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IMPROVED THERMORADIATIVE BELT DRYER WITH AIR RECUPERATION AND AUTONOMOUS VENTILATION

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This study considers the process of IR drying of organic raw materials and semi-finished products of mixed composition. A limitation of this process is the insufficient uniformity of drying and preservation of biologically active substances. To address this challenge, the structure of a film-like electric heater of radiating type has been improved by combined heat supply and conductive drying under autonomous ventilation conditions (15…30 W). A universal conveyor belt with replaceable modules expands the range of organic agricultural raw materials and semi-finished products of mixed composition during low-temperature drying (45…65°C).

The drying duration is reduced by 30…35% with an increase in the residual content of biologically active substances by 15…20% compared to the base device. For apples of the Gala variety, the residual content of vitamin C after IR drying was 82.0 ± 3.1 mg/100 g, which is 20% more than in the prototype (68.0 ± 2.5 mg/100 g). In carrots of the Shantane variety, the residual content of β-carotene after IR drying was 87 ± 2.5%, which is 17% higher than in the prototype (70 ± 3%). In chokeberry, the preservation of anthocyanins is 92 ± 3%, in contrast to the prototype (76 ± 4%), in parsley, the preservation of chlorophylls is 82 ± 4% (the prototype is 65 ± 5%). In meat and vegetable semi-finished products, the preservation of antioxidant activity is 84 ± 2% (versus 72 ± 3%).

The combination of film-like heating, recovery of secondary warm air, autonomous ventilation by Peltier elements, solar collector, and photovoltaic panel with battery contributes to resource saving (20…30%) and stabilization of the temperature field (ΔT = 12…18°C). The results confirm the functional and modular properties of the improved device for the "from farm to fork" system for the production of functional semi-finished products with a high degree of readiness

Keywords: low-temperature drying, mobile IR dryer, unified conveyor belt, autonomous ventilation, secondary air recovery

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1. Introduction

Competitive processing of agro-food products by drying organic raw materials contributes to the production of functional products with a wide range of uses in the form of independent semi-finished products and natural ingredients included in the formulations of new generation products [1]. Everyday use of traditional equipment with significant energy and metal consumption and intermediate heat carriers leads to the loss of natural ingredients important for the daily human diet and changes in the organoleptic and rheological properties of products [2]. This creates a need to implement innovative resource-saving and circulation innovative models of processing of agro-raw materials to support the food security of European countries in the face of modern challenges [3].

For example, for countries involved in military conflicts, the destruction of infrastructure (agricultural, food, energy, logistics and others) is inevitable; in addition, with the deterioration of the environmental situation, the spread of chronic diseases and various pandemics increases. This necessitates the introduction of innovative mobile heat and mass exchange complexes, in particular drying ones, to support their own agricultural enterprises in terms of resource-saving low-temperature processing of organic raw materials into semi-finished products of a high degree of readiness and semi-finished products of mixed composition [4]. This approach forms the support and sustainable development of food security of countries, providing consumers with an affordable natural diet to confront modern challenges in the field of production of functional healthy food. This also creates interest in the implementation of innovative approaches in the design of competitive resource-saving and functionally mobile equipment for drying organic raw materials and semi-finished products of mixed composition in the agri-food sector and craft industries of European countries.

The most practical engineering and technological solutions for modern dryers are the formation of low-temperature processing by using flexible film electric heaters with a geometric arrangement in the working chamber to obtain mixed heat supply (IR radiation and conductive). The use of Peltier elements on the grounded working surfaces of the dryer contributes to the conversion of secondary thermal energy into low-voltage voltage for autonomous power supply of the ventilation system, and therefore – the formation of the convective component of drying. In addition, the introduction of secondary air recirculation systems and solar collectors into the design will contribute to increasing the resource efficiency of dryers and their autonomy for mobile use at agricultural enterprises with simultaneous stabilization of low-temperature operating parameters [5]. In turn, the use of a universal conveyor belt in dryers for installing replaceable modules (flat, perforated, and cassette-geometric) expands the range of use of devices for resource-saving processing of organic agricultural raw materials and combined semi-finished products [6].

The relevance of using modern engineering and technological solutions for the design of an innovative improved mobile thermal radiation belt dryer relates to the rational preservation of biologically active substances (BAS) of the processed raw materials. The scientific and practical implementation of the above approaches will contribute to energy and technological independence and competitiveness in the production of high-grade functional organic semi-finished products in the context of the global trend of sustainable development "from farm to fork" and supporting food security. Thus, the global challenges of resource conservation and preserving the quality of new products in combination with the local consequences of military operations form the need for mobile drying systems for effective processing of agricultural raw materials.

