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Evaluating and Optimizing Energy-Efficient Microclimate Control Systems in Vegetable Storage Facilities

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ABSTRACT

The significance of this research stems from the limited attention given to the automation of fruit storage infrastructure and equipment modernization in earlier studies. This investigation delves into diverse storage options, the benefits of automated systems, and the influence of air's physical properties on the structure of fruits and vegetables. The primary objective of this article is to examine the impact of key microclimate system parameters on the physical and chemical properties of plant products and to explore strategies for enhancing energy efficiency in vegetable storage facilities. The authors employed analytical and comparative methods to evaluate storage environment parameters, fruit and vegetable preservation techniques, and suitable equipment, as well as the synthesis of existing technologies in fruit product storage. Factors such as temperature regime, humidity level, air composition, and circulation within the storage facility affect product quality. The implementation of automated control systems and alternative energy sources is recommended to ensure energy supply, simplify the storage process, reduce the risk of product damage, and minimize human error. Fundamental principles of microclimate regulation to maximize fruit suitability were examined, the advantages and disadvantages of storage methods were compared, and a series of solutions for modernizing vegetable storage facilities in the southern regions of the Republic of Kazakhstan were presented. This study holds practical value in the design and modernization of vegetable storage facilities.

1. INTRODUCTION

Food security is of paramount importance to the well-being of individuals, communities, and nations, as it pertains to the ability to access sufficient, safe, and nutritious food to meet dietary needs and preferences for an active and healthy life. The COVID-19 pandemic in 2020 led to a global food crisis, disrupting supply chains and increasing the demand for quality storage of fruit products. Ensuring year-round access to nutrient-rich plant products is crucial for public health, necessitating the development of advanced vegetable storage facilities capable of preserving product quality over extended periods.

Recent statistics indicate that the Republic of Kazakhstan has seen growth in its agricultural sector, with the gross yield of vegetable products increasing from 954.9 thousand tons in 1991 to 3800 thousand tons in 2020 [1]. Favorable natural and climatic conditions in the southern regions of Kazakhstan have promoted the development of vegetable cultivation. However, a lack of modern vegetable storage facilities has negatively impacted the agro-industrial complex of the republic [2, 3]. Inadequate equipment heightens the risk of desiccation, structural damage, and disease in fruits, while energy-intensive storage facilities necessitate the implementation of energy-saving technologies during the design phase.

A review of recent literature reveals that various strategies have been proposed to enhance the efficiency of vegetable storage facilities and product preservation. Akimbekova et al. [4] evaluated the agricultural development process in Zhambyl Region, Republic of Kazakhstan, highlighting the need for increased state financing and promotion of energy-saving technologies. Azatbek et al. [5] assessed the storage infrastructure for fruit and vegetable products and found that most facilities were in poor condition, with only 20% meeting global standards. This study emphasizes the need for energy-saving technologies to improve the economic efficiency of storage facilities.

International research has also explored innovative approaches to preserving fruit and vegetable products. Huang et al. [6] suggested using hydrogen sulfide to regulate physiological processes and decrease fruit structure deterioration during storage. Jiang et al. [7] recommended ultrasonic processing as a means of slowing the aging process and maintaining the physico-chemical properties of fruits and vegetables. Zhang et al. [8] investigated the impact of electrolyzed water on preservation capabilities, determining that this method disinfects products, prevents fungal infections, and extends shelf life.

While these studies offer valuable insights into preserving the physico-chemical properties of fruits and vegetables, they largely overlook the automation of storage infrastructure and equipment modernization. Most Kazakh research on this topic focuses on the economic aspects without proposing technical solutions [9, 10]. This study aims to provide a more comprehensive understanding of how the physical properties of air affect fruit and vegetable structure, as well as explore the advantages of storage methods and automated systems.

The primary objective of this research is to analyze the main parameters of microclimate control in vegetable storage facilities and to identify the current state of technologies that can enhance energy efficiency. To achieve this, the study will: (1) examine how microclimate parameters affect product properties, (2) determine the most effective technologies that meet storage requirements, and (3) provide recommendations for the modernization of vegetable storage facilities in the southern regions of Kazakhstan.

It has been concluded that factors such as temperature regime, humidity level, air composition, and air circulation within the storage facility influence product quality. The implementation of automated control systems and alternative energy sources is recommended to ensure energy supply, streamline storage processes, reduce the risk of product damage, and minimize human error. This research explores the fundamental principles of microclimate regulation for maximizing fruit compatibility, compares the advantages and disadvantages of various storage methods, and presents a series of solutions for modernizing vegetable storage facilities in the southern regions of the Republic of Kazakhstan.

2. MATERIALS AND METHODS

The methodology approach of this article is based on methods of analysis and comparison of major microclimate parameters of vegetable storage facility, technological equipment as well as types of vegetable and fruit product storage to increase energy saving as well as synthesis of the most appropriate and rational ways of storage design in southern regions of Kazakhstan. Using analysis of main requirements to preservation of various fruit and vegetable products, the authors determined how the vegetable storage system is capable to preserve nutritive value and structure of the fruits, making them more stable against external effects. The comparison of plant product storage approaches and microclimate management systems helps to define the most effective variants. The synthesis of obtained data suggested optimal management and design solutions for vegetable storage facilities with introduction of automated system in South Kazakhstan region. The research took place in five stages.

The first stage necessitated control over energy consumption when storing fruit and vegetable products. The authors named the main microclimate parameters of the vegetable storage facilities. The researchers described processes arising in fruits in case of changing temperature, relative humidity, air structure and its circulation. The authors determined what vegetable cultures should be stored under increased humidity and how to manage environmental parameters for fruit products of different degree of ripening, with examples provided. The researchers studied oxygen and carbon dioxide effect on biological processes inside products depending on their percentage and made suggestions for the need of adjusting ethylene level and product nitrogen processing.

The second stage described advantages of automated management system of the vegetable storage facility. The authors proved necessity of regular air conditioning of the storehouse and revealed some specifics of this process. The researchers provided proofs of small efficiency of air conditioning system and standard refrigerator units. They described elements of automated system of the vegetable storage facility and its function.

Third stage involved automated storage methods in bulk or in containers. There is a description of devices applicable in each management system. The authors named the elements enabling air circulation and temperature and relative humidity change. The researchers described air passage process within system contour. They presented existing methods of container storage for fruit and vegetable products. This list includes both classical and modernized versions with use of automatics. This stage involves study of energy saving refrigerator units. The authors observed an example of refrigerator design with functioning based on vortex tube. They presented the description of physical processes occurring under this construction. The researchers analysed their pros and cons.

The fourth step covered specifics of agricultural complex of South Kazakhstan with recommendations to optimize energy saving fruit and vegetable storage facilities. It involved promoting advantages of alternative energy sources for supply of refrigerator chambers. It included the example of automated management system in some agricultural companies of Kazakhstan. There was a justification made of using modern technologies in fruit and vegetable product storage industry.

The final stage demonstrated comparison of obtained results with recent international articles. The authors made conclusions about specifics of the fruit product storage in South Kazakhstan and outlined the ways for further research.

3. RESULTS

The control over the consumption of electricity and water resources in vegetable storage facilities is extremely important, as it requires a considerable amount of energy resources for generation and maintenance of optimal temperature and humidity. The researchers should consider temperature mode, humidity and gas balance in the air to formulate specific microclimate in vegetable storage facilities. Air conditioning systems, artificial cooling and moisturising systems, technological heating systems as well as drying and gas medium regulation systems provide required parameters.

An important principle of fruit and vegetable storage process is maintaining certain temperature level. The temperature increase boosts intensity of internal reactions in the fruit and temperature decrease leads to slowing down of biological processes. In order to ensure long-term preservation of product condition, there is a requirement to lower metabolism in the fruits without affecting physiological properties. The temperature mode directly influences relative air humidity. The fruits generate moisture and heat and evaporation rate depends on difference in water vapour saturation rate in the environment of fruit and vegetable storage facilities. Certain types of plant products require high value of this parameter, more than 95%, however the most fruits fall within 90-95% range. The ripening degree also contribute to this. For example, potato storage requires 90-95% RH (relative humidity) level. The early varieties after collection store at 21°C within 4-5 days, followed by decrease to 10°C. The young potato culture can be stored around 2 months under this condition. The late varieties should store at relative humidity of 95% within the range of 10-16°C from 10 to 14 days, followed by decrease to 4-7°C, variety dependent. These conditions contribute to suberization process, in other words, to restoration of original peel resistance capacity. The lack of high long-term humidity increases vaporisation of product moist, which reduces water content in vegetables, leading to degradation of taste and decrease of nutritive substances. This is the reason for artificial air moisturizing in vegetable storage premises. On other hand, the excessive humidity breaks exchange processes, destroys fruit structure and decreases resistance to external effects. When building microclimate parameters, the researchers should consider fruit variety specifics, as water evaporation rate from fruits depends on peel tissue structure. Therefore, it can be established relative humidity within the range of 80-90% for pumpkin and melon. However, tomato, carrot and onion require higher value [11].

It is important to calculate oxygen rate, carbon dioxide rate and ethylene rate in vegetable storage facilities. Lowering oxygen in the premise environment leads to decrease of ethylene production in fruits, reduction of oxygenation, degradation of soluble pectin substances and chlorophyll. Therefore, it can be extended fruit storage term, slow down ripening process and odour formation and prevent product diseases. Increase of carbon dioxide gas rate slows down ripening, enzymatic rate and spread of infections as well as destruction of chlorophyll. Small ethylene content in vegetable storage facility leads to accelerating fruit ripening rate. There are various combinations of gas content in vegetable storage facility environment. The classic method requires oxygen rate not more than 12% and carbon dioxide rate should fall within the range of 5-7%. During lowered oxygen rate, these parameters are 5% and 7% accordingly. The most frequent technology nowadays is the one using ultra-low oxygen rate, where gas percentage is less than 2% and 1.5% accordingly. The method involves reduction of oxygen and carbon dioxide rates to parameters required, adjustment of ethylene level and follow-up nitrogen filling [12].

To ensure long-term preservation of ripened products, a regular ventilation is required to remove heat and ethylene emitted from fruits. It requires proper air conditioning, drying and cooling of the storage premise. The natural ventilation system does not provide necessary air circulation and applicable only for small vegetable storage facilities when standard refrigerator chambers do not provide proper cooling. It is important to meet the air conditioning specifics for products. The ventilation system should be running at full power 24 hours a day since deposit of vegetables. This stage can last from one to three days. During the treatment period, which can last up to thirty days, the frequency of activation of the fans shows decrease with reduction of load on the system. During the cooling period, it is necessary to reduce the temperature in the vegetable storage facility to ambient levels. Determining the exact values requires calculation for each type of product. There is the need in airtight refrigeration units, devices for nitrogen generation and carbon dioxide absorption as well as automated microclimate control system in vegetable storage. This type of system contains temperature and humidity sensors, controllers and various actuators. The required parameters can be set manually or using special microclimate control programs. The advantages of automated control are to increase the storage period of products and to reduce the risk of infection and rotting of vegetables. In addition, this system is energy efficient: it is able to maintain the required values of temperature and humidity, provide quality air ventilation, control the level of carbon dioxide and condensate, and monitor parameters in vegetable storage facilities with efficient consumption of energy resources [13]. The sensors read the data. Devices for measuring temperature and humidity are set inside the bulk and at ceiling level as well as inside the pressure channel through which the air enters the vegetable storehouse. The carbon dioxide level meter is set in the exhaust airflow [14].

The fruits are stored in bulk or in containers. The first type is mainly applicable for storing potatoes, onions and beets. Creating the desired microclimate requires air treatment equipment, placed in an individual chamber and separated from the vegetable storage with outside wall. Certain volume of air enters the preparatory chamber with the help of inlet valves. Air recirculation valves, humidifiers, heating and cooling devices that regulate air parameters are located here. High-pressure blower fans transfer processed air into the subfloor ducts. Then the air enters the room correcting the product properties and is goes out from the storage facility. If there is no possibility of installing subfloor ducts, the vegetable storehouse should be equipped with perforated air ducts. The vegetable storage facility should have dispersal fans installed to prevent condensation. There are controllers "Aries", applicable in automated microclimate management systems in these types of vegetable storehouses, which enable to expand the number of sensors used and to simplify the control system through subsystems. Installation of proportional integral-differential regulators makes adjustments of the parameter range of the vegetable storage facility more accurate. A valuable factor is the correct design of the room in accordance with climatic conditions and the proper choice of building materials with regard to thermal conductivity [15].

The second method of storage is more convenient and provides a high level of product safety. At the same time, the cost of container storage of vegetables is quite high. Carrots, cabbage, garlic and onions are stored mostly in containers. There are several approaches to this method. Aspiration wall ensures air circulation in the storage facility using vacuum fans. This technology applies for potatoes, onions, garlic and beets. The "slit wall" system is also used. In this case, the airflow through the containers moves from bottom to top, resulting in insufficient ventilation at the top. To use this method, the length of the storage should be at least 14 meters. The airflow goes more intensely through the containers in the pressure wall system with self-pumping air tubes. In many ways, this technology is similar to the "aspiration wall" system. While the cost of this system is higher, it maintains a higher level of product safety. The upgraded versions of the above technologies are EveryAir and Dragon-M. EveryAir is an improved version of the pressure wall. It increases the volume of ventilation of the fruits. Dragon-M uses ventilation and cooling units, allowing installation of heating and cooling elements, control valves and high-pressure blower fans. This technology is more economical and suitable for small vegetable storage facilities [16]. The climate parameters are under control by automation system in all cases.

In addition to compression refrigeration units, there are vortex tube devices. These are more economical and can generate hot and cold compressed air streams, thereby heating vegetable storage facilities in winter. The formation of two opposing temperature fractions is due to the Ranque-Hilsch effect or vortex effect. The gas is swirled in a cylindrical or conical chamber and separated into two streams. Hot flux emerges in the peripheral area and cold flux in the central area. Their directions of rotation are opposite to each other. In this type of system, temperature, airflow and power consumption can be adjustable with a control valve. Shut-off valves make certain operating modes to be set depending on the time of year. During the warm period, hot airflows come into the environment and cold airflows go into the supply air duct and vice versa during the cold period. Despite its simplicity, this technology has a significant disadvantage: the economic efficiency of vortex refrigerator units decreases with longer operating periods because they consume more energy to produce the working medium (compressed air) of the vortex tubes [17].

Around 80% of vegetable storage facilities in the southern regions of Kazakhstan operate since the early 2000s and require modernisation. The wear-off of the infrastructure leads to decrease of the marketing product quality. In addition, one of the main reasons for the stalled development of Kazakhstan's agro-industrial complex is that the final profit of agricultural producers is not equivalent to the costs of storage, processing and marketing. Lack of required equipment, low level of organised trade led to increased import and reduced competitiveness of Kazakhstan's vegetable products. The development of the agricultural complex is extremely important for South Kazakhstan, as the volume of vegetable production reaches about 70% of the total share in the whole country. However, the occupancy rate of vegetable storage facilities in the southern regions is no more than 85% [18]. The vegetable storage systems in southern regions require elevated air humidification, which increases energy consumption. The use of alternative energy sources is advisable. There is a heat pump heating and cooling system designed for hot climates with dry air. This system uses biofuel from vegetable storage waste to feed the refrigerator chamber and has two adjustable operating modes: cooling and heating. It enables the utilisation of ventilation emissions and the heat generated by the fruits, thus saving energy consumption [19, 20].

Nowadays, some companies in Kazakhstan are already using low-temperature processing and storage technology for vegetables. For example, the Limited Liability Partnership (LLP) Birlik-4 offers modern energy-saving technologies to preserve fruit and vegetables in their warehouses. The container method is suitable to preserve potatoes. Compared to bulk storage, the containers ensure uniform pressure on the fruits, good ventilation, provide the control over damaged products and simplified container transport. Carrots and onions come in plastic bags that control the humidity of the vegetables and protect them from contamination. For efficient use of energy resources, LLP Birlik-4 conducts thermal engineering calculations at various daily product loads using software Guntner and Bitzer. The first applies to the selection and calculation of heat exchangers and the second to cycle calculation and compressor selection. This helps to determine the optimum value for the daily loading of vegetables, to prevent a drastic load increase on the refrigeration units and to monitor temperature fluctuations in the storage room [21-24].

As vegetable farming is concentrated in the southern regions of Kazakhstan, storage facilities need to be modernised and equipped with automation systems. Balancing temperature and humidity, controlling air composition and movement requires a lot of energy. In addition, energy consumption for cooling and moisturising vegetable storage facilities should increase due to the hot and dry climate. The use of automated controls will contribute to improved energy efficiency of structures as well as productivity and rational use of resources and work force. Moreover, these systems will contribute to the prevention of accidents.

4. DISCUSSION

Vegetables and fruit tend to spoil quickly. Many factors are important with regard to shelf life thus maintaining their marketability. The authors Lee and Robertson [25] investigated the storage of dried vegetables and developed a mathematical model for predicting changes in the product properties depending on the degree of humidity in the storage facility. The authors used differential equations for water vapour penetrability and degree of fruit quality. The study objects were dried onions, cabbage and green beans. The researchers placed vegetables in polyolefin waterproof and hydrophilic packaging. Temperature varied between 20-40°C, relative humidity between 60-100%. As a result, it was determined that the temperature indicator influenced the shelf life of the vegetables more than the relative humidity. The vegetables in polyolefin packaging were less susceptible to rotting at high temperatures and humidity for a longer period than those that were stored in moisture-sensitive packaging.

The authors Chavan et al. [26] discussed the principles of thermoelectric cooling and provided a description of the device and an overview of various environmentally friendly cooling technologies. Compared to vapour compression refrigeration systems, thermoelectric systems are more compact, quieter and environmentally friendly. A mathematical model of a thermoelectric refrigerator with steam cooling made entry in a joint paper Chavan et al. [27]. This system is also suitable for transporting fruit and vegetables. The thermal properties of the materials used and the geometric dimensions of the chamber contributed to the design of this unit. A disadvantage of the technology comes from its indicated use for small storage volumes.

The introduction of artificial intelligence into the vegetable storage system has not been subject of this paper. Artificial neural network algorithms, fuzzy logic, adaptive neuro-fuzzy inference system and genetic algorithm have found application in agricultural industry. The author Salehi [28] states that these patterns can be used for condition monitoring and modelling and in sorting of vegetable and fruit products, thus predicting physical and chemical characteristics during storage. It has been determined that these algorithms increase the efficiency and energy savings of vegetable storage facilities and suitable to detect fruit damage due to cooling. In addition, they improve microclimate control and predict moisture content [29]. An adaptive neuro-fuzzy inference system has proven to be the most effective model. The authors Xie et al. [30] updated the ventilation system with automation. The use of a programmable logic controller, frequency controllers, the technology of self-tuning of proportional integral-differential regulator parameters significantly improves the functioning of the automated control system of vegetable storage facilities, resulting in increased equipment efficiency and energy saving of the construction design.

The specific features of a refrigeration system based on the Peltier effect are the subject in the work of Sitorus et al. [31]. This system is also energy efficient and environmentally friendly. However, the minimum temperature that this refrigeration unit can reach is around 17°C. This value does not allow long-term product storage. The issue of extending the storage period of tomatoes has coverage in the article of Ayomide et al. [32]. Their paper presents a developed vegetable storage system with automated temperature control. A similar theme exists in a study of Al-Dairi et al. [33], where the authors studied the intensity of damage to tomatoes during transport. The duration of conservation and temperature in the storage facility affects physical properties such as weight, colour and resilience. The authors point out that it is important to keep the temperature from 10°C and below for preservation of tomatoes.

The authors Jia et al. [34] have developed a system with precise temperature control and internal circulation system. Spraying of ozone and titanium dioxide in the vegetable storehouse is capable to prevent damage of the fruit from cooling and darkening and the spread of fungal infections. The presented system achieves a minimum temperature variation of ± 0.1 to ± 0.2°C. In comparison, normal storage value varies from ± 0.5 to ± 1.0°C. To confirm the effectiveness of the technology, the authors conducted experiment in which the fruit retained its structure for 60 days of storage and the overall percentage of rotting happened to be small. The authors Lu et al. [35] discussed the changes in the structure of sweet potatoes during post-harvest storage. This period lasts up to 20 days. The authors studied chemical processes taking place inside the potatoes under different parameters of the storage room environment and their influence on the overall structure of the fruit.

The effect of ultraviolet treatment on reducing the incidence of disease in fruits and vegetables has coverage by Zhang and Jiang [36]. The authors determined that the use of ultraviolet radiation could induce the production of protective systems in the fruits, which directly increases the resistance of the products to infections and thermal damage. Nitric oxide and melatonin are also applicable to improve the quality of stored products. The authors Zhang et al. [37] studied the use of these chemical compounds and as a result confirmed the effectiveness of their use. The researchers Wang et al. [38] found that postharvest treatment of blueberries with hydrogen peroxide reduces weight loss, preserves nutrients and extends shelf life. The authors Chen et al. [39] investigated the effect of glycine betaine on products during storage and found that its use led to an increase in antioxidant content and reduction in infection of the fruits. The scholars Zhang et al. [40] revealed how the use of nitric oxide affects grape storage. The ageing of table grapes is associated with damage to reactive oxygen types. The researchers have determined that nitric oxide mitigates oxidative processes at storage temperature 0°C. The authors Feigl et al. [41] have also explored this issue and determined that nitric oxide reduces the negative effects of salts, temperature and exposure to heavy metals on fruits and vegetables.

The effectiveness of ozone application has description in the article of Pandiselvam et al. [42]. The researchers note that ozone is safe for food products and the environment and has disinfecting properties. This article examines the effect of ozonation at different concentrations on fruit storage. The authors Botondi et al. [43] reviewed the main studies on the effects of gaseous ozone and ozonised water treatment on nutrient retention and extension of shelf life of fruits and vegetables. They noted that this type of treatment does not cause the release of hazardous chemicals adversely affecting fruit and nature. The researcher Asghari [44] suggests the use of jasmonates as these compounds are safe and increase the resistance of food products to various pests, diseases, water losses and other negative influences. The use of chemical compounds in the storage of the fruits is particularly important because even if all microclimate requirements are correct, vegetables and fruits can be susceptible to infections and various damage [45]. The authors Fang and Wakisaka [46] reviewed modern fruit and vegetable storage technologies. They identified the most promising inventions of recent years as well as systems in need of refinement.

The shortcomings of this article include insufficient detailing of the microclimate parameters for the safe storage of different varieties of fruits and vegetables and limited analysis of the effect of chemical compounds on the safety of products. Nevertheless, the work suggests energy-efficient ways to store fruits in the climate of the southern regions of Kazakhstan, which can reduce the cost of operating vegetable storage facilities and reduce crop losses.

The managerial implications of this research are significant. Managers of vegetable storage facilities can benefit from the findings of this study by implementing the recommended technologies and techniques to increase the energy efficiency of their facilities. Automated control systems and alternative energy sources can be used to simplify the storage process, reduce the risk of product damage, and minimize human intervention. The study also provides basic guidelines for controlling the microclimate to improve the quality of stored fruits and vegetables, which can help managers to maintain product quality and reduce losses.

The research also provides recommendations for the modernization of vegetable storage facilities in the southern regions of Kazakhstan. These recommendations can be used by policymakers and facility managers to improve the infrastructure and equipment of storage facilities and to promote the adoption of new technologies. The study can also be useful for investors who are looking for opportunities in the vegetable storage industry in Kazakhstan. Overall, the findings of this research can help to improve the efficiency, productivity, and profitability of vegetable storage facilities in Kazakhstan and other countries. Managers and policymakers can use this information to make informed decisions about the design, construction, and operation of these facilities.

5. CONCLUSIONS

This article fills a gap in the research in the direction under consideration, because, firstly, it emphasizes the importance of automation of storage infrastructure and equipment modernization, which has not been widely discussed in previous studies. Secondly, it provides a detailed analysis of the impact of microclimate parameters on the quality of fruits and vegetables in storage. Thirdly, it explores the most effective technologies meeting storage requirements and provides recommendations for modernizing vegetable storage facilities in southern regions of Kazakhstan.

The article enriches the study of this stream by providing a comprehensive and detailed analysis of the impact of microclimate parameters on the quality of fruits and vegetables in storage. It also offers recommendations for the modernization of storage facilities, taking into account the use of automated control systems and alternative energy sources to increase energy savings, streamline the storage process, and reduce the risk of product damage. This article provides useful information for researchers, practitioners, and policymakers seeking to improve the efficiency of vegetable storage facilities in southern regions of Kazakhstan.

The main parameters of the microclimate system in vegetable storage facilities are temperature and relative humidity. Both circulation and air composition are of similar importance. Ventilation, temperature control, humidification, draining systems and gas regulation systems consume a high level of energy resources and consequently increase the cost of operating the storage facilities. An important aspect is the environmental pollution caused by maintenance. High-tech automated control systems are in demand to improve the cost-effectiveness and environmental performance of vegetable and fruit storage structures. In this study, the authors investigated the influence of these parameters on the safety of the plant's products, the importance of temperature and humidity regimes.

The microclimate is a key control factor depending on the type of fruit product and its degree of ripening. Thus, most fruits require a relative humidity of at least 90% inside the vegetable storehouse, whereas melon crops require 80-90%, as their cover tissue structure is less prone to moisture loss than that of tomatoes, carrots or onions. It is important to bear in mind that young and ripened fruits of the same crop require different storage conditions. The regular ventilation of fruit and vegetable products is essential for the timely removal of the ethylene that the fruit releases as it ripens. Carbon dioxide and oxygen also affect the storage process. Their ratio in the environment of the vegetable storage room is important factor to regulate.

This complex technological process can be simpler when the human factor is minimised by automation systems. Due to the lack of the required number of modernised vegetable storage facilities in the South Kazakhstan region, it is necessary to increase funding for the country's agricultural sector. When designing storage facilities, the energy-efficient technologies that use renewable energy sources should be favoured. For example, the use of biofuel to power refrigeration plants, produced from food waste. Given the hot and dry climate in the southern regions of Kazakhstan, the energy consumption for storage cooling is much higher than in temperate climate regions. This confirms the need for energy-efficient microclimate control systems. Further research should look more closely at how renewable energy sources are applicable to improve the energy efficiency of vegetable storage facilities, as this field is currently underdeveloped. There is a recommendation to make familiar with the potential applications of artificial intelligence in the agricultural industry.

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