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## Современные методы сушки растительного сырья: аналитический обзор

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**Аннотация. Введение.** В условиях растущей конкуренции в агропромышленности, особенно в растениеводстве, важно разрабатывать инновационные методы переработки сырья. Эти методы должны оптимизировать энергетические затраты, повышать качество продукции и снижать потери. Сушка — ключевой технологический процесс, применяемый на разных этапах переработки. В условиях меняющейся геополитической обстановки совершенствование сушильного оборудования становится критическим для конкурентоспособности на внутреннем и международном рынках, а также для производства высококачественной продукции, соответствующей современным стандартам.

**Материалы и методы.** Современные исследования направлены на изучение тепловых процессов, окислительных реакций, изменений структуры и физических свойств растительного сырья. Ключевая проблема - термолабильность материалов, которая приводит к разрушению ценных компонентов при высоких температурах. Работы А. В. Лыкова и А. Ф. Буляндра заложили основы теоретических моделей и практических методов. Особое внимание уделяется кинетике переноса влаги, параметрам энергетической освещенности, спектральным характеристикам и скорости сушки.

**Результаты и обсуждение.** В рамках данного исследования был проведен всесторонний анализ сушильных установок, применяемых в современной практике обработки растительного сырья. Эти установки демонстрируют значительное разнообразие конструктивных параметров, что обуславливает их классификацию по множеству критериев. Данная систематизация позволяет осуществлять детальный сравнительный анализ различных типов оборудования, что, в свою очередь, способствует углубленному пониманию технических аспектов процесса сушки и оптимизации производственных процессов. **Заключение.** Совершенствование технологий сушки и разработка новых сушильных установок позволит повысить конкурентоспособность сельского хозяйства, повысить энергоэффективность и снизить экологическое воздействие.

**Ключевые слова:** растительное сырье, методы сушки, пневмосушильные установки, сублимационная сушка, инфракрасная сушка, вакуумная сушка, микроволновая сушка.

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Research article

## Modern methods of drying vegetable raw materials: an analytical review

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**Abstract. Introduction.** In the context of growing competition in the agro-industry, especially in crop production, it is important to develop innovative methods of raw material processing. These methods should optimize energy costs, improve product quality, and reduce losses. Drying is a key technological process used at different stages of processing. In the changing geopolitical environment, improving drying equipment becomes critical for competitiveness in domestic and international markets, as well as for producing high-quality products that meet modern standards. **Materials and methods.** Modern research focuses on studying thermal processes, oxidative reactions, and changes in the structure and physical properties of plant raw materials. The key challenge is the thermolability of materials, which leads to the destruction of valuable components at high temperatures. The works of A. V. Lykov and A. F. Bulyandra laid the foundations for theoretical models and practical methods. Special attention is paid to the kinetics of moisture transfer, energy illumination parameters, spectral characteristics, and drying rates. **Results and discussion.** This study provides a comprehensive analysis of drying units used in modern plant processing practices. These units exhibit a wide range of design parameters, leading to their classification based on various criteria. This systematization allows for a detailed comparative analysis of different types of equipment, which in turn contributes to a deeper understanding of the technical aspects of the drying process and the optimization of production processes. **Conclusion.** Improving drying technologies and developing new drying units will increase the competitiveness of agriculture, improve energy efficiency, and reduce environmental impact.

**Keywords:** plant raw materials, drying methods, freeze-drying units, sublimation drying, infrared drying, vacuum drying, microwave drying.

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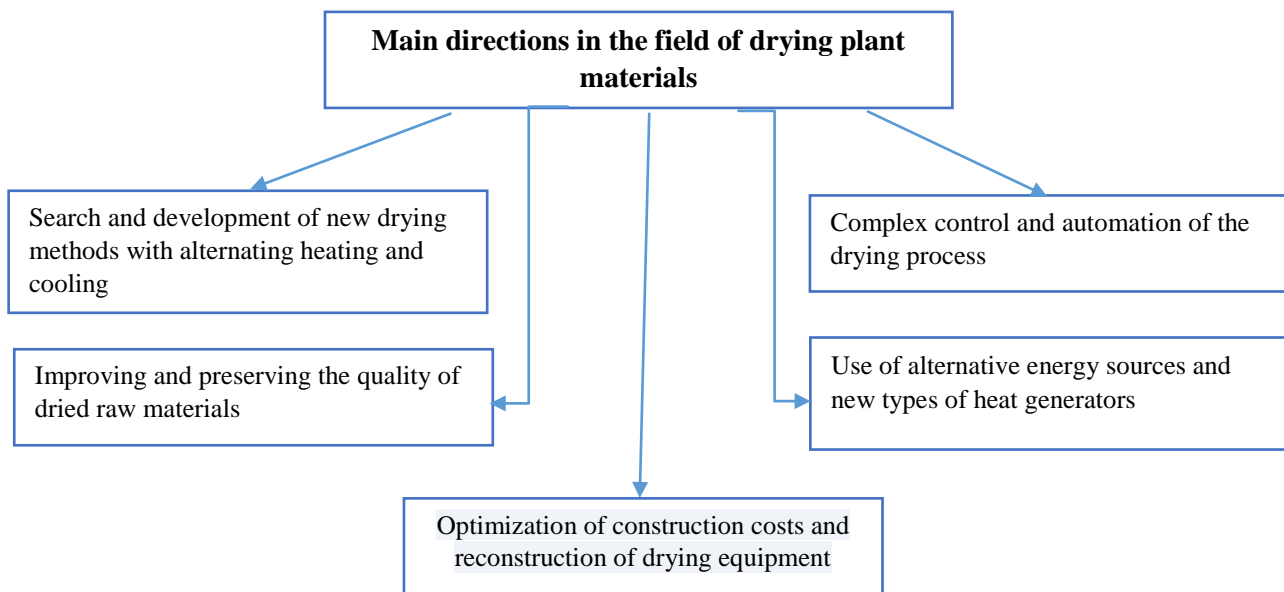
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**Introduction.** Competition in the crop production industry forces producers and researchers to seek innovative methods for processing raw materials in order to reduce energy costs, improve the quality of finished products, and minimize losses.

Drying is a key technological process in agriculture, used at various stages of processing. Given the changing geopolitical situation in the modern world, improving drying equipment to ensure competitiveness in both domestic and international markets is critical for producing high-quality products.

**Research materials and methods.** Modern research on the drying process of plant materials involves thermal processes accompanied by oxidative reactions, changes in structure and physical properties, and the formation of crystalline hydrates that negatively impact the nutritional value of the raw materials. One of the main causes of these negative effects is the heat instability of plant materials, which destroys valuable components at high temperatures.

The development of drying technologies is aimed at maximum preservation of the properties and value of the original raw materials.



**Figure 1. Main trends in the field of drying plant materials**

The selection of drying methods for wet materials is based on a thorough analysis of moisture transfer and removal kinetics. Particular attention is paid to optimizing irradiance, the spectral characteristics of the materials, drying rate, and the spectral distribution of the radiation.

The fundamental theoretical studies of moisture distribution in capillary-porous materials, such as agricultural crops, were conducted by A. V. Lykov and A. F. Bulyandra. These studies were further developed by their students and other scientists.

Thermal drying methods, such as convective, conductive, and radiation drying, implemented in various drying unit designs, can significantly intensify moisture removal processes. However, these methods are highly energy-intensive, necessitating the development of technologies aimed at increasing energy efficiency while maintaining product quality and environmental friendliness.

The main objectives of the drying process in the agro-industrial complex include:

- Intensification of drying to reduce production cycle time.
- Maintaining the maximum permissible and stable temperature at a given level.
- Development of energy-saving drying equipment.
- Optimization of production processes taking into account economic and environmental aspects.

Thus, improving technologies for drying plant materials is a key factor in increasing the competitiveness of agricultural products in the global market.

Modern theoretical and practical research into the drying process of plant materials reveals a complex set of physicochemical and biochemical phenomena that accompany thermal processing. Specifically, thermal processes induce oxidative reactions, structural modifications, and the formation of crystalline hydrates, which leads to a reduction in the nutritional value of the final product. The key issue driving these undesirable changes is the insufficient attention paid by drying equipment manufacturers and technologists to the phenomenon of thermal instability of plant materials.

Thermal instability is a complex of physicochemical properties of raw materials characterized by their susceptibility to destructive changes when exposed to elevated temperatures. These changes include the degradation of valuable biologically active components, such as vitamins, enzymes, and antioxidants, as well as a deterioration in the organoleptic and textural characteristics of the product. Therefore, the development and implementation of methods that minimize thermal exposure and preserve the original properties of raw materials are of paramount importance.

Over the past decades, significant progress has been made in the field of research and optimization of plant material drying processes, including:

1. The development of innovative methods based on alternative cyclic heating and cooling regimes. These methods enable more efficient management of thermodynamic processes, reducing thermal stress and minimizing the negative effects of heat treatment.

2. Implementation of modern control and automation systems that ensure high-precision process parameter control and reproducible results. These systems also enable rapid response to dynamic changes in environmental conditions and raw material characteristics.

3. Developing differentiated approaches to preserving the quality of various agricultural crops. These approaches take into account the biotechnical characteristics of each crop, including optimal temperature regimes and heating rates, which minimizes the degradation of valuable components.

4. Research and implementation of alternative energy sources such as solar and geothermal energy, as well as the development of new types of heat generators, contribute to reducing energy costs and increasing the environmental sustainability of drying plants.

5. Optimization of costs for the design and reconstruction of drying equipment is a key factor in increasing the economic efficiency of agricultural production.

Modern agricultural practices offer a variety of moisture removal methods and systems for artificially drying produce and plant materials. One of the most common and cost-effective approaches is natural drying, which utilizes solar radiation and natural convective heat exchange mechanisms. This method is characterized by low design and construction costs for drying systems, making it attractive in certain economic conditions.

However, natural drying has several significant limitations. Firstly, it only achieves equilibrium moisture content in raw materials, significantly limiting the ability to produce high-quality products with high energy potential. Secondly, products dried by this method are often characterized by low purity and the potential presence of contaminants. Despite the simplicity of the process and the relatively low capital costs of equipment, natural drying is not cost-effective for large-scale industrial production and is inferior in end-product quality to more modern technologies.

**Research results and discussion.** Plant materials are complex systems of colloidal capillary-porous bodies with a multilayer microstructure. Significant shrinkage occurs during drying, which

significantly impacts the analysis of the drying curve. The elastic walls of the capillaries undergo a reversible increase in volume upon wetting and a decrease during drying, which facilitates more efficient moisture delivery to the surface by transforming the capillaries into conical structures with narrow ends directed toward the material's surface.

Under optimal conditions, including low coolant temperature, low air velocity, and sufficient humidity, many plant materials exhibit two-period drying kinetics. However, there are exceptions, such as berries, sedum, some apple varieties, bread, and others, which exhibit a single-period drying process, with a dominant period of decreasing drying rate and a simultaneous increase in material temperature. In this case, the difference between the material and coolant temperatures is 1-2 degrees, indicating that diffusion processes predominate over moisture exchange.

The dynamics of the drying process are determined not only by the operating parameters and characteristics of the material, but also by its initial moisture content and the degree and shape of cutting. Before drying, a thorough examination of the cellular structure of the raw material, especially its outer shell, is necessary. This allows for the optimization of process parameters, minimization of product quality loss, and more efficient drying control.

In modern plant material processing, a variety of drying systems are widely used, classified based on a multitude of design parameters. This classification allows for a detailed analysis and comparison of different equipment types, which, in turn, facilitates a deeper understanding of the technical nuances of the drying process and optimization of production operations.

The classification of drying installations is shown in Fig. 2.

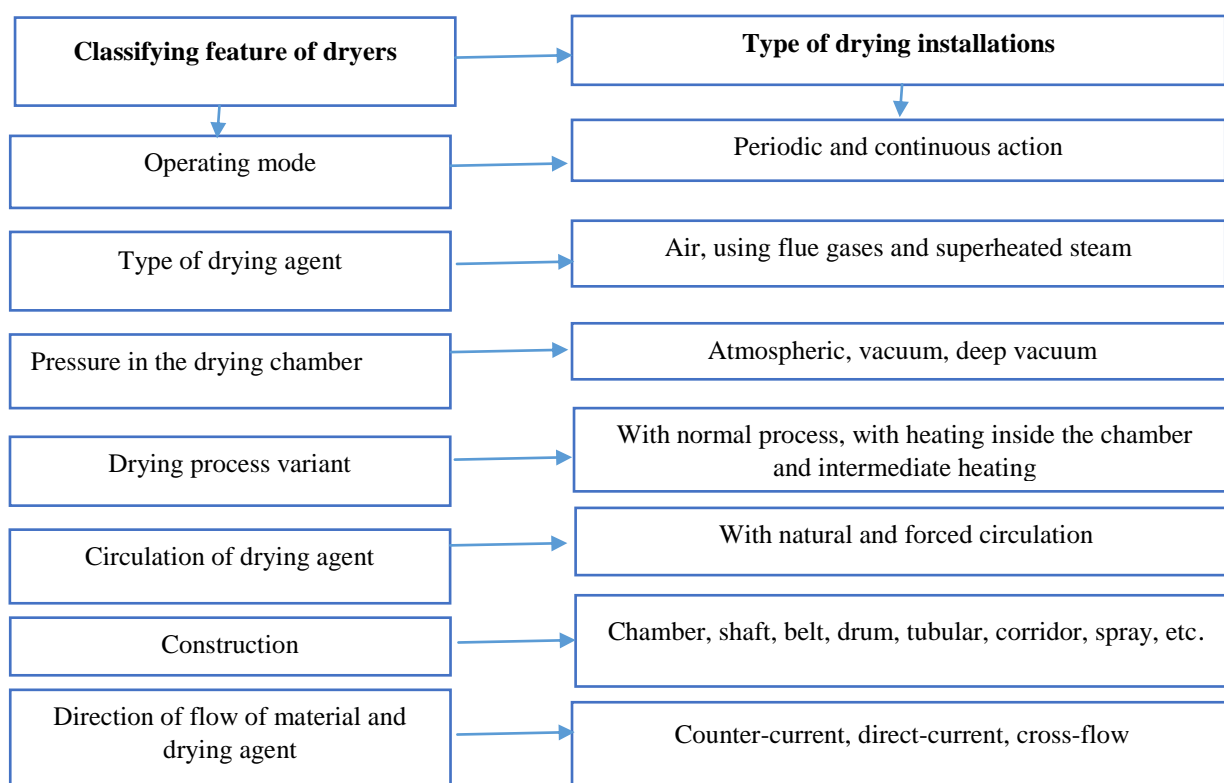
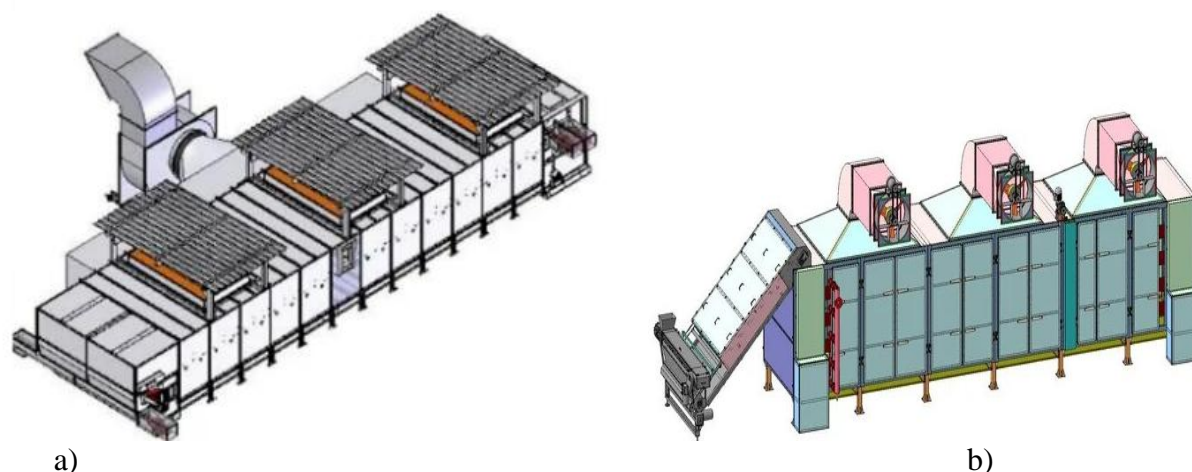


Figure 2. Classification of drying installations

### **Installations for drying lump and granular raw materials in dense and loose layers.**

Dense-bed drying systems are high-tech equipment designed to effectively remove moisture from various types of materials. The dense-bed drying process involves processing the raw materials in a compact arrangement, ensuring intensive heat exchange and uniform moisture evaporation. Tunnel and chamber drying systems are examples of this type of equipment.

Tunnel: belt (Fig. 3a), conveyor (Fig. 3b). Chamber: cabinet, trolley (with mobile trolleys).



**Figure 3. Examples of designs of some drying installations**  
3a – belt; 3b – conveyor

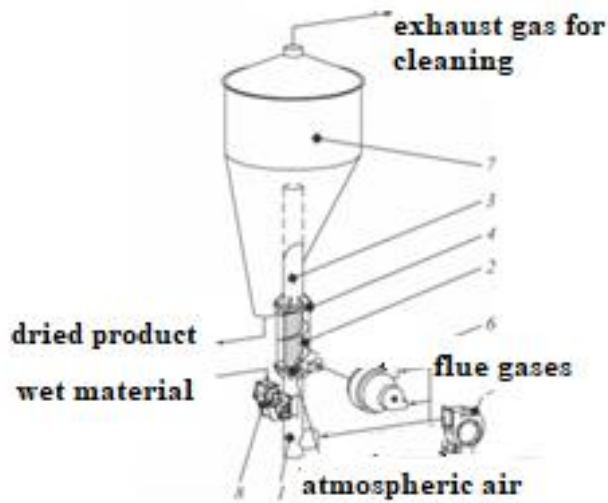
**Pneumatic drying units.** Pneumatic drying units (pneumatic dryers) are highly efficient technological systems designed for the dehydration of finely dispersed plant materials (flour and starch). They operate on the principle of forced circulation of the wet material in a stream of heated air or combustion products, ensuring uniform and intensive moisture evaporation. This drying method is characterized by high process speed and minimal thermal impact on the processed material, while preserving the original physicochemical properties and biological activity of the raw materials.

Types of pneumatic drying units:

1. Pneumatic tubes enable the process to be accomplished by counter-current movement of gas and material, with the gas acting as both a drying and transporting agent. This method ensures effective moisture removal from the material through intensive gas circulation.
2. Cyclone and vortex dryers. These units feature a cylindrical body containing various baffles. The feedstock is introduced tangentially into the gas flow, creating vortex flows that promote a more uniform moisture distribution throughout the material.
3. Two-stage pneumatic dryers with material recirculation, used for processing difficult-to-dry materials, require extended drying times. They operate by repeatedly recirculating the material through the drying chamber, allowing for more efficient moisture removal and achieving the desired dryness level.
4. Ring dryers. In these units, the pipe can form a closed loop through which finely dispersed material circulates until the required moisture content is reached. The residence time of the material in the dryer varies depending on the particle size, allowing the drying process to be optimized for different types of materials [8].

In their scientific studies, Braginets S.V., Bakhchevnikov O.N., Kuzmenko D.A. analyzed modern pneumatic drying units used in Russia and abroad [8, 9, 10, 11].

In pneumatic drying systems, the dehydration process of materials is carried out by transporting them vertically in an ascending flow of heated gas, which allows for the effective removal of moisture from pre-dispersed material [10, 11]. An example is the pneumatic drying unit developed by Russian scientists A.A. Seliverstov, I.E. Timofeev, E.A. Shestakov, and S.A. Shestakov (Fig. 4) [13].

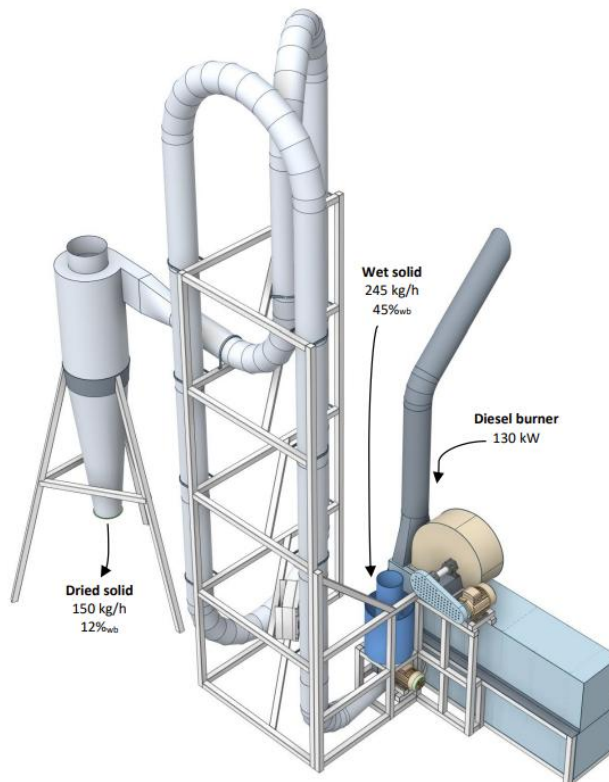


**Figure 4. Example of a pneumatic dryer**

1 – lower section; 2 – middle section; 3 – upper section; 4 – heat-insulating insert;  
 5 – fan; 6 – firebox; 7 – unloading device; 8 – feeder  
 [Seliverstov A.A., Timofeev I.E., Shestakov E.A., Shestakov S.A., 13]

Thus, pneumatic drying systems demonstrate high efficiency, ease of operation, and compactness, making them attractive for use in drying and transporting fine plant materials. In this regard, it is worth noting that specialized technologies and equipment developed under the supervision of A. Chapuis and M. Precoppe are actively used in this field.

As part of their research, the design of a pneumatic dryer (Fig. 5) for cassava was developed and carefully specified, enabling comprehensive experimental studies aimed at optimizing the drying tube geometry and establishing rational process parameters. The results of these studies are essential for improving the efficiency and quality of plant material drying [27, 28, 29].



**Figure 5. Pneumatic dryer for cassava (M. Precoppe)**

**Vortex drying** is an improved modification of pneumatic technology aimed at intensifying the dehydration process [8, 9, 10, 11].

In this configuration, intensification is achieved by creating a vortex motion of the gaseous heat-transfer medium in the working chamber, as well as through additional mechanical grinding and dispersion of the material using a rotor element. These measures contribute to more efficient removal of bound moisture from the material being processed, as confirmed by research results [11].

In the works of Tan, X.; Jiang, W.; Su, J.; Yu, F. in an analytical review, modern drying technologies are considered using the example of obtaining dried orange peel and a comparative analysis of drying technologies is given: hot air drying (HAD) and the sublimation drying method.

Convective drying remains the most widely used method in industrial practice. This is due to the simplicity of drying unit designs and the high efficiency of thermal energy transfer through convection processes. The convective approach is characterized by its versatility and reliability, making it popular in the food industry, ensuring consistent end product quality.

**Hot air drying (HAD)** is an inexpensive method for dehydrating plant materials at a temperature of 60–80°C. Its disadvantage is the deterioration of organoleptic properties and a decrease in nutritional value. During convective drying, the key parameters determining the efficiency and quality of the final product are the temperature of the drying agent, the layer thickness, and the density of the material. One of the significant disadvantages of this method is the relatively low value of the heat transfer coefficient from the drying agent to the material surface. In capillary-porous bodies, the convective component of heat transfer is significantly inferior to the conductive one during the drying process, which is due to the peculiarities of the microstructure of these materials [2]. It should be noted that fibrous materials of plant origin have low thermal conductivity and are classified as good thermal insulation materials with a thermal conductivity coefficient of  $\lambda=0.053\div 0.11$  W/(m °C). In this drying method, high temperatures in dark teas and in orange peel production increase the content of polyphenols and flavonoids [31].

**Freeze-drying (FD)** preserves quality by freezing and sublimating ice in a vacuum. This method eliminates thermal degradation, but requires specialized equipment and a long drying time (up to 22 hours for blueberries and 72 hours for mango peels). Pre-treatment reduces this time but is not always suitable for industrial applications.

More efficient technologies need to be developed to reduce the time and cost of freeze-drying to meet the growing demand for quality dehydrated products.

In recent decades, the spray drying method has become widespread in the technology of processing plant raw materials, especially in the context of the production of functional drinks with the addition of nutraceuticals, which allows for a significant increase in the shelf life of products, expansion of the range of functional food products and the efficient utilization of agricultural waste [14, 15].

Spray drying is based on the dispersion of liquid raw materials into an aerosol, forming tiny droplets. These droplets rapidly undergo desublimation by interacting with a heated air flow, the inlet temperature of which varies between 140–200 °C and the outlet temperature decreases to 40–90 °C [85]. This results in the formation of dry particles with a controlled level of residual moisture and a specified particle size distribution, ensuring the production of high-quality powdered products.

However, applying this method to fruit juices containing high levels of low-molecular-weight carbohydrates (fructose, glucose, sucrose) and organic acids poses certain technological challenges. Specifically, there is a tendency to form sticky and lumpy agglomerates, which negatively impacts the quality of the final product and its functional properties.

Thus, despite the obvious advantages of spray drying as a food processing technology, there are a number of factors that require further study and optimization to achieve higher standards of quality and production efficiency.

In recent years, innovative drying methods have been integrating with traditional technologies to improve the efficiency, cost-effectiveness, and quality of food processing. Particular attention has been given to microwave (MW) and infrared (IR) drying, which have demonstrated significant effectiveness in various applications.

**Microwave drying** is a method based on the action of high-frequency electromagnetic radiation on water molecules (typically in the range of 2450 to 9150 MHz), which accelerates moisture evaporation and significantly reduces the drying time. However, microwave drying has limitations, such as the potential degradation of color and nutrients.

To overcome these shortcomings, microwave drying is combined with other methods, such as convective drying and vacuum processing. For example, when drying pear slices, the use of microwave radiation in combination with convective drying significantly reduces processing time but leads to undesirable color changes. Meanwhile, the use of microwave drying under vacuum conditions for sohiong fruit (*Prunus nepalensis*), with reduced radiation power and increased vacuum, preserves color, anthocyanins, antioxidant activity (measured by free radical scavenging activity), and phenolic components. The low oxygen content in a vacuum minimizes oxidation processes, which increases the nutritional value of the final product.

Current trends in food dehydration are characterized by the active implementation of infrared-based technologies. This method demonstrates significant advantages, including efficiency and the ability to preserve the cellular structure and organoleptic properties of products. Infrared drying, which utilizes the osmotic mechanism of moisture evacuation, minimizes thermal damage and preserves high levels of bioactive components.

**Infrared drying** is based on the use of infrared radiation (in the spectral range of 700 to 1000 nm). This method ensures uniform heat distribution, reduces energy consumption, and accelerates the drying process compared to traditional technologies. Infrared drying is particularly effective for sublimation processing.

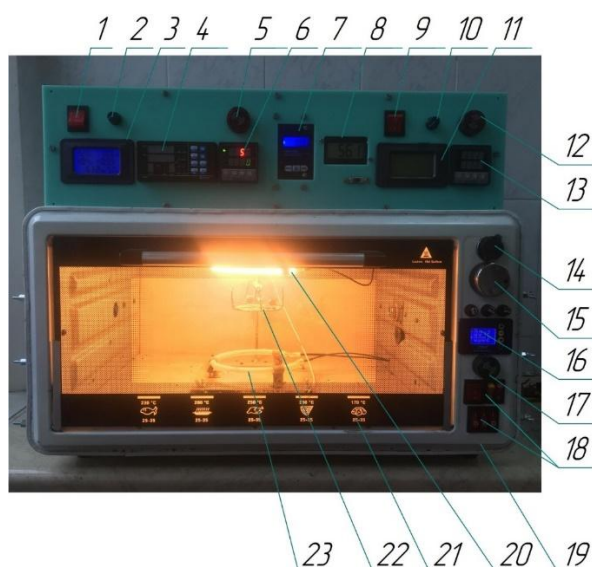
The use of infrared heating in solar dryers has demonstrated high efficiency. For example, using infrared heating to dry pineapples increases the moisture evaporation rate to 0.95 kg of water per kg of dry matter per hour, improves the moisture diffusion coefficient to  $2.59 \times 10^{-10} \text{ m}^2 / \text{s}$ , and preserves quality characteristics such as color, phenolic content, and antioxidant activity. Research also shows that infrared heating improves the structural integrity and crispiness of banana slices, optimizes the drying of strawberry snacks, and enhances the quality of sweet potato slices, despite potential color and firmness changes due to increased temperature midway through the process.

Particular attention should be paid to the ability of infrared drying to ensure a high degree of nutrient preservation, making it the preferred method for processing fruits and vegetables. Optimal temperature settings and process duration allow for maximum biological value in dried products and also enable their subsequent rehydration to near-original volume, opening up new possibilities for functional ingredients.

An infrared drying unit, shown in Figure 6, was created at the A.F. Korshunova Department of Technology and Organization of Food Production at the DonNUET.

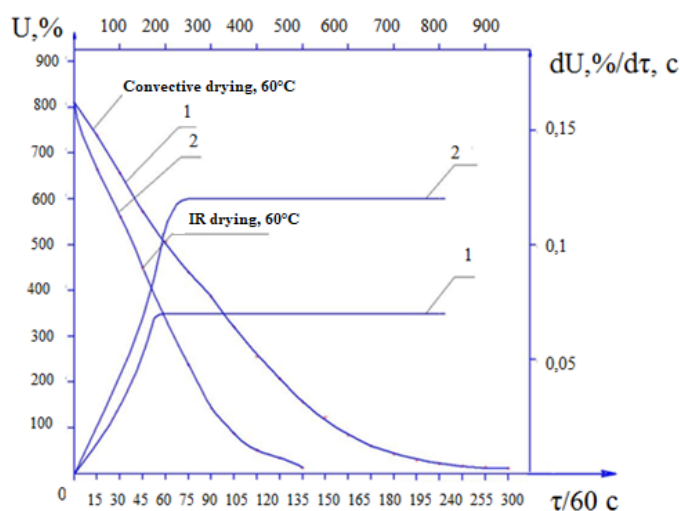
The apricot dehydration process is a multifactorial kinetic system comprising two clearly delineated phases: a constant-rate phase and a decreasing-rate phase. The initial stage, which involves heating the material to equilibrium temperature, is practically invisible on kinetic graphs, as changes in moisture content during this period are minimal. The critical transition point from the constant-rate phase to the decreasing-rate phase is determined by the moisture content of the apricots and is approximately 15–20% (Figure 7) [33, 34].

A comparative analysis shows that using infrared (IR) heating reduces dehydration time to 9,000 seconds, which is significantly shorter than closed-loop convective drying, where the process takes 18,000 seconds. Using IR heating reduces drying time by 50%, demonstrating its high efficiency, all other things being equal.



**Figure 6. Infrared drying unit:**

1 – Button for turning on and selecting a thermostat or a thermostat with a control unit for the upper heating element; 2 – Upper heating element power regulator; 3 – Digital meter for readings of the upper heating element (wattmeter, voltmeter, ammeter, frequency of line voltage fluctuations, phase tester); 4 – Thermostat with an electronic control unit for the upper heating element with the ability to connect to a PC; 5 – Upper thermostat fault indicator; 6 – Upper heating element thermostat; 7 – Electronic scales (accuracy 0.01 g); 8 – Temperature meter for the core of the product; 9 – Button for turning on the lower thermostat; 10 – Lower thermostat power regulator; 11 – Digital meter for readings of the lower heating element (wattmeter, voltmeter, ammeter, frequency of line voltage fluctuations, phase tester); 12 – Lower thermostat fault indicator; 13 – Thermostat for the upper heating element; 14 – Socket for connecting the ozonizer; 15 – Heating element selection switch knob (4-position); 16 - timer for ozonizer operation or timer for recording the experiment time; 17 - time indicator for taking experiment readings; 18 - keys for selecting the desired operating mode of the drying unit; 19 - body of the drying unit; 20 - upper IR heating element; 21 - glass door of the drying unit; 22 - product hanger; 23 - lower heating element



**Figure 7. Kinetic curve of drying of fruit raw materials (apricot)**

$$U\% = \left( \frac{m_w}{m_{\text{free}}} \right) \times 100, \text{ where:}$$

$m_w$  - mass of moisture in the product;  $m_{\text{free}}$  - mass of dry substances in the product; where:  $dU = U_i - U_{i-1}$ ,  $d\tau = \tau_i - \tau_{i-1}$

Modifying the apricot piece size from 10×10×20 mm to 5×5×10 mm, while maintaining the same parameters, results in a 25% reduction in drying time. This effect can be explained by the increased specific surface area of the material, which facilitates enhanced moisture transfer.

Changing the IR heating temperature from 50°C to 70°C reduces drying time by 55%, indicating a nonlinear relationship between temperature and dehydration rate. Increasing the temperature from 60°C to 70°C leads to an additional 45% reduction in drying time, confirming the importance of temperature in process optimization.

The obtained results form the basis for determining optimal parameters for apricot dehydration and for developing and designing drying systems. Based on these data, it can be concluded that infrared drying systems are recommended for minimizing apricot drying time and ensuring high-quality final products. It is recommended to process the material with the smallest possible piece sizes (approximately 5 x 5 x 10 mm) and a temperature of approximately 60°C, which will maximize the efficiency of the dehydration process.

This method ensures rapid and uniform moisture evaporation, preserving the fruit's aesthetic appearance, high nutrient content, and dehydration properties. IR drying is a promising approach to berry processing, given the need to preserve its integrity, flavor, and high antioxidant content.

Integrating microwave and infrared drying with other processing methods significantly improves the efficiency and quality of food products. These technologies open up new opportunities for preserving nutrients, improving organoleptic properties, and increasing the cost-effectiveness of processing.

T.G. Pavlenko proposed an alternative method for vacuum drying plant materials, offering high efficiency and preservation of biologically active compounds, while optimizing the production process. Vacuum drying significantly reduces heat consumption by conducting the process at low temperatures, not exceeding 50°C. This accelerates raw material dehydration, minimizing the thermal destruction of valuable compounds. As a result, most of the biologically active substances are preserved, making this method preferable for industrial use. The hermetic seal of the vacuum chamber ensures sterility. To implement the vacuum drying process, it is advisable to use a specialized equipment complex, including a raw material preparation section equipped with commercially available equipment from both domestic and foreign manufacturers, as well as a drying section operating using the vacuum dehydration method. Vacuum drying units are relatively expensive, but significantly reduce operating costs, reducing thermal energy consumption by 25–40% [2].

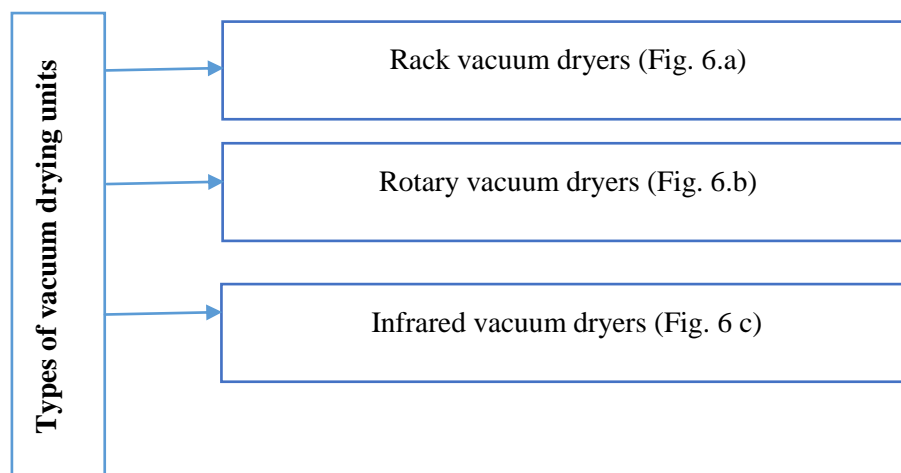
Vacuum drying is carried out at a material temperature in the range of 40-50°C, under a vacuum of 5-20 kPa, which promotes the effective removal of moisture and minimization of thermal impact on the sample [3, 4].

The most effective are combined two-stage convection -vacuum-pulse dryers. The residence time of the material in the drying chamber is determined by the critical moisture content point. If moisture content changes in plant materials during the drying process are minor, the vacuum-pulse stage can be used exclusively, especially for plant materials that do not have a distinct first drying period (e.g., stems and leaves), as well as materials susceptible to loss of biologically active substances (BAS) due to oxidation. These factors necessitate the search for innovative design and technological solutions for upgrading vacuum-pulse dryers and other drying methods.

Drying plant material using a vacuum method, at subatmospheric pressure, allows for the liquid to boil within the pores of the plant matrix at temperatures below 100°C. The boiling point of a liquid under vacuum conditions is a function of the depth of vacuum. This phenomenon is due to the fact that under reduced pressure, the boiling point of the liquid decreases, allowing for its evaporation at lower temperatures [5, 6, 7].

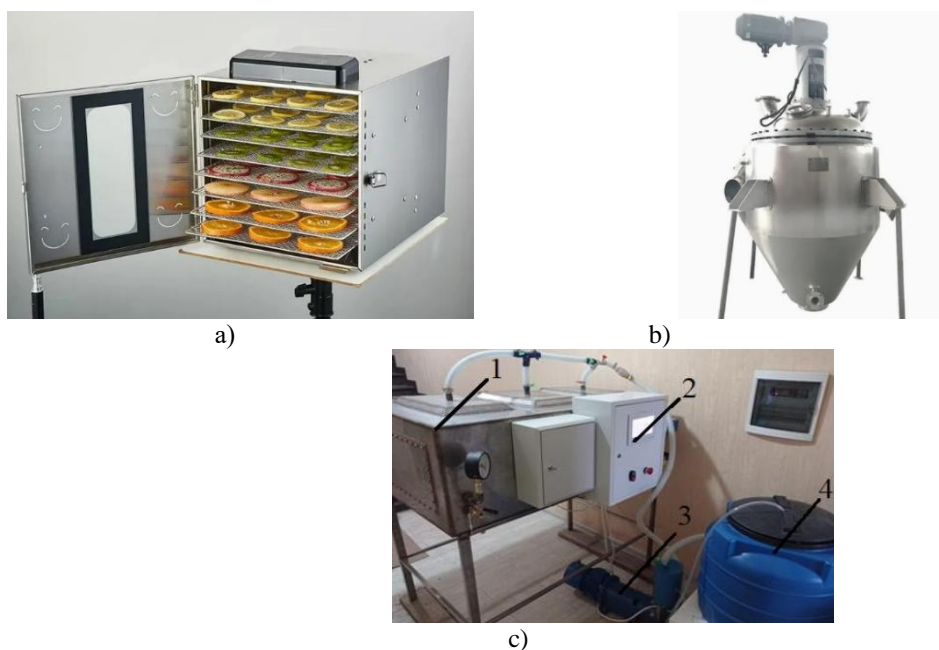
**Vacuum drying (VD)** is a dehydration method based on reducing the pressure in the processing chamber. This process significantly reduces the boiling point of water and ensures moisture evaporation at subcritical temperatures. The vacuum environment is characterized by a low oxygen concentration, which minimizes oxidative processes and prevents product darkening, preserving their biological value and organoleptic properties.

Specialized vacuum drying units operating at reduced pressure are widely used in the vacuum drying of plant materials. These devices provide optimal conditions for removing moisture from various materials, minimizing thermal degradation and preserving bioactive components. The main types of vacuum dryers are shown in Fig. 7 and Fig. 8.



**Figure 8. Types of vacuum drying units [25]**

Rack vacuum dryers are chambers with shelves on which trays or containers of material are placed. Heating can be delivered either through the chamber walls or directly through the shelves, allowing for effective temperature control. This type of dryer is particularly effective for processing large batches of raw materials, ensuring uniform heat distribution and preventing localized overheating.



**Figure 9. External appearance of vacuum drying units [25, 26]** a) external appearance of a rack vacuum drying unit; b) external appearance of a vacuum rotary drying unit; c) external appearance of an infrared vacuum drying unit: 1 – drying chamber; 2 – automated control box; 3 – liquid ring vacuum pump; 4 – water tank

Rotary vacuum dryers are characterized by a cylindrical shape and a rotating mechanism, which ensures uniform mixing of the material and its uniform application to the heat source. These devices are especially suitable for powdered and crystalline substances, where it is necessary to prevent clumping and ensure product homogeneity.

Infrared vacuum dryers are an advanced low-temperature drying method based on the use of infrared radiation. These units operate under high vacuum conditions, allowing for significantly lower drying temperatures without compromising product quality. This method is particularly effective for processing heat-sensitive materials, such as food products, medicinal plants, and their extracts. Infrared radiation penetrates the material at the molecular level, ensuring deep dehydration while preserving valuable bioactive components.

However, prolonged exposure of products to low pressure conditions can lead to irreversible deformation due to structural stress. To address this issue, pulsed vacuum drying (PVD), which involves periodically changing the vacuum level during the drying process, is being actively researched. This approach promotes more uniform pressure distribution and minimizes mechanical stress in the material.

Pulsed vacuum drying also causes a "tunneling" effect, which alters the microporous structure of the food matrix. This process improves the uniformity of moisture evaporation, reducing the risk of localized over- or under-drying and, consequently, minimizing the likelihood of deformation. Furthermore, capillary channels formed in the material as a result of pressure pulsations effectively remove moisture, preventing localized volume changes and significantly reducing the risk of structural damage.

The combined use of these mechanisms makes pulsed vacuum drying particularly effective for preserving the structural integrity of heat-sensitive materials. In recent years, this method has been successfully used to dry a variety of products, including citrus fruits (lemon, orange), berries (sea buckthorn), and dried fruits (jujube).

For example, research conducted by Xu et al. demonstrated the effects of different vacuum drying parameters on the quality of bitter orange (*Citrus aurantium* L.) segments. The experiment employed different vacuum pressure levels (20, 15, and 10 kPa) and vacuum to atmospheric pressure time ratios (5:10, 5:15, and 5:20 minutes). The results showed that sudden pressure changes (e.g., 10 kPa at a ratio of 5:20 minutes) resulted in significant color degradation ( $\Delta E = 10.39$ ) and an increase in the browning index (BI = 32.73 for peel), indicating possible structural stress. Optimal conditions were achieved at a pressure of 10 kPa and a vacuum to atmospheric pressure time ratio of 5:15 minutes, minimizing quality loss and maximizing drying efficiency.

Excessive pressure fluctuations outside this range can lead to structural damage, including balloon bulge or collapse, as evidenced by increased  $\Delta E$  and BI values under extreme conditions. These results highlight the importance of optimizing vacuum drying parameters to maintain product quality and structural integrity.

Research conducted by Yu. V. Rodionov, D. V. Nikitin, O. A. Zorina and others demonstrated the advantage of using combined technologies using the example of drying cauliflower of the Francoise variety. To implement the experimental studies, a two-stage convective-vacuum-pulse drying unit was used, consisting of a convective dryer with a fluidized bed in the first stage and a vacuum cabinet in the second stage, which ensures the effective removal of moisture from the processed materials through convective heat exchange and subsequent vacuum action, which allows achieving the required degree of dehydration with minimal loss of quality [30, 31, 32].

One of the priority areas of drying plant materials is preliminary treatment with ozone.

Pretreatment with ozone ( $O_3$ ) is an advanced food dehydration method that demonstrates high efficiency and improves the quality of the final product. Ozone's mechanism of action is based on oxidative reactions that initiate the destruction of the cell walls and membranes of pathogenic microorganisms, significantly reducing their quantitative content. This aspect makes ozone particularly valuable for disinfecting food products before drying. Research confirms its ability to

significantly reduce levels of bacteria, enterobacteria, coliform bacteria, yeasts, and filamentous fungi [18, 19, 20, 21, 22, 23, 24].

In addition, ozone has a unique detoxifying ability for pesticide residues, which significantly improves the safety of dried products. For example, Bae, J.; Lee, D.; Oh, K.; Jeong, D.; Lee, D.; Kim, J. (2023) demonstrated a 57.9% reduction in dimethomorph and thiamethoxam content in dried red pepper after ozone pretreatment.

Ozone also affects the microstructure of food surfaces, increasing moisture diffusion and accelerating dehydration processes. However, its effectiveness depends on factors such as ozone concentration, treatment duration, and the characteristics of the material being processed.

Unlike traditional disinfection methods such as chlorination, ozone provides a higher level of food safety by leaving no harmful residues.

An example of the successful application of ozone is the treatment of orange peel. Deng, L.; Mujumdar, A.; Zhang, Q. et al. (2019) showed that treatment of orange peel with ozone at a concentration of 4–40 µg/L for 2 h prior to convective drying at 40–60 °C resulted in a significant reduction in phenolic content (from 9.81 to 6.89–8.05 mg gallic acid/g). However, the high reactivity of ozone can cause the degradation of sensitive nutrients, such as proteins and phenolic compounds, and alter the organoleptic properties of dried products. This highlights the need to achieve an optimal balance between dehydration efficiency and the preservation of bioactive compounds.

Studies have also found that ozone improves drying efficiency and color retention in apples and increases the antioxidant activity of lemon peel, despite causing oxidative browning. These findings highlight the dual nature of ozone: while it accelerates dehydration processes, it can also negatively impact product quality.

It's important to note that ozone is unstable at room temperature and must be generated directly at the point of use. Long-term exposure to ozone can pose a health risk, causing respiratory problems, so strict safety precautions and regulations are necessary for its use.

**Conclusion.** Drying technologies for plant materials and their processed products are critical processes that ensure the stability and high quality of end products. In recent decades, significant attention has been paid to innovative methods, such as pulsed vacuum drying, which significantly improve the efficiency of these technologies. These improvements are particularly relevant for products requiring a high degree of preservation of biologically active components.

Thermal drying methods, including spray drying, are fast; however, high temperatures can lead to the degradation of heat-labile compounds and color changes. In contrast, spray drying demonstrates a higher degree of color retention, phytochemicals, and antioxidant activity, although it requires significant time and energy. Pre-treatment of raw materials with ozone significantly increases the efficiency of these processes and helps preserve biologically active compounds.

Spray drying is particularly effective for citrus products such as citrus tea and snacks, preserving flavor and nutrients. Freeze-drying remains the preferred method for maximizing nutrient retention. Depending on the specific application, various specialized drying methods are used: microwave drying for extracting essential oils, spray drying for optimal powder solubility, hybrid drying for preserving snack quality, and convective drying for processing pomace on an industrial scale.

Promising scientific research is aimed at developing drying methods that maximize the preservation of phytochemicals. These advances could significantly expand the range of plant-based products, enhance their nutritional value and commercial appeal, opening up new opportunities for the global functional food and pharmaceutical markets.

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