by day 270, had increased by 137.1–142.1% compared to their content in fresh pepper samples (**Table 10.7**). In particular, the total flavonoid content in fresh fruits of the Atlant variety was 141.26 ± 0.23 mg/100 g, increasing to 334.93 ± 0.16 mg/100 g after 270 days of storage. In the Sonechko variety, the initial content was 143.9 ± 0.27 mg/100 g, rising to 348.42 ± 0.29 mg/100 g after 270 days.

The increase in the total content of phenolic compounds of various groups in sweet peppers during low-temperature storage after freezing can be attributed to several factors. These include the decomposition of complex compounds formed by the interaction of different flavonoid groups, as well as the gradual transformation of the biochemical composition through oxidative and reductive reactions occurring in frozen products. Additionally, the freezing of water leads to a relative increase in the concentration of chemical substances. The synergistic action of vitamins C and P also appears to play a significant role. Phenolic compounds inhibit the oxidation of ascorbic acid, which in turn exerts a stabilising effect on bioflavonoids. Moreover, a portion of ascorbic acid exists in a bound form, forming complexes with phenolic compounds. The breakdown of these complexes may also contribute to the observed increase in flavonoid content.

Sweet pepper fruits are characterised by a relatively high content of pectic substances. The content of water-soluble pectin in fresh sweet pepper fruits of the Atlant and Sonechko varieties was 608.79 and 612.63 mg/100 g, respectively (**Table 10.7**). After freezing and 10 days of storage, the water-soluble pectin content increased by 80.9% in Atlant and 41.8% in Sonechko fruits. However, during further low-temperature storage, the content of water-soluble pectin decreased significantly. After 270 days, it was reduced to 295.70 ± 0.07 mg/100 g in Atlant and 290.56 ± 0.32 mg/100 g in Sonechko. Thus, by day 270 of storage, the water-soluble pectin content in Atlant and Sonechko fruits had decreased by 51.4% and 52.6%, respectively, compared to fresh samples.

**Table 10.7 Content of carotenoids, phenolic compounds, and pectic substances in sweet peppers during storage, mg/100 g**

| Sweet pepper variety | Storage period, days | Carotenoids | Content of phenolic compounds | | | | | Content of pectic substances | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Anthocyanins | Leucoanthocyanins | Catechins | Flavonols | Total flavonoid content | Water-soluble pectin | Protopectin | Total pectic substances |
| Atlant | Fresh | 22.5±0.50 | 1.06±0.15 | 52.20±0.29 | 56.00±0.25 | 32.00±0.48 | 141.26±0.23 | 608.79±0.15 | 367.60±0.07 | 976.39±0.11 |
| | 10 | 19.40±0.14 | 1.11±0.29 | 57.30±0.32 | 66.00±0.41 | 34.60±0.14 | 159.01±0.23 | 1101.1±0.19 | 371.60±0.12 | 1472.70±0.16 |
| | 90 | 19.11±0.08 | 1.76±0.17 | 99.70±0.41 | 96.20±0.32 | 60.40±0.35 | 258.06±0.25 | 483.74±0.26 | 738.80±0.27 | 1222.54±0.28 |
| | 180 | 18.83±0.14 | 1.65±0.15 | 99.70±0.09 | 131.2±0.25 | 83.42±0.45 | 315.97±0.31 | 347.50±0.10 | 732.50±0.25 | 1080.00±0.16 |
| | 270 | 18.63±0.26 | 1.53±0.08 | 100.80±0.12 | 136.8±0.14 | 95.80±0.14 | 334.93±0.16 | 295.70±0.07 | 673.25±0.06 | 968.95±0.06 |
| Sonechko | Fresh | 15.60±0.14 | 1.10±0.08 | 52.20±0.32 | 55.60±0.32 | 35.00±0.14 | 143.9±0.27 | 612.63±0.08 | 500.80±0.43 | 1113.43±0.26 |
| | 10 | 13.02±0.33 | 1.24±0.14 | 52.70±0.22 | 66.20±0.19 | 37.00±0.32 | 157.14±0.29 | 868.60±0.14 | 552.30±0.16 | 1420.90±0.15 |
| | 90 | 12.91±0.05 | 2.36±0.07 | 96.80±0.07 | 97.80±0.07 | 79.20±0.08 | 276.16±0.10 | 580.20±0.14 | 1120.00±0.04 | 1700.20±0.09 |
| | 180 | 12.84±0.10 | 2.34±0.04 | 103.27±0.19 | 131.2±0.53 | 89.40±0.24 | 326.21±0.33 | 350.20±0.12 | 1060.00±0.23 | 1410.20±0.18 |
| | 270 | 12.83±0.15 | 2.32±0.11 | 109.50±0.19 | 135.3±0.25 | 101.30±0.31 | 348.42±0.29 | 290.56±0.32 | 930.70±0.12 | 1221.26±0.21 |

The content of protopectin in fresh sweet pepper fruits varied significantly, being 367.60 ± 0.07 mg/100 g for the Atlant variety and 500.80 ± 0.43 mg/100 g for the Sonechko variety (**Table 10.7**). After freezing and low-temperature storage for 10 days, the protopectin content in the sweet pepper fruits increased, specifically by 1.1% in Atlant and by 10.3% in Sonechko fruits compared to fresh samples. During further storage for 90 days, the protopectin content continued to rise, reaching 738.80 ± 0.27 mg/100 g in Atlant and 1120.00 ± 0.04 mg/100 g in Sonechko. This represented an increase of 101.0–123.6% compared to the protopectin content in fresh peppers. However, after more than 90 days of storage, the protopectin content in the fruits began to decrease. Specifically, after 270 days of storage, the protopectin content in Atlant fruits decreased compared to the content after 90 days, but remained 83.1% higher than in fresh samples. A similar trend in protopectin content was observed in the Sonechko variety, where after 270 days of storage, the protopectin content was 85.8% higher compared to fresh fruits.

The total content of pectic substances in fresh sweet pepper samples was 976.39 ± 0.11 mg/100 g for the Atlant variety and 1113.43 ± 0.26 mg/100 g for the Sonechko variety (**Table 10.7**). Freezing the pepper samples and storing them under low-temperature conditions for 10 days resulted in an increase in pectic substances content by 50.8% for Atlant and 27.6% for Sonechko, compared to fresh samples. During further storage, the Atlant variety experienced a decrease in pectic ubstances content, which after 270 days amounted to 968.95 ± 0.06 mg/100 g, representing a 0.8% reduction compared to the fresh samples. In the case of the Sonechko variety, the pectic substances content initially increased to 1700.20 ± 0.09 mg/100 g after 90 days of storage, but then decreased to 1221.26 ± 0.21 mg/100 g after 270 days, still showing an increase of 9.7% compared to the fresh samples. The decrease in the amount of water-soluble pectin corresponds to the softening of the fruit pulp consistency, while the increase in protopectin content is associated with the acquisition of considerable rigidity in the peripheral cell layers, as cell walls consist of approximately 30% pectin substances. The sharp increase in pectin substances due to freezing is likely caused by the formation of uronic acids as a result of the oxidation of monosaccharides.

Thus, the quality attributes of sweet pepper – both chemical composition and sensory properties – undergo changes during storage, which are influenced by the variety, storage conditions, and duration. Similarly, D. Tsegay et al. [26] reported that the postharvest quality and shelf life of sweet pepper fruits were affected by variety, harvesting stage, and storage period. As noted by E. R. Bayogan et al. [23], the visual quality of pepper fruits was significantly influenced by both the variety and the storage conditions.

## 10.6 Conclusions

Low-temperature storage following freezing had a significant impact on the nutritional value and quality of sweet peppers. The content of colloidally bound water in the pepper fruits decreased from 23.6–26.7% to 9.2–9.4% after 270 days of storage, primarily as a result of the destructive effects of low temperatures during the freezing process. In contrast, the proportion of osmotically bound water increased from 66.3–69.0% to 83.3–83.5%. Meanwhile, the soluble solids content remained relatively stable throughout the 270-day storage period of the pepper fruits.

During low-temperature storage, the sugar content in peppers fluctuated, increasing and decreasing at different stages. In some pepper cultivars, after prolonged storage (270 days), the sugar content decreased by 0.9–6.5% compared to fresh fruits, while in others, it increased by 1.4–1.5%. Throughout the entire storage period, the vitamin C content in sweet pepper fruits gradually decreased, reaching a reduction of 24.1–33.4% by the end of the 270-day storage period. Similarly, the titratable acid content decreased in all pepper cultivars during storage. The fruits of the Sonechko variety showed the greatest reduction, at 33.3%, compared to the level prior to storage.

Prolonged storage at low temperatures also affected the carotenoid content of pepper fruits, which decreased gradually throughout the storage period. This resulted in a reduction of 17.2–17.8% compared to initial levels in fresh fruits. The most intensive decline was observed at the start of the storage period. Conversely, the level of phenolic compounds increased during storage. The anthocyanin content of different pepper varieties fluctuated throughout the storage period, initially increasing and then slowly decreasing towards the end of the 270-day period. Nevertheless, even at this final stage, the anthocyanin content remained 44.3–110.9% higher than that of fresh fruit. Throughout the entire low-temperature storage period, the levels of leucoanthocyanins, catechins, and flavonols in sweet pepper fruits increased by 93.1–109.8%, 143.3–144.3%, and 189.4–199.4%, respectively, by day 270 compared to their initial levels in fresh fruits.

Regarding the pectin fractions, the content of water-soluble pectin in pepper fruits increased initially by 41.8–80.9% during the first 10 days of storage, but subsequently decreased by over 51.4–52.6% by day 270. The protopectin content in sweet pepper increased by 101–123.6% after 90 days of storage, but then began to decline; however, by day 270 it remained 83.1–85.8% higher than in fresh fruit.

Evaluation of the sensory attributes of sweet pepper fruits during long-term storage showed that the Atlant and Sonechko varieties retained favourable sensory and nutritional qualities, demonstrating their suitability for prolonged frozen storage.

It was also established that the freezing method had a significant impact on the microstructure of pepper tissue. Cryogenic freezing (using liquid nitrogen or its vapour) resulted in the formation of small intracellular ice crystals, which better preserved tissue cohesion and reduced cell separation. Freezing in cryoprotective solutions, such as marinades, also showed promise in maintaining a microstructure comparable to that achieved by cryogenic methods, indicating that cryoprotectants may effectively mitigate freeze-induced damage.

Future research should focus on optimising freezing parameters and investigating the use of natural cryoprotectants to further enhance the preservation of sweet pepper quality and microstructure during long-term low-temperature storage.

**References**

1. Statistical Yearbook of Ukraine 2017: Statistical collection. (2018). State Statistics Service of Ukraine. Kyiv. Available at: https://www.ukrstat.gov.ua/druk/publicat/Arhiv_u/01/Arch_zor_zb.htm Last accessed: 23.04.2019
2. Yuan, Q., Jiang, Y., Yang, Q., Li, W., Gan, G., Cai, L. et al. (2024). Mechanisms and control measures of low temperature storage-induced chilling injury to solanaceous vegetables and fruits. Frontiers in Plant Science, 15. https://doi.org/10.3389/fpls.2024.1488666
3. Fruit and vegetables – your dietary essentials (The international year of fruits and vegetables) (2021). Rome: FAO, 82. https://doi.org/10.4060/cb2395en
4. Mi, S., Li, T., Shi, Q., Zhu, W., Wang, X. (2023). Cold shock precooling improves the firmness of chili pepper during postharvest storage and the molecular mechanisms related to pectin. Food Chemistry, 419, 136052. https://doi.org/10.1016/j.foodchem.2023.136052
5. Hossain, A., Akhtaruzzaman, Md., Mondal, Md. H. T., Islam, Md. R., Roy, J., Hasan, S. M. K., Sarker, Md. S. H. (2024). Development and performance evaluation of a refrigerated storage structure for preserving fresh fruits and vegetables. Discover Food, 4 (1). https://doi.org/10.1007/s44187-024-00156-x
6. Sustainable Food Cold Chains: Opportunities, Challenges and the Way Forward (2022). Nairobi, Rome: UNEP FAO, 122. https://doi.org/10.4060/cc0923en
7. Priss, O., Kalitka, V. (2014). Effect of hot treatment by antioxidants on the shelf life and quality of sweet pepper. Eastern-European Journal of Enterprise Technologies, 2 (12 (68)), 14–18. https://doi.org/10.15587/1729-4061.2014.23717
8. Barbosa de Lima, W. C. P., Nascimento, L. P. C., Lima Dantas, R., Lima Tresena, N., Silva Júnior, J. B. (2020). Heat Transfer in the Cooling, Freezing and Post-Freezing

of Liquid Food: Modeling and Simulation. Diffusion Foundations, 25, 37–53. https://doi.org/10.4028/www.scientific.net/df.25.37
9. Grover, Y., Negi, P. S. (2023). Recent developments in freezing of fruits and vegetables: Striving for controlled ice nucleation and crystallization with enhanced freezing rates. Journal of Food Science, 88 (12), 4799–4826. https://doi.org/10.1111/1750-3841.16810
10. van der Sman, R. G. M. (2020). Impact of Processing Factors on Quality of Frozen Vegetables and Fruits. Food Engineering Reviews, 12 (4), 399–420. https://doi.org/10.1007/s12393-020-09216-1
11. Simakhina, G., Kaminska, S. (2020). The state and the perspectives of development of the domestic market of frozen fruit and berry half products. Scientific Works of National University of Food Technologies, 26 (3), 234–242. https://doi.org/10.24263/2225-2924-2020-26-3-26
12. Simakhina, G. O., Kaminska, S. V. (2020). The market of frozen fruit and berry half products in Ukraine. Scientific Notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences, 2 (3), 67–71. https://doi.org/10.32838/tnu-2663-5941/2020.3-2/12
13. Bilichenko, O. S., Lotkina, T. Ye. (2020). Perspektyvy zastosuvannia tekhnolohii shokovoi zamorozky v plodoovochivnytstvi. Suchasni pidkhody do vyroshchuvannia, pererobky i zberihannia plodoovochevoi produktsii. Mykolaiv: MNAU, 131–133.
14. Efektyvni sposoby zberihannia pertsiu: yak zberehty ovochi svizhymy. Ahrarii razom. Available at: https://agrarii-razom.com.ua/article/efektivni-sposobi-zberigannya-percyu-yak-zberegti-ovochi-svijimi
15. Podpriatov, H. I., Tsvihovskyi, H. K., Tarhonia, V. S., Leshyshak, O. V., Drahniev, S. V. (2015). Sposoby ta tekhnichne zabezpechennia zberihannia plodoovochevoi produktsii. Kyiv: TsP "Komprynt", 199.
16. Afolabi, A. S., Choi, I.-L., Lee, J. H., Kwon, Y. B., Kang, H.-M. (2023). High-Relative-Humidity Storage Reduces the Chilling Injury Symptoms of Red Sweet Peppers in the Breaker Stage. Horticulturae, 9 (1), 116. https://doi.org/10.3390/horticulturae9010116
17. Kravchenko, V. A., Prylipka, O. V. (2009). Perets solodkyi. Baklazhan: selektsiia, nasinnytstvo, tekhnolohii. Kyiv: Zadruha, 160.
18. Koltunov, V., Kalaida, K. (2018). Nutritional and energy value of sweet pepper fruit depending on variety. Food Resources, 6 (10), 150–158. https://doi.org/10.31073/foodresources2018-10-17
19. Kalaida, K., Zabolotna, A., Pyrkalo, B. (2018). Economic and commodity assessment of varieties of sweet pepper, cultivated in Ukraine. Commodities and

Markets, 26 (2), 110–120. Available at: https://journals.knute.edu.ua/commodities-and-markets/article/view/1047

20. Grune, T., Lietz, G., Palou, A., Ross, A. C., Stahl, W., Tang, G. et al. (2010). $\beta$-Carotene Is an Important Vitamin A Source for Humans. The Journal of Nutrition, 140 (12), 2268S–2285S. https://doi.org/10.3945/jn.109.119024
21. Schudel, S., Prawiranto, K., Defraeye, T. (2021). Comparison of freezing and convective dehydrofreezing of vegetables for reducing cell damage. Journal of Food Engineering, 293, 110376. https://doi.org/10.1016/j.jfoodeng.2020.110376
22. Díaz-Pérez, M., Hernández-García, J. J., Carreño-Ortega, Á., Velázquez Martí, B. (2024). Post-Harvest Behavior of Seedless Conical and Mini-Conical Peppers: Weight Loss, Dry Matter Content, and Total Soluble Solids as Indicators of Quality and Commercial Shelf-Life. Foods, 13 (12), 1889. https://doi.org/10.3390/foods13121889
23. Bayogan, E. R., Salvilla, R., Majomot, A. M. C., Acosta, J. (2017). Shelf life of two sweet pepper (*Capsicum annuum*) cultivars stored at ambient and evaporative cooling conditions. South Western Journal of Horticulture, Biology and Environment, 8 (1), 1–15.
24. Kasampalis, D. S., Tsouvaltzis, P., Ntouros, K., Gertsis, A., Gitas, I., Moshou, D., Siomos, A. S. (2021). Nutritional composition changes in bell pepper as affected by the ripening stage of fruits at harvest or postharvest storage and assessed non-destructively. Journal of the Science of Food and Agriculture, 102 (1), 445–454. https://doi.org/10.1002/jsfa.11375
25. Rao, T. V. R., Gol, N. B., Shah, K. K. (2011). Effect of postharvest treatments and storage temperatures on the quality and shelf life of sweet pepper (Capsicum annum L.). Scientia Horticulturae, 132, 18–26. https://doi.org/10.1016/j.scienta.2011.09.032
26. Tsegay, D., Tesfaye, B., Mohammed, A., Yirga, H., Bayleyegn, A. (2013). Effects of harvesting stage and storage duration on postharvest quality and shelf life of sweet bell pepper (*Capsicum annuum L.*) varieties under passive refrigeration system. International Journal for Biotechnology and Molecular Biology Research, 4 (7), 98–104.