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IDENTIFICATION OF PATTERNS IN SUGAR BEET STORAGE CONDITIONS DEPENDING ON ENZYMATIC ACTIVITY

The object of the research is the storage conditions of sugar beets (Beta vulgaris). One of the most challenging areas is the reduction in sucrose content during storage under normal conditions prior to processing. The study focused on storing sugar beets in a refrigerated chamber to preserve the quality of the raw material, slow down respiration processes, minimize sugar loss, and extend shelf life. This allows for the use of sugar beets not only during the mass harvest but also over a long period, ensuring a uniform plant load and creating a reserve of environmentally friendly and technologically suitable raw materials for the stable operation of sugar production during the off-season.

The study utilized various methods of storing sugar beets in a refrigerated chamber, including storage at temperatures of +2 to +3°C and at a relative humidity of 85–95%. The study also employed the same storage conditions but with the use of sulfur dioxide. It was found that when stored in a refrigerated chamber with sulfur dioxide fumigation every ten days, sucrose content decreased by 2.6%. After 90 days, a decrease of 5.9% and 3.3%, respectively, was recorded, and on the last day of storage, i. e., after 120 days, a decrease of 7.2% and 3.9% was recorded. This is due to the fact that the use of sulfur dioxide inhibits the activity of oxidoreductases and hydrolases, which reduces the consumption of sucrose and other nutrients in the respiration process. This increases the shelf life of sugar beets and allows them to be used not only during the mass harvest but also over a long period, ensuring a uniform plant load. Under these conditions, the content of sucrose and other nutrients decreases slightly, and the yield of granulated sugar increases. Compared to similar known sugar beet storage methods, this method provides a supply of environmentally friendly and technologically suitable raw materials for the stable operation of sugar production during the off-season.

Keywords: *sugar beet, storage, sulfur dioxide, enzymes, oxidoreductases, hydrolases, quality indicators.*

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1. Introduction

The environmental friendliness of granulated sugar and other food products has a positive impact on human health. Environmentally unsafe, genetically modified products, in addition to negatively impacting human health, cause various forms of malignant diseases [1]. Therefore, specialists working in the food industry, including sugar production, must provide people with environmentally friendly products. It is crucial that refined sugar, which is part of the daily diet, is safe. Since the Republic of Azerbaijan has a temperate climate, it has very favorable conditions for growing sugar beets, which are of great economic importance and considered a valuable crop [2].

The problem of providing people with environmentally friendly foods, including sugar, remains relevant today. It is known that environmentally unsafe foods are a source of risk for various diseases [3]. Therefore, it is crucial to provide people with sugar using environmentally friendly, local raw materials, namely sugar beets. After all, more than 60% of the body's energy needs are met by sugars. According to researchers, the human diet should contain 4–5 times more sugar than protein. Metabolism, which is essential for life, is impossible without sugar, and even sugars are essential for better nourishment of brain cells. Sugar is also crucial for the development of thinking and intelligence [4].

The relevance of the study is confirmed by the creation of a year-round raw material base for sugar production by expanding and maintaining sugar beet crops and cultivation in the country. The optimal storage option for sugar beets at different temperatures for the production of granulated sugar is being determined.

It seems advisable to expand sugar beet crops and cultivation not only in the lowlands of the country but also in other regions. It is crucial to produce granulated sugar exclusively from locally grown sugar beets, which is crucial for human health and meeting the population's need for environmentally friendly sugar.

The storage of plant-based foods has attracted human attention since ancient times. It is known that plant-based foods contain organic and inorganic substances that are not found in animal products. The need for such products must be met throughout the year [4]. Otherwise, various unpleasant complications arise [5]. Furthermore, the products used for storage must also be environmentally friendly. From the literature and our research, it became clear that the long-term storage of environmentally unfriendly food products is quite complex. Therefore, it is advisable to use environmentally friendly products for long-term storage.

Short-term storage of plant products is achieved under normal conditions, while long-term storage requires artificial cold, freezing, UV radiation, and the addition of varying doses of sulfur and other antiseptics to the storage chamber.

It is known that controlled atmospheres have recently been used in cold storage chambers for storing plant products (grapes, apples, root vegetables, etc.). The main goal is to create an environment with high carbon dioxide content in the cold storage chamber. This principle is based on the fact that in an environment with a high carbon dioxide content, the activity of enzymes that accelerate the oxidation-reduction processes of pathogenic microorganisms is significantly slowed down or suppressed [6]. However, the use of a controlled atmosphere requires high equipment and operating costs, requiring a sealed storage facility with a system for monitoring and regulating the gas composition (O_2, CO_2, N_2), significant installation, maintenance, and energy costs for sugar content. Sugar beets are very sensitive to fluctuations in oxygen and carbon dioxide levels; the slightest violation of the regime can lead to accelerated rotting or loss of sugar; under anaerobic conditions with low oxygen levels, fermentation can begin, forming ethanol, methanol, and other undesirable products. Unlike fruits, beets cannot be stored for a long time even in a controlled atmosphere without weight loss, and the optimal shelf life is up to 3–4 months, after which losses increase.

This method significantly reduces natural and microbiological product losses, extends shelf life, and is more cost-effective than other storage methods. The main disadvantage of this method is the relative difficulty of regulating the gas mixture in the refrigeration chamber. Long-term storage of fruits and berries, including tubers, by freezing is also economically disadvantageous, as it requires extensive manual labor [7]. To ensure a long-term supply of raw materials to sugar factories in many countries, sugar beets are stored in piles (pits) under normal temperature conditions. This method also involves manual labor and natural and microbiological losses [8]. Furthermore, storing sugar beets in piles causes them to lose sugar and moisture. Sugar content losses can reach 5–10% or more, especially during long-term storage. High humidity and temperature fluctuations lead to rapid development of rot, mold, and bacterial spoilage. Particularly dangerous is the so-called phoma rot, which spreads quickly and affects large volumes. Cultivated sugar beets are vulnerable to freezing, thaws, precipitation, and strong winds. Without effective cover (straw, sheets, or film), beets suffer from temperature fluctuations. Insufficient air circulation within the cultivated sugar beets leads to steaming and spoilage. Packing the sugar beets too tightly creates anaerobic zones where undesirable microflora develops. Sugar beets can typically be stored in cultivated sugar beets for no more than 2–3 months without significant losses. Longer storage periods increase biochemical losses.

When storing sugar beets, it is important to consider their enzymatic system. Oxidative enzymes in sugar beets play a vital role in metabolism, respiration, and the storage and processing of sugar beets. They catalyze oxidation reactions of organic compounds, which affects both the physiological state of the plant and the technological properties of raw materials in sugar production. The main oxidative enzymes of sugar beet regulate the processes of respiration, aging, and beet resistance to adverse conditions. During storage, they can determine the degree of sugar loss, since active respiration and oxidative processes lead to the consumption of sucrose [9]. During beet processing, high activity of peroxidase and polyphenol oxidase is considered a negative factor, as it leads to darkening of the juice, an increase in the content of colored and difficult-to-remove impurities [10]. These enzymes are involved in oxidation reactions, especially under stress (low temperatures and damage), which leads to the oxidation of metabolites and a decrease in tissue resistance to spoilage. During storage of sugar beet, enzymatic processes play a significant role in the deterioration of its quality. The enzymatic system of the root crop remains active after harvesting and initiates a series of reactions leading to sugar loss and deterioration in commercial properties. It's important to highlight the deficiencies in sugar beet storage related to the enzymatic system, a natural process that leads to sugar loss, especially at elevated storage temperatures. Furthermore, mechanical damage activates enzymes, primarily hydrolases. Activation of invertase breaks down sucrose into glucose and fructose. These sugars are less stable and easily utilized by microflora, leading to accelerated decay. Damaged beets lose sugar 2–3 times faster than undamaged ones. Increased activity of hydrolases, including pectolytic enzymes, destroys cell walls, promoting tissue softening and the development of rot. Long-term storage and stressful conditions activate enzymatic pathways that convert sugars into organic acids, alcohols, and other byproducts. This not only reduces sugar content but also impairs the technological properties of beets during processing.

Thus, oxidative enzymes in sugar beet perform a dual role: on the one hand, they are necessary for normal metabolism and tissue protection [11]. On the other hand, their activity complicates the storage and processing of raw materials, reducing the yield and quality of sugar [12]. Activation of oxidative enzymes during storage of sugar beet leads to a number of adverse consequences that reduce its quality, sugar content, and technological value. These enzymes are activated especially intensively in the presence of tissue damage, stressful storage conditions, and violations of the temperature regime. These enzymes catalyze the oxidation reactions of phenolic compounds, lipids, and other substances, which leads to the destruction of cellular structures. When oxidative enzymes are activated, the surface and cut surfaces of the beet darken, which leads to an increase in the color of the diffusion juice and a deterioration in purification during processing. The activity of peroxidase and catalase is associated with the breakdown of peroxides and the protection of cells from oxidative stress. However, during long-term storage, their activity may become insufficient, especially under hypoxic or hypothermic conditions. Activation of oxidative enzymes leads to the accumulation of reactive oxygen species in cells, which damages membranes and accelerates beet spoilage. Oxidative enzymes, acting on phenolic and protein compounds, release metal ions (Fe^{2+}, Cu^{2+}), which activate other enzymatic and chemical reactions. This intensifies sucrose hydrolysis, increasing sugar loss during storage. Tissue damage and the formation of oxidation products reduce tissue resistance to infection and create a breeding ground for bacteria and fungi.

Hydrolase enzymes catalyze hydrolysis reactions – the breakdown of organic compounds involving water. In root crops, they participate in the conversion of carbohydrates, proteins, and other biopolymers, which is important both for plant life and for the technological processing of raw materials [13]. The main hydrolases of sugar beet are invertase and pectinesterase. Invertase (β-fructofuranosidase) catalyzes the hydrolysis of sucrose to glucose and fructose. During storage of root crops, invertase activity can lead to sucrose loss and the accumulation of reducing sugars, which reduces the technological quality of raw materials and the sugar yield at factories. Pectinesterase destroys the pectin substances of cell walls [14]. Their activity promotes tissue softening and increased permeability of cell membranes. During processing, increased pectinesterase activity contributes to an increase in the amount of colloidal impurities in the diffusion juice, complicating its purification. Invertase and pectinesterase activity are undesirable in sugar production, as they lead to sucrose loss and the accumulation of difficult-to-remove impurities [15]. The activation of pectolytic enzymes during sugar beet storage causes cell wall breakdown, which degrades the physical, microbiological, and technological qualities of the root crops. These enzymes are particularly active in the presence of tissue damage, high humidity, and elevated storage temperatures. Pectin enzymes break down the pectin substances that form the "cementing" substance of cell walls. As a result of the loss of tissue strength, the root crops soften. Destroyed tissues become an easy breeding ground for microorganisms, and bacterial rot develops particularly quickly, as pathogens themselves secrete pectinases, accelerating tissue breakdown. Softened tissues retain water less effectively and lose mass more quickly through respiration. The destruction of the cellular structure facilitates the access of oxygen and enzymes to sugar, enhancing its breakdown, which ultimately reduces sugar yield during processing. Destroyed cells release more colloids and impurities into the raw juice, which impairs filtration and increases the viscosity of the juice, making purification more difficult. Pectin breakdown products interact with other substances, increasing the color and turbidity of the raw juice.

Thus, sugar beet hydrolases are enzymes that are both essential for plant life and can negatively impact the sugar production process [16].

Therefore, when storing sugar beets, it is important to create conditions that inactivate or reduce the activity of both enzyme classes. For this purpose, the activity of oxidoreductase and hydrolase enzymes was studied during refrigerated storage of sugar beets at different temperatures.

Literary data has shown that when sugar beets are stored under normal conditions, in piles, nutrients are consumed by respiration. Heat increases enzymatic activity, intensifying the breakdown of nutrients. Freezing sugar beets and storing them in a storage facility cooled to temperatures close to freezing using mechanical ventilation degrades their quality [17].

Under the influence of cold, the cellular structure of the beets is destroyed, the beet juice drains, and when the beets are crushed into chips before being fed into the diffusion apparatus, a homogeneous mass is obtained. This ultimately leads to a decrease in sugar yield [18].

Cold storage of sugar beets is one of the most effective methods for preserving the high quality of the root crop, minimizing sugar loss, and extending shelf life. This method is based on slowing down physiological, enzymatic, and microbiological processes by reducing the temperature. At low temperatures, cellular respiration rates decrease sharply, resulting in reduced sucrose consumption, reduced mass and energy loss, and slowed tissue aging. Cold inhibits the activity of hydrolytic and oxidative enzymes, allowing beets to retain their structural integrity, color, flavor, and processing properties longer. Most putrefactive and pathogenic bacteria, as well as mold, do not develop or develop very slowly at low temperatures. Under optimal temperature and humidity conditions (90–95%), root vegetables lose less moisture; beets remain firm, do not wilt, and do not lose weight.

There are certain limitations to refrigerated storage of sugar beets that must be considered. Firstly, at temperatures below 0°C, root vegetables freeze, lose turgor, and increase the secretion of cell sap, increasing the risk of microbiological contamination. At higher temperatures, respiration intensifies, leading to increased sugar loss. At low humidity, beets quickly wilt, losing weight, and losing sugar content. Excessive humidity and condensation on the surface of root crops increase the risk of rot. When stored in sealed refrigeration chambers, CO_2 accumulation negatively impacts respiration and biochemical processes. Excessive carbon dioxide concentrations and a lack of oxygen lead to anaerobic processes and the formation of undesirable metabolites. Mold and bacteria develop rapidly under high humidity conditions. Damaged or diseased root crops can contaminate healthy ones during storage.

The aim of this research was to select the optimal storage conditions for sugar beets in a refrigeration chamber to preserve the quality of the raw material and slow down respiration processes. To achieve this objective, the following tasks must be completed:

1. To study the activity of oxidoreductase and hydrolase enzymes under different storage conditions for sugar beets.
2. To study the quality indicators of sugar beets under different storage conditions.
3. To study the quantitative change in sucrose during daily storage of sugar beets.
4. To calculate the amount of natural loss during storage of sugar beets using the three storage options.
5. To calculate the sulfite acid content of sugar beets using the third storage option.

2. Materials and Methods

2.1. Research Materials

The object of this research is the storage conditions of sugar beets using different methods for sugar production. Sugar beet (*Beta vulgaris L.*) was used as the research material. Sugar beet has a large, fruitful root, weighing 0.5–3.0 kg, and in some cases up to 4.0 kg. The root is white and conical in shape. Sugar beet is structurally divided into four parts. The head of the root contains the leaf buds, while the neck portion lacks leaf buds. The main root contains fringed areas in furrows on the sides, and the stem, located in the lower quarter of the root [17]. The main root system of the beet extends through the stem into the deep soil layers. The growing season of mature sugar beets is 180 days [19]. During this time, the cellular structure of the sugar beet is fully formed. Its nutrient content, primarily sucrose, is at its highest [20]. Prior to storage, sugar beets were placed in 10 kg wooden crates.

2.2. Research Methods

Storage of locally grown sugar beets for sugar production was conducted in three temperature-controlled configurations:

– In the first configuration, sugar beets delivered to the plant were stored under normal conditions at 18–22°C for ten days before processing. In the second configuration, sugar beets were stored in a refrigerated chamber for an extended period at a temperature of +2...+3°C and an air humidity of 85–95% for four months. In the third configuration, sugar beets were stored in a refrigerated chamber for an extended period, fumigated with sulfur dioxide at a rate of 1.0–1.5 g of sulfur per 1 m^3 of area, as in the second configuration. In the first sugar beet storage variant, enzyme activity was analyzed on the first, third, fifth, eighth, and tenth days.

– In the second and third variants, changes in the activity of certain enzymes contained in sugar beets were studied once a month for four months.

The activity of the enzymes listed below was studied during sugar beet storage at different temperatures.

Enzyme activity was determined using a method described in the literature [21].

Pectinesterase activity was determined potentiometrically.

The following qualitative parameters of sugar beets were analyzed:

– Vitamin C – using the dichlorophenolindophenol reagent [21];
– Sulfuric acid – using the iodometric method [21];
– Cellulose – using the Küschner and Hanak method as modified by Kogan [22];
– Sucrose on a ProStar-MS-500 high-liquid chromatograph, Varian, USA.

3. Results and Discussion

This research study examines the activity of certain enzymes of the oxidoreductase and hydrolase classes and determines the optimal storage option for sugar beets. The main theoretical issue is that during short-term processing and long-term storage of sugar beets, it is necessary to regulate the activity of enzymes that accelerate metabolic processes (anabolism and catabolism) and nutrient breakdown.

Various storage methods were used to regulate enzyme activity. Changes in enzyme activity during short-term and long-term storage of sugar beets at different temperatures prior to processing are presented in Table 1.

Table 1

Changes in sugar beet enzyme activity during storage, %

Enzymes	Storage under normal conditions	Long-term refrigerated storage (without sulfur dioxide fumigation)	Long-term refrigerated storage (with sulfur dioxide fumigation)
ascorbate oxidase	+17.3	–23.1	–40.4
o-diphenol oxidase	+21.9	–20.3	–40.2
peroxidase	+25.3	–17.0	–38.3
catalase	+18.7	–28.1	–43.7
invertase	+38.9	+6.0	–39.7
pectinesterase	+22.7	+5.2	–43.8

As can be seen from Table 1, during short-term storage of sugar beets under normal conditions before processing, the activity of all the studied enzymes steadily increased from 17.3% to 25.3%. In this case, the increased activity of enzymes, namely oxidoreductases and hydrolases, creates conditions for accelerating the respiratory process. Studies conducted during long-term storage of sugar beets in a refrigerated chamber without fumigation with sulfur dioxide showed that oxidoreductase activity decreased (17.0% to 28.1%), while hydrolase activity increased (5.2% to 6.0%).

The data in Table 1 indicate that during long-term refrigerated storage of sugar beets without fumigation (SO_2 combustion) with sulfur dioxide, a gradual decrease in oxidoreductase activity leads to a weakening of metabolic processes, while an increase in hydrolase activity leads to the breakdown of sucrose and pectin.

This suggests that some of the nutrients contained in sugar beets are utilized in small quantities, while others are utilized in relatively large quantities for the respiratory process.

Table 1 shows that during long-term refrigerated storage of sugar beets without sulfur dioxide fumigation, the activity of the studied oxidoreductases and hydrolases steadily decreased – from 38.3% to 43.8%. While ascorbate oxidase activity increased by 17.3% during short-term storage, by 23.1% in the second case, and by contrast, by 40.4% in the third case. These values can also be attributed to the other oxidoreductases studied. The dynamics of oxidoreductase activity during sugar beet storage, depending on various temperature conditions, are shown in Fig. 1.

Fig. 1 shows that oxidoreductase activity increased during short-term storage of sugar beets, while it decreased in other conditions. A more pronounced decrease in enzyme activity was recorded during long-term storage of sugar beets in a refrigerated chamber with fumigation with sulfur dioxide.

The data in Table 1 show that when sugar beets were stored under normal conditions for ten days before processing, invertase enzyme activity increased by 38.9%, by 6.0% in the second condition, and by 39.7% in the third condition. Pectinesterase enzyme activity increased by 22.7% in the first condition, by 5.2% in the second condition, and decreased by 43.8% in the third condition. Changes in the activity of hydrolase enzymes during storage of sugar beet at different temperature conditions are shown in Fig. 2.

The data in Table 1, Fig. 1, 2 show that the greatest decrease in enzyme activity was observed in the third variant.

Quantitative changes in the quality indicators of sugar beets were studied during storage. Quantitative changes in some quality indicators during storage are presented in Table 2.

Table 2 shows that a quantitative decrease in the analyzed quality indicators was observed in all variants. While the total pectin content of sugar beets decreased by 25% during ten-day storage before processing, in the second variant this indicator decreased by 18.8%, and in the third variant, i. e., during long-term storage of sugar beets in a refrigerated chamber fumigated with sulfur dioxide, a decrease of 12.5% was observed.

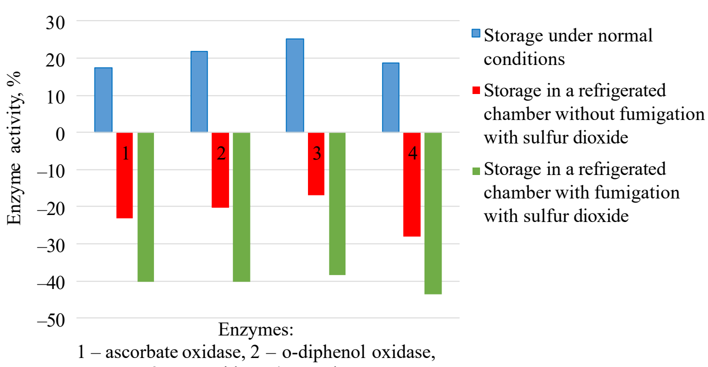

Fig. 1. Changes in oxidoreductase enzyme activity during sugar beet storage

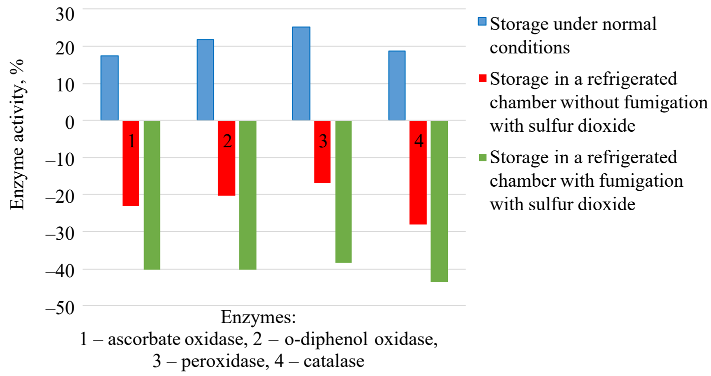

Fig. 2. Changes in sugar beet hydrolase enzyme activity during storage

Table 2

Changes in quality indicators of sugar beets during storage, %

Indicators	Short-term storage under normal conditions	Long-term storage in a refrigerated chamber without fumigation with sulfur dioxide	Long-term storage in a refrigerated chamber with fumigation with sulfur dioxide
Pectic substances	25.0	18.8	12.5
Pectin	22.0	22.2	22.2
Protopectin	28.5	28.6	14.3
Cellulose	16.7	16.7	8.3
Sucrose	9.2	7.2	3.9
Vitamin C	66.6	58.3	41.6

The vitamin C content, considered one of the key quality indicators of sugar beets, decreased by 66.6% in the first variant, by 58.3% in the second, and by 41.6% in the third. The significant decrease in vitamin C in sugar beets during storage is due to increased activity of the enzyme ascorbate oxidase. Table 2 shows that the smallest decrease in vitamin C or its consumption for respiration occurs during long-term storage of sugar beets in a refrigerated chamber with sulfur dioxide fumigation.

The data in Table 2 show that the content of sucrose, the main quality indicator of sugar beets, decreased by 9.2% in the first variant, i. e., during storage under normal conditions before processing, in the second variant by 7.2%, and in the third variant by 3.9%. As can be seen, when storing sugar beets in a refrigerated chamber with sulfur dioxide fumigation every ten days, sucrose consumption for respiration was approximately 2.0–2.5 times lower than in the other variants. The daily changes in sucrose content are presented in Table 3 and Fig. 3.

Table 3 shows that a 2.0% decrease was observed on the third day of sugar beet storage under normal conditions at a temperature of 18–22°C before processing. On the fifth day, this indicator decreased by 3.9%, on the eighth day – by 7.9%, and on the tenth day – by 9.2%. Sucrose losses were also determined during long-term storage of sugar beet in a refrigerated chamber at a temperature of +2...+3°C. Analysis of the conducted study revealed that the lowest sucrose losses were recorded in the variant of long-term storage of sugar beet in a refrigerated chamber with fumigation with sulfur dioxide. When storing sugar beets in a refrigerated chamber for 30 days without fumigation with sulfur dioxide, the amount of sucrose decreased by 2.6%, whereas when stored in a refrigerated chamber with fumigation with sulfur dioxide every ten days, this indicator decreased by 1.3%. When storing sugar beets in a refrigerated chamber for 60 days, a decrease in sucrose content of 4.6% was recorded. When storing in a refrigerated chamber with fumigation with sulfur dioxide every ten days, sucrose decreased by 2.6%. After 90 days, a decrease

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of 5.9 and 3.3%, respectively, was recorded, and on the last day of storage, i. e. after 120 days, a decrease of 7.2 and 3.9%.

Table 3

Quantitative changes in sucrose during sugar beet storage by day, %

Days	Short-term storage under normal conditions	Long-term storage in a refrigerated chamber without fumigation with sulfur dioxide	Long-term storage in a refrigerated chamber with fumigation with sulfur dioxide
3	2.0	–	–
5	3.9	–	–
8	7.9	–	–
10	9.2	–	–
30	–	2.6	1.3
60	–	4.6	2.6
90	–	5.9	3.3
120	–	7.2	3.9

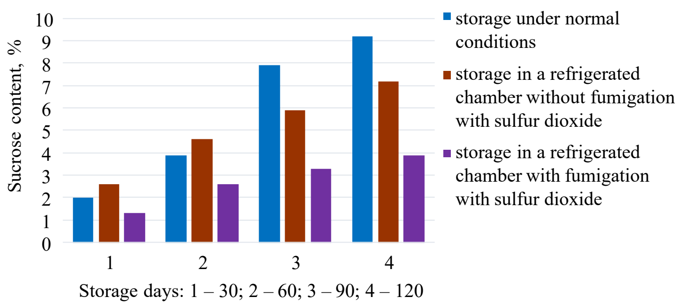

Fig. 3. Quantitative change in sucrose during storage, %

Fig. 3 clearly shows the sucrose content during storage for different storage conditions. The data presented in the figure shows that the lowest sucrose loss during long-term storage of sugar beets was observed in the third condition.

The study also determined the natural losses of sugar beets during storage. The results are presented in Table 4. As can be seen from the data in Table 4, the lowest natural loss was recorded during long-term storage of sugar beets in a refrigerated chamber fumigated with sulfur dioxide. Thus, while in the first condition, natural losses before processing amounted to 5.7%, in the second condition, this figure was 6.1%, and in the third, 4.1%.

Table 4

Natural loss during sugar beet storage, %

Variants	Before storage, kg	After storage, kg	Difference	In %
Short-term storage under normal conditions	101.2	94.6	5.6	5.7
Long-term storage in a refrigerated chamber without fumigation with sulfur dioxide	101.5	95.3	6.2	6.1
Long-term storage in a refrigerated chamber with fumigation with sulfur dioxide	101.7	97.5	4.2	4.1

The research results showed that long-term storage of sugar beets in a refrigerated chamber with sulfur dioxide fumigation for four months or more can create a high-quality raw material base for year-round plant operation.

Thus, the data presented in Table 4 show that when storing sugar beets under normal conditions at a temperature of 18–22°C for ten days before processing, sugar losses of 9.2% were observed. With long-term storage in a refrigerated chamber without sulfur dioxide fumigation, the loss was 7.2%, and with storage in a refrigerated chamber with sulfur dioxide fumigation, the loss was 3.9%. Sugar content and natural losses were low in the third variant. The main reason for the preservation of sucrose and reduced natural loss is the reduced activity of enzymes that accelerate oxidation-reduction processes in sugar beets during refrigeration with sulfur dioxide fumigation every ten days.

Therefore, let's believe it is advisable to store sugar beets at low temperatures to prevent the acceleration of oxidation-reduction processes. When storing sugar beets before processing, a technological regime should be chosen that slows the metabolic processes occurring within them, or more precisely, weakens or stops the activity of enzymes belonging to the class of oxidoreductases and hydrolases.

Analyzing the study results, it can be concluded that during long-term refrigeration of sugar beets with sulfur dioxide fumigation every ten days, the reduced activity of the enzymes studied, caused by exposure to sulfur dioxide, hinders the consumption of nutrients contained in the beets for the respiratory process. Due to the sulfur combustion treatment of beets in a refrigeration chamber, the free and total sulfite acid content of the root crops was determined until the end of the storage period (Table 5).

Table 5 shows that long-term storage of sugar beets in a refrigerated chamber with sulfur dioxide fumigation increases the content of free and total sulfite acid. While free sulfite acid in the root crops was 0.28 mg/100 cm^3 before storage, by the end of storage it had increased by 21.5% to 0.34 mg/100 cm^3. These data coincided with the total sulfite acid value.

It should be noted that the obtained values are significantly lower than the maximum permissible limits established by health authorities for food products containing sulfur [23]. The study results showed that sulfur combustion in the chamber, thanks to its antioxidant and antimicrobial properties, prevents oxidation processes and the development of microbiological diseases.

The results of the conducted research indicate that the most efficient method for processing sugar beets, both immediately after harvesting and after extended refrigeration storage, is sulfur combustion. This method enables a long-term supply of environmentally friendly raw materials to the sugar refinery and also offers significant cost-effectiveness.

Table 5

Change in sulfite acid content in sugar beets, %

Sulfic acid (mg/100 cm^3)	Before storage	After storage	Difference	%
Free	0.28	0.34	+0.6	21.5
Total	0.52	0.70	+0.18	34.6

The practical importance of storing sugar beets lies in preserving raw materials for the sugar industry, ensuring year-round operation of sugar refineries, as harvest processing lasts longer than the harvest period. Maintaining a stable supply of raw materials allows for uniform loading of production capacity and reduces seasonal losses. Proper storage reduces respiratory losses and promotes the preservation of sucrose in the roots. This reduces the risk of microbiological and enzymatic degradation of sugar. Losses from weight and quality losses in the roots are reduced, and high sugar content is maintained, increasing the yield of finished products. Maintaining a stable supply of raw materials contributes to sustainable sugar production. Timely and proper storage prevents the accumulation of undesirable substances (organic acids, decomposition products), which impair the technological properties and quality of sugar.

Storing sugar beets in a refrigerated chamber with sulfur dioxide fumigation entails additional restrictions related to both the physiology of the beets and sanitary standards. Excessive SO_2 exposure can lead to the accumulation of free and bound sulfurous acid in beet tissue.

This leads to changes in the biochemical composition, specifically a decrease in sugar content due to their interaction with sulfurous acid. Prolonged exposure to sulfur dioxide disrupts normal respiration of beet tissue. Damage to the cellular structure is possible, accelerating aging and decomposition. SO_2 inhibits the growth of mold and bacteria, but its effectiveness is limited: at low concentrations, protection is insufficient, while at high concentrations, toxicity to the product itself occurs. Even with the use of SO_2, beets cannot be stored for too long: it is possible to extend the period by several weeks, but it is impossible to completely prevent sugar loss.

Thus, the research results showed that sulfur dioxide gas inhibits enzymes that catalyze oxidation-reduction processes. Compared to other options, the greater reduction in enzyme activity in the third option resulted in a smaller quantitative change in sugar beet quality parameters. Storing sugar beets in a refrigerated chamber with sulfur dioxide fumigation for four months or more will create a high-quality raw material base for the long-term operation of a sugar mill. When storing sugar beets for long periods before processing, the sugar beets arriving at the mill should be processed promptly to prevent loss of sugar and other nutrients.

Storing sugar beets in a refrigerated chamber with sulfur dioxide fumigation before processing significantly reduces sugar loss. To ensure the production of high-quality, environmentally friendly sugar, a sugar mill can operate year-round by producing raw sugar from sugar beets with a dry matter content of 65–70%. Ensuring the long-term operation of a sugar mill can improve the social status of workers, create new jobs, and foster the continued growth of the country's economy.

Promising approaches to refrigerated sugar beet storage include optimizing temperature and humidity conditions, precisely controlling the microclimate using automated systems, and maintaining a constant temperature, which will reduce shrinkage and minimize microbial growth and enzymatic activity. The development and use of natural antifungal and antibacterial agents derived from beneficial bacteria and fungi, as well as plant extracts with antiseptic properties, will enable environmentally friendly and safe microbial suppression without the use of chemical preservatives. Current and future developments in refrigerated sugar beet storage are aimed at comprehensively optimizing conditions, implementing biotechnology and computer technologies, and reducing losses while maintaining environmental friendliness and economic efficiency.

4. Conclusions

1. The study results revealed that during short-term storage of sugar beets under normal conditions before processing, the activity of all the studied enzymes steadily increased, fluctuating between 17.3% and 25.3%. During long-term refrigerated storage of sugar beets without sulfur dioxide fumigation, the activity of the studied oxidoreductases and hydrolases steadily decreased, ranging from 38.3% to 43.8%.

2. Studies conducted during long-term storage of sugar beets in a refrigerated chamber without sulfur dioxide fumigation showed that oxidoreductase activity decreased by 17.0% to 28.1%, while hydrolase activity increased by 5.2% to 6.0%. During long-term refrigerated storage of sugar beets without fumigation (SO_2 combustion) with sulfur dioxide, a gradual decrease in oxidoreductase activity leads to a weakening of metabolic processes, while an increase in hydrolase enzyme activity leads to the breakdown of sucrose and pectin. This suggests that some of the nutritional components of sugar beets are utilized in small quantities, while others are utilized in relatively large quantities for the respiratory process. The greatest decrease in enzyme activity was observed in the third variant.

3. The results of sugar beet storage under different variants revealed that changes in the quantitative ratio of its quality indicators are also associated with enzyme activity. Vitamin C content, considered one of the main indicators of sugar beet quality, decreased by 66.6% in the first variant, by 58.3% in the second, and by 41.6% in the third. A significant decrease in vitamin C in sugar beets during storage is due to increased activity of the enzyme ascorbate oxidase. The content of sucrose, the main quality indicator of sugar beets, decreased by 9.2% in the first variant, i. e., during storage under normal conditions before processing, in the second variant by 7.2%, and in the third variant by 3.9%. When storing sugar beets in a refrigerated chamber with sulfur dioxide fumigation every ten days, the sucrose consumption for respiration was approximately 2.0–2.5 times lower than in other variants.

4. The results of determining the natural losses of sugar beets during storage showed that the lowest natural loss was recorded during long-term storage in a refrigerated chamber with sulfur dioxide fumigation. Thus, while natural losses before processing in the first variant amounted to 5.7%, in the second variant this figure was 6.1%, and in the third – 4.1%.

5. Due to the beet treatment with sulfur combustion in a refrigeration chamber, the content of free and total sulfite acid in the roots was determined until the end of the storage period. Studies have shown that with long-term storage of sugar beets in a refrigeration chamber with fumigation with sulfur dioxide, the content of free and total sulfite acid increases. Before storage, free sulfite acid in the roots was 0.28 mg/100 cm^3, and by the end of storage, it increased by 21.5%, reaching 0.34 mg/100 cm^3. These data coincided with the total sulfite acid value. The obtained values were significantly lower than the maximum permissible levels established by health authorities for food products containing sulfur. The study results showed that sulfur combustion in the chamber, thanks to its antioxidant and antimicrobial properties, prevents oxidation processes and the development of microbiological diseases.

Conflict of interests

The authors declare no conflicts of interest, whether financial, personal, proprietary, or otherwise, that could influence this research and the results presented in this article.

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The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of this work.

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