2. Literature review and problem statement

The issue of improving technological equipment for the production of powder semi-finished products is considered in work [7] with the analysis of traditional devices, which are practically impossible to adapt to low-temperature and resource-saving processing of organic raw materials while preserving their natural properties. Thus, in [8], a systematization was carried out to determine the efficiency of drying during the processing of grain, fruits and vegetables. Under the conditions of using various known drying methods, including hot air, IR radiation, vacuum, heat pump, solar energy and sublimation technologies, it is important to study the formation of resource-saving process when combining them. In particular, the use of combined IR drying provides low-temperature drying with a reduction in total technological costs by 25…30%; however, the efficiency for functional mobile dryers remains insufficiently studied, which confirms the feasibility of further research.

Thus, in work [9], research continues on increasing the energy efficiency of the drying process by implementing innovative solutions to increase alternative energy savings in the global energy balance, taking into account structures, heat and mass transfer, and the resulting quality. In addition, the authors state that in most practical cases, only 50...60% of the heat in the working chamber of dryers is used to evaporate moisture from the raw material. At the same time, the remaining heat (40...45%) is lost in the form of secondary air under convective removal conditions, which reduces the resource efficiency of drying, in particular in a fluidized bed. The generalized dependence of the drying process on the type of heat source, the consistency of the raw material, the uniformity of the temperature field, and the possibilities of recovering secondary air for technological needs is emphasized. However, the work does not include research on the effectiveness of using metal-free film electric heaters of the radiant type in the drying process during the modernization of classical equipment and the development of functional mobile dryers. This may be partly due to the conduct of certain studies under conditions of direct dependence between the design and technological cycle and the preservation of BAS and organoleptic properties of the resulting semi-finished products of a high degree of readiness. This emphasizes the feasibility of scientific and practical research to determine the possibilities of forming functional modular devices with a low-temperature range of drying organic plant raw materials for the needs of the agro-food sector and craft industries. For example, in [10], scientific research continues on the systematization of the efficiency of using combined technologies for drying various agricultural raw materials under conditions of using a fluidized bed compared to combining IR-convective drying. However, the research does not consider the issue of implementing engineering solutions aimed at using recuperation systems and autonomy of structural elements, thereby complicating the functional mobility necessary for the agro-food sector. Special attention is required for drying thermolabile organic raw materials (fruits, vegetables, berries, herbs, meat-vegetable mixtures), for which the loss of BAS (vitamin C, carotenoids, anthocyanins, and others) during high-temperature processing on classic energy-intensive equipment can reach 30...50%. A review of scientific and practical research indicates an insufficient number of works that simultaneously analyze the drying modes and preservation of BAS in the field of combining methods for drying organic products under conditions of resource-saving technology.

In [11], the design of a thermoradiation single-drum roller dryer with a combined heat supply method (IR + conductive + convective) for obtaining a powdered semi-finished product with a content of 3…5% dry matter (SD) was considered. Drying of a pre-blended pasty semi-finished product (45% SD) based on apple, sea buckthorn, chokeberry, beetroot, and pumpkin with different recipe ratios was carried out at a temperature of 65°C. The proposed design solution contributes to obtaining high-quality semi-finished products due to low-temperature drying. However, the issues of the possibility of using secondary exhaust air and recovery systems remain out of consideration. From the diagram of the device, it can be concluded that it is stationary and works in conjunction with evaporators for simultaneous drying of the pasty semi-finished product, which expands the functional spectrum of use of secondary agricultural raw materials. This may be due to the implementation of engineering solutions aimed at improving industrial structures; however, today there is a need to improve functionally modular devices, which, in turn, requires scientific and practical research in this direction.

For example, in [12], a scientific and practical approach to low-temperature processing of delicatessen meat products, which occupy a significant share in the diet of many versts of the population, is presented. The low-temperature design involves the use of a flexible film-like electric heater with the possibility of cooling the product by autonomous fans powered by the voltage of Peltier elements. The model structure provides a 2.6-fold reduction in specific costs compared to traditional devices (methods), which emphasizes the feasibility of adapting such solutions in functionally mobile dryers for decentralized processing of agricultural raw materials. And in work [13] data on concentration of multicomponent puree mass (apple, pumpkin, and beet) in a gentle temperature range (50...55°C) in a rotary film apparatus to a content of 45% DM within 1.25...2.0 min are reported. The obtained paste-like semi-finished product of high degree of readiness was used as a recipe natural ingredient in the production of marshmallow under conditions of replacement of 75% of apple puree with an experimental blend. This, in turn, allowed the authors to increase the content of physiologically functional ingredients in marshmallow. Thus, the demand for improvement of functional-modular equipment for processing agricultural raw materials into semi-finished products of high degree of readiness under conditions of low-temperature processing of plant raw materials to preserve BAS is supported [14].

In [15], a new hybrid dryer is designed that can operate around the clock using solar energy as an alternative source of temperature and biomass as the main energy source. During the research, it was found that the efficiency of heat supply is about 85% and is characterized by a reduction in the duration of heating by 16.7% during the testing of potato drying. However, the use of biomass limits the mobility of the structure and requires the use of appropriate raw materials for work, namely biomass, and the issue of recovery is not considered in the work. The need for scientific and practical research and the search for innovative solutions for the development of functionally modular dryers is emphasized, which are especially necessary for countries in which military operations are taking place or the energy situation is complicated.

In particular, in [16], it was found that up to 40% of usable heat is lost through the ventilation ducts of dryers during the drying of wood particles. At the same time, issues aimed at recovering the waste heat volume to increase the resource efficiency of the technological cycle during convective drying are not considered in any way, which may be partly due to the use of conventional obsolete equipment. One of such solutions is reported in [17], which provides a detailed analysis of the impact of the percentage of secondary air recovery on the level of preservation of the total energy potential, taking into account the raw materials being dried. Comparative analysis confirms the feasibility of implementing secondary air recovery systems, but it is advisable to determine the effectiveness of these measures when improving functional modular structures. For example, the practical use of solar collectors in drying technologies contributes to the formation of an alternative energy source in mobile structures of agricultural complexes with the simultaneous possibility of autonomous operation of the devices for 6 hours [18]. However, issues related to determining the efficiency of secondary air recovery in such devices were ignored, which emphasizes the feasibility of scientific and practical research into this area. One such solution is given in [19], which investigated the drying process of solid dispersed semi-finished products using hybrid combined IR drying processes. However, the studies were carried out without considering the feasibility of introducing mobility and autonomy of devices in decentralized use, which is important for supporting front-line areas. An important factor in the present and decentralized use of mobile devices is ensuring reliable remote transmission of technological parameters and operational control over the hardware and technological cycle, which can be carried out by transmitting data via short-packet communication systems that are stable under conditions of limited energy consumption [20]. Despite the fact that this technology belongs to the field of telecommunications, it is precisely such approaches that make it possible to ensure resource-saving autonomy of systems in decentralized drying technological cycles in agricultural complexes and craft industries through digitalization. Thus, it can be stated that the practical decentralized use of hybrid IR drying during corn drying [21] is characterized by a reduction in the energy consumption of the technological cycle by simultaneous conductive and radiant heating and requires remote control of the heat and mass transfer process. But the work does not consider the probable influence of the secondary heat flow, which is inevitably formed in the process of combined drying of agricultural raw materials. This emphasizes the feasibility of research into this area for the implementation of effective recovery systems.

The average heat losses through the secondary air ventilation channels of dryers are on average 15...20% [22] in designs without recovery systems, the process is characterized by a direct dependence on the method of heat supply and the temperature range of thermal treatment of raw materials. For example, in the course of experimental and practical studies with IR-assisted drying of pollen [23], uniform dehydration and high quality of the obtained raw materials were determined. However, the questions regarding possible effective ways of stabilizing the temperature profile and uniformity along the moving layer of the air medium to prevent local zones, and as an option, the use of Peltier elements in them, remain unresolved.

Work [24] reports the results of studies on the effectiveness of using microwave technologies during the processing of fruit and vegetable raw materials, considering the risk of local overheating, which will lead to inevitable losses of BAS and organoleptic properties. This emphasizes the feasibility of processing agricultural raw materials and combined semi-finished products of mixed origin, obtained by blending vegetable, fruit and vegetable, cereal, protein-fat or meat-vegetable components of low-temperature hybrid drying modes. For example, even cyclic supply of heated air to the working chamber of the dryer leads to a reduction in energy consumption within 25...30% [25]; however, from a practical point of view, it requires additional use of exhaust secondary air regeneration systems for preheating the primary air before the technological cycle. In particular, the thermodynamic analysis of the technological process of drying carrots, given in [26], confirms the advantages of gentle temperature ranges (55°C) for preserving carotenoids. At the same time, long cooling/heating cycles during drying, on the contrary, can lead to vitamin degradation, and therefore requires research into this area.

One of the practical solutions of low-temperature drying under reduced pressure is given in [27] to achieve preservation of the final quality of agricultural raw materials. However, this, in turn, requires a complex vacuum system, thereby complicating the mobility and functionality of the technological solution. On the other hand, under the conditions of mobility of heat and mass exchange equipment and its decentralized use, there is a practical need to assess the technological costs and efficiency of the technological cycle under conditions of limited resources. This can be partially solved by using simulation approaches when modeling the cost of telecommunication services [28]. Such actions would make it possible to model the resource efficiency of the raw material drying process, taking into account the structural and technological systems of low-temperature dryers to optimize the cost structure and operating costs while maintaining maximum product quality.

The introduction of thermoelectric systems based on Peltier elements could contribute to the combined combination of hybrid IR heating and cooling of secondary air under the conditions of recovery and obtaining low-voltage power supply for autonomous operation of structural elements of belt dryers [29]. This, in turn, would provide a certain counterbalance to stationary hybrid complexes based on solar and microwave energy [30], which demonstrate a certain technological efficiency. However, the functional mobility of decentralized devices requires the use of less complex systems under conditions of maximum preservation of the initial properties of the raw materials. In particular, work [31] describes a study on the process of concentrating multicomponent pastes in rotary film devices, which emphasizes the feasibility of using film heating of the puree mass under the conditions of forming a resource-saving process. This emphasizes the general limitation of scientific and practical research necessary for the formation of integrated decentralized belt systems for low-temperature drying of organic raw materials and semi-finished products of mixed composition. There is no complete data on the effectiveness of using film-like IR emitters, secondary air recovery systems, and autonomous ventilation systems based on Peltier elements to expand the functionality of equipment even in front-line areas. The problem is posed by a limited number of effective practical resource-saving solutions aimed at obtaining functionally mobile dryers capable of ensuring uniform drying with maximum preservation of the original properties of raw materials. This is relevant even under the conditions of limited resources of front-line regions and the need to support agro-food sectors and craft industries to ensure food security of countries.

3. The aim and objectives of the study

The aim of our work is to improve the functional-modular IR belt dryer for organic agricultural raw materials and semi-finished products of mixed composition. The implementation of the proposed engineering and technological solutions will contribute to the low-temperature drying of organic raw materials and semi-finished products of mixed composition with the preservation of natural properties under the conditions of decentralization of the production cycle and remote digital control of drying.

To achieve the set goal, the following tasks must be solved:

– to design a model structure of an IR belt dryer with the combined use of FEhRt, Peltier elements with autonomous fans, a recuperation system, a unified conveyor belt with replaceable modules, a solar collector of a photovoltaic panel with a battery;

– to experimentally substantiate the effectiveness of the improved thermal radiation belt dryer by comparing the drying duration and the level of preservation of bioactive substances in different types of raw materials (grain, vegetable, fruit and berry, herbal, and meat and vegetable) with the control prototype.

4. The study materials and methods

The object of our study is the process of IR drying of organic raw materials and semi-finished products of mixed composition.

The hypothesis of the study assumes that the combination of the use of FEhRt, autonomous fans based on Peltier elements, and a recuperation system of secondary warm air would ensure increased resource efficiency of the drying process. It is assumed that the additional use of a unified conveyor belt with replaceable modules, a solar collector, and a photovoltaic panel would contribute to the autonomy of the apparatus for low-temperature drying of organic raw materials.

The assumptions and simplifications adopted were based on the assumption of uniform thickness and identical geometry of the test samples across the entire width of the belt without affecting local moisture deviations and simplifications.

The research was implemented at the production facilities of the scientific and educational center "Innovative resource-saving technologies for processing organic products", the State Biotechnological University (Kharkiv, Ukraine).

During the experimental and practical testing of drying organic agricultural raw materials and semi-finished products of mixed composition, a wide range of experimental raw materials was used. These include wheat of the "Podolyanka" variety, carrots of the "Shantane" variety, beets of the "Bona" variety, pumpkin of the "Perlyna" variety, apples of the "Gala" variety, