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ANALYSIS OF METHODS AND MEANS OF DRYING OF AGRICULTURAL MATERIALS

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Most agricultural materials contain a significant amount of water, which is part of plant tissues and is their necessary component. However, excess water reduces the nutritional value of agricultural materials, increases storage and transportation costs, and can cause spoilage due to the activity of various microorganisms. Every year, Ukraine harvests a significant harvest of vegetables, fruits, and berries. But no more than 65% of the grown crop reaches the consumer. For long-term preservation of fruit and vegetable raw materials and other agricultural materials, special processing is necessary to prevent their spoilage. One type of such processing is drying.

Preserving products by drying is one of the methods known since ancient times. There are many agricultural products in which drying occurs spontaneously in nature. In modern conditions, mechanization and intensive use of energy in the food and agricultural industries are also applied to drying processes. In the shortest terms, the drying process can be defined as the removal of water from solids.

An analysis of methods and means of drying of agricultural materials and their classification for further implementation in practice of the most energy-efficient drying method is carried out in this article. The analysis of existing methods and means of drying of agricultural materials made it possible to identify the shortcomings of the drying process, which in the future will allow developing promising ways of improved drying technology.

Considering that the development of technical solutions aimed at intensification and energy saving of the drying technological process is an urgent scientific and technical task of the agro-industrial production sector in Ukraine, based on the generalization of literature data, the co-authors of the article developed two ways to intensify the drying process of agricultural materials: improving the means of drying of agricultural materials and improving the methods of drying of agricultural materials.

Key words*: drying of agricultural materials, drying methods, drying means, humidity, moisture evaporation, heated surface, technological process, intensification of the drying process.*

Fig. 1. Table. 3. Ref. 29.

1. Problem formulation

The increase in production volumes in the food and processing industries against the background of rising energy prices creates a need to develop promising energy- and resource-saving technologies and equipment. The largest energy consumption in these industries is accounted for by heat and mass transfer processes, in particular the drying process. Existing drying equipment is inefficient, the drying quality is low. They are bulky, metal-intensive, energy-intensive, difficult to maintain and repair, and are characterized by high cost.

Solving this problem is possible through the development and application of new equipment and technologies that should increase the efficiency of production of high-quality food products, ensure the release of new types of products, and reduce the loss of raw materials, energy, and material resources.

Therefore, further research should focus on creating innovative drying units that combine high productivity with low energy consumption, ensuring precise control of drying parameters and uniform moisture removal across the material layer. The integration of renewable and waste heat sources, along with automation and intelligent control systems, will significantly enhance the energy efficiency and environmental performance of drying equipment. The implementation of such advanced technologies in the food and processing industries will not only improve product quality and storage stability but also reduce production costs and contribute to sustainable development in Ukraine's agro-industrial sector.

2. Analysis of recent research and publications

In the technical literature, various methods of dehydration of raw materials of plant and animal origin are described. In relation to agriculture and food industries, this is associated with the general task of increasing the storage of fruit and vegetables and other agricultural products, for which numerous technologies for drying various products have been created in recent decades. Moreover, these technologies are increasingly widely used [1-5], and there is an increase in the production of dried vegetables and fruits.

At any scale of use of drying technologies, the main task is to implement a number of technical and economic parameters, such as: minimum possible energy intensity of the process; maximum uniformity of drying; minimum time to reach a given humidity and other characteristics of the drying process. These parameters can be ensured by a rational approach to the selection of the most suitable for a given specific situation basic physical processes leading to dehydration of products, corresponding drying technologies and, finally, by creating equipment on which the specified processes and technologies can be implemented.

Properly organized drying of agricultural materials is impossible without knowledge of the peculiarities of the drying process and the physical and mechanical properties of the material. Such studies were conducted in different years in Ukraine and abroad. These include the works of Kotov B.I. [6], Kalinichenko R.A. [7], Lisetsky V.O. [8], Didukh V.F. [9], Spirin A.V. [10], Snezhkin Yu.F. [11], Pazyuk V.M. [12], Bandura V.M. [13], Tsurkan O.V. [14], Zozulyak I.A. [15], Yaroshenko L.V. [16], Tverdokhlib I.V. [17], Voznyak O.M. [18], Prysyazhnyuk D.V. [19], Yaropud V.M. [20], Babin I.A.[21], Cook E. [22], Brooker D. [23], Bala B. [24] etc. However, very little attention has been paid to the direct study of the drying process of agricultural materials using various methods and the search for ways to intensify the process.

3. The purpose of the article

The purpose of this study there are analysis of methods and means of drying of agricultural materials and their classification for the possibility of further implementation in practice of the most efficient, from an energy point of view, drying method.

4. Results and discussion

Drying of materials is one of the most common technological operations found in almost all industries.

Drying of agricultural crops is an important stage of post-harvest processing, which involves removing excess moisture to ensure long-term storage of the crop, and with the right mode, it improves their quality and destroys pests.

Comparing different drying methods, it can be stated that drying wet materials is not only a heat-technical, but also, above all, a technological process. The main goal of grain drying is to obtain grain with the best properties, therefore the choice of a specific method is determined by the properties of the given material and the optimal drying modes.

Agricultural materials are dried by various methods based on two main principles (Table 1) [25, 26]:

1) removal of moisture from the material without changing its state of aggregation, i.e. in the form of a liquid;

2) removal of moisture from the material by changing its state of aggregation, that is, by converting it into steam.

The first method of moisture removal includes sorption and mechanical methods.

The sorption method is carried out by direct contact of wet grain with hygroscopic substances (sodium sulfate, activated carbon, dry grain, etc.). In this method, the wet material is mixed with a moisture absorber and kept for a certain time. The same principle is used when mixing wet grain with drier grain of the same crop. In this method, part of the moisture passes from the wetter grain to the less moist one, and the moisture content of the entire grain mass is equalized [21].

Table 1

Classification of methods and techniques for drying of agricultural materials

Drying methods	Drying methods
Without changing the state of aggregation of moisture	Mechanical dehydration: - pressing; - filtration; - centrifugation
	Sorption drying
With a change in the state of aggregation of moisture	Convective drying - at atmospheric pressure; - vacuum drying
	Conductive drying
	Radiation drying: - natural; - artificial
	Electric drying
	Molecular drying
	Acoustic drying
	Combined drying

Mechanical dehydration is a method of removing free moisture [18]. In this case, free moisture is removed by gravity and centrifugal force.

The second method of moisture removal with a change in the aggregate state is thermal drying. This method is associated with the expenditure of heat to change the aggregate state of water, transforming it from a liquid state to a gaseous state [27].

Depending on how heat is transferred to the drying object, the following methods of thermal drying are distinguished: convective, conductive (contact), radiation, electrical (high-frequency currents), molecular, acoustic, and combined.

The use of certain drying methods is determined by the energy of the bond between moisture and the material.

The convective method is used for drying grain, feed, etc. The heat required to heat the material and evaporate moisture from it is transferred by convection from a moving gaseous heat carrier – the drying agent, which is heated air. The drying agent not only transfers heat to the drying object, but also absorbs and removes the moisture evaporated from it.

Conductive, or contact, is the drying method in which the grain comes into contact with a heated surface and receives heat directly from it through conduction (thermal conductivity).

In the radiation drying method, heat is supplied to the wet material in the form of radiant energy. Radiation drying can be divided into natural (solar) and artificial (infrared). The simplest drying method is natural radiation or solar drying. However, the possibilities of this method depend on the season, weather and climatic conditions.

Infrared dryingis characterized by a high heat flux voltage, which occurs on the surface of the irradiated material. Thermal radiation infrared heat application (micronization) [20] causes intense heating of the grain, so the moisture contained in it, evaporates. Given the rapidity of this process, the pressure of water vapor increases, and, as is known, an increase in temperature and pressure significantly accelerates the course of chemical reactions, and to a certain extent biochemical ones. In connection with This results in significant destruction of toxic substances, partial Protein denaturation occurs, the structure of raw starch is destroyed. After such processing, the grain is suitable only for feed purposes, for feeding animals. The advantages of this method include: short duration and high efficiency of the process. Therefore, its application is limited by the properties of the materials being dried. Along with this, dryers that operate on this principle have a high fire hazard and process temperature, negatively affect the nutrient conservation and significant electricity consumption [5, 8].

Electrical drying of agricultural materials, in particular grain, with high-frequency currents, despite a number of advantages (fast and uniform heating of the material, very high drying intensity), is not widely used due to the high consumption of electrical energy (over 3 kWh per 1 kg of evaporated moisture).

Sublimation(or molecular drying) is carried out under conditions of deep vacuum. The sublimation drying method is used for drying fruits, vegetables, and various biological preparations. However, this method has not been widely used due to the relatively low productivity of drying plants, the complexity of the equipment, and the high cost of the drying process.

Also one of the effective methods is acoustic drying [10, 11]. Acoustic drying of products is based on the effect of intense ultrasonic waves on the product being dehydrated. This drying process is cyclical, the wave “knocks out” the moisture on the surface of the product, then the remaining moisture is evenly distributed through the capillaries and the process is repeated again. This happens until the product reaches a given humidity.

The fundamental feature of the method is that the acceleration (by 2...6 times) of the drying process of products occurs without increasing their temperature. The so-called "cold drying" is implemented. This circumstance eliminates the negative consequences associated with the thermal effect on the product. That is why acoustic drying is the only method suitable for drying heat-sensitive materials and substances that are easily oxidized.

The use of combined methods allows to significantly increase drying speed, reduce energy consumption, achieve more flexible process management and as a result not only reduce all valuable qualities of the material being dried, but also often improve them. To the combined The methods include: radiation-convective, conductive-convective, etc. For example, rapid heating in a field of high-frequency currents with evaporation of moisture by a stream of heated air allows for more than twofold reduction in electricity consumption (compared to high-frequency) and increase the drying speed twice (compared to convective).

Today, the most effective method of heat transfer for drying of agricultural materials is convective. Depending on the design, dryer, it may use a certain method that characterizes the state of the material during the drying process.

In agricultural production, installations of various technological designs and different operating principles are used for grain drying at elevators and grain receiving enterprises. When developing technological designs of grain dryers, the main attention is paid to saving thermal energy at each stage, which accounts for 90% of all energy costs [2, 6, 7].

The main feature that significantly affects the design and technological scheme of drying plants is the drying methods implemented in them. Dryer designs are extremely diverse, they differ in the principle of operation, in by the features of the supply of the drying agent, by the frequency of its use and by the design. Analyzing the known designs of dryers, we can propose the following classification, which is presented in Table 2. In addition to the indicated main features (see Table 2), for a more detailed classification of drying units it is necessary to take into account the type of drying agent (natural atmospheric air, heated atmospheric air, superheated steam, furnace or inert gases), the state of the drying agent (normal pressure, vacuum), etc.

Table 2

Classification of drying equipment for agricultural materials

Classification feature	Types of drying equipment
Mode of operation (method of action)	Periodic action
	Continuous action
	Cyclic action
Construction	Cabinet-shaped
	Chamber
	Corridor (tunnel)
	Tubular
	Screws
	Waltz
	Cylindrical
	Turbine
	Cascading
	Carousel
	Conveyors (belt, box, tube, etc.)
	Pneumatic
	Spraying
	Vibrating
	Mines
	Blinds

Type of drying agent	Air
	Gas
	Gas-air
	Steam
	Liquid
Type of drying facility	Solid
	Granular (dispersed)
	Dusty
	Pasty
	Liquid (solution)
The method of supplying heat to thedrying object	Convective
	Conductive
	Radiation
	Electric
	Combined
Pressure in the drying chamber	Hermetically sealed chambers with excess pressure
	Atmospheric
	Vacuum sealed chambers with pressure above the triple point
	Medium vacuum and deep vacuum (with pressure below the triple point for water vapor)
Circulation of drying agent	Natural circulation of drying agent
	Forced circulation of the drying agent using axial or centrifugal fans
The nature of the movement of the drying agent relative to the material	Direct flow (with the same direction of movement of the drying agent and material)
	Counter-flow (with opposite direction of movement of drying agent and material)in)
	With the penetration of the layer of the drying object by a flow of drying agent
Method of heating the drying agent	Drying units with steam heaters
	Drying units with water heaters
	Drying units with fire heaters
	Drying units with electric heaters
Drying process option	Throwing the drying agent outside
	With recirculation of drying agent
	With intermediate heating of the drying agent
	With additional heating of the drying agent in the drying chamber
Method for removing steam and regenerating spent drying agent	Exhausting steam with spent drying agent to the outside
	Mixing with fresh agent and heating (recirculation)
	Drying with reagents (silica gel, etc.)
	Condensation of steam in a condenser
	Freezing of steam in the condenser using refrigerant
Using a drying agent	With one-time use of drying agent
	With reusable drying agent
Mobility	Stationary
	Mobile
	Mobile

The most widespread method of heat transfer in dryers is the convective method [2, 3, 5, 6, 14, 23]. In this case, the main technological characteristic is the state of the material layer during the drying process. In convective drying, the drying object can be in the state of a dense stationary, gravitational, fluidized, vibro-boiling, falling or suspended layer.

The designs of drying plants depend on the scale of production and the properties of the material, drying in which is carried out under atmospheric pressure or vacuum, while the material can be at rest, moving, or mixed. Table 3 shows comparative technological indicators of grain drying depending on the methods and designs of the plant.

Peasant and farm households, unlike large commodity producers, mainly use slow-moving drum-type installations for grain drying, which implement the method of high-temperature convective drying of bulk materials [26, 27].

Table 3

Technological indicators of drying methods depending on the design of the drying equipment

Waydrying	Specificenergy consumption, kWh per 1 kg of steam. moisture	Difficulty ratingequipment			Environmental safety of the method	Heating time,hour	Humidity reduction, %
		Metal capacity	Complexity of technology	Difficulty in maintaining equipment			
Induction	0.6…0.8	Medium	Low	Does not require specialists	Safe	0.5…1	24…16
Convective	1.6…2.5	High	Medium	Does not require specialists	Safe	4…5	19…15
Conductive	1.5…1.7	Medium	Medium	Does not require specialists	Safe	2…4	20…15
Radiative(infrared radiation)	0.9…1.2	Low	Low	Does not require specialists	Safe	1…2	20…14
Currenthigh frequency	2.3	Medium	High	Requiresspecialists	Dangerous	1…2	19…15
Micro-nizationgrains (microwave processing of grains)	0.2…0.25	Low	High	Requiresspecialists	Dangerous	1…2	20…14

The development of technical solutions aimed at intensification and energy saving of the technological process of grain drying is a relevant scientific and technical task of the agro-industrial production sector in Ukraine.

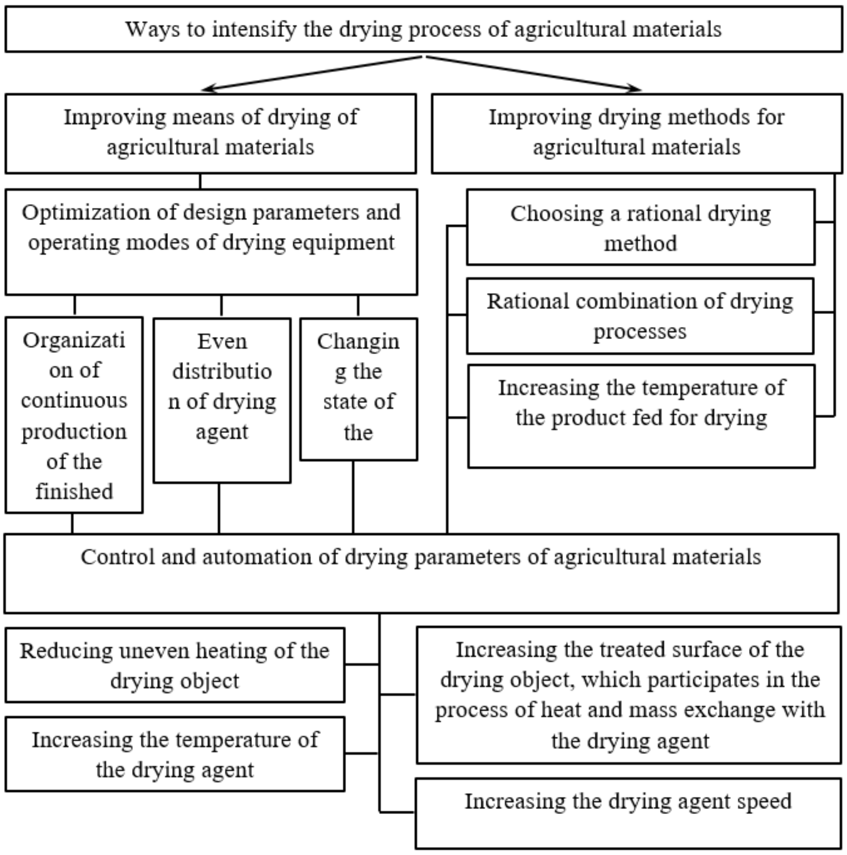

Fig. 1. Ways to intensify the drying process of agricultural materials

The intensification of the drying process should be based on measures that take into account the regularities of the phenomena of internal moisture transfer and external heat and moisture exchange. A comprehensive impact on the intensification of external moisture exchange and internal moisture transfer can be achieved on the basis of an optimal combination of technological methods used for dehydration of agricultural materials in dryers that are operated and designed.

The generalization of literature data [1-20, 28, 29] and the conducted studies allowed us to develop two ways to intensify the drying process of agricultural materials (Fig. 1).

In the area of internal moisture transfer, the process can be intensified by increasing the grain temperature and eliminating the inhibitory effect of thermal moisture conductivity. This can be achieved based on a combination of physical mechanisms of influence, in particular, using high-frequency voltage, the application of which leads to a number of technical advantages of the relevant technological processes:

- the uniformity of humidity by volume of dried products is significantly increased due to the absence of local overheating of the product due to the specific selective nature of the release of high-frequency energy, and the preservation of food products during the drying process is increased;
- if necessary, during high-frequency drying, the maximum achievable final moisture content of the dried product can be reduced;
- it is possible to significantly reduce the drying time and reduce the energy intensity of the technological process (especially for processes in which it is necessary to obtain low final moisture contents).

In the field of external moisture exchange, the process can be intensified by increasing the temperature and speed of the drying agent, as well as increasing the active surface of the grains participating in the process of heat and moisture exchange with the drying agent. For this purpose, dryers with a suspended layer of material with different hydrodynamics are used, which determines the residence time of the dried material in the apparatus, the permissible temperature of the drying agent, the intensity of the heat and mass exchange processes, and the energy costs for the drying process. The use of active hydrodynamic modes allows you to significantly intensify the drying process without reducing economic efficiency, ensuring high quality of the finished product, complete safety and processability of the process.

5. Conclusion

1. Analysis of existing methods and means of drying of agricultural materials made it possible to identify the shortcomings of the drying process, which are mainly associated with poor-quality processing of raw materials, significant energy consumption, and complexity of equipment operation, significant metal consumption and cost of drying plants.

2. At any scale of use of drying technologies, the main task is to implement a number of technical and economic parameters, such as: minimum possible energy intensity of the process; maximum uniformity of drying; minimum time to reach a given humidity and other characteristics of the drying process. These parameters can be ensured by a rational approach to the selection of the most suitable for a given specific situation basic physical processes leading to dehydration of products, corresponding drying technologies and, finally, by creating equipment on which the specified processes and technologies can be implemented.

3. In the practice of agricultural production, various techniques are used to intensify the drying process of agricultural materials: the use of heated air, preheating the drying object, the use of recirculation modes, vacuuming the drying zone, changing the gas composition of the drying chamber, and many others.

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АНАЛІЗ МЕТОДІВ І ЗАСОБІВ СУШІННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ МАТЕРІАЛІВ

У більшості сільськогосподарських матеріалів міститься значна кількість води, яка входить до складу рослинних тканин та є необхідною їх складовою. Однак, надлишок води знижує поживну цінність сільськогосподарських матеріалів, збільшує витрати на зберігання і транспортування та може викликати псування внаслідок життєдіяльності різних мікроорганізмів. Щорічно в Україні збирається значний урожай овочів, фруктів і ягід. Але до споживача з вирощеного урожаю доходить не більше 65%. Для тривалого збереження плодоовочевої сировини та інших сільськогосподарських матеріалів необхідна спеціальна обробка з метою запобігання її псування. Одним з видів такої обробки є сушіння.

Зберігання продуктів шляхом сушіння – це один із методів, відомих з давніх часів. Існує багато сільськогосподарських продуктів, в яких сушіння відбувається спонтанно в природі. У сучасних умовах механізація та інтенсивне використання енергії в харчовій та сільськогосподарській галузях також застосовуються до процесів сушіння. У найкоротшому вираженні процес сушіння може бути визначений як видалення води з твердих речовин.

У даній статті проведено аналіз методів та засобів сушіння сільськогосподарських матеріалів та запропоновано їх класифікацію для подальшої реалізації на практиці найбільш ефективного з енергетичної точки зору методу сушіння. Аналіз існуючих методів і засобів сушіння сільськогосподарських матеріалів дав змогу визначити недоліки процесу сушіння, що в майбутньому дасть змогу розробити перспективні шляхи удосконаленої технології сушіння.

Враховуючи те, що розробка технічних рішень, спрямованих на інтенсифікацію та енергозбереження технологічного процесу сушіння є актуальною науково-технічною задачею галузі агропромислового виробництва в Україні, на основі узагальнення літературних даних співавторами статті розроблено два шляхи інтенсифікації процесу сушіння сільськогосподарських матеріалів: удосконалення засобів сушіння сільськогосподарських матеріалів та удосконалення методів сушіння сільськогосподарських матеріалів.

Ключові слова: *сушіння сільськогосподарських матеріалів, методи сушіння, засоби сушіння, вологість, випаровування вологи, нагріта поверхня, технологічний процес, інтенсифікація процесу сушіння.*

Рис. 1. Табл. 3. Літ. 29.

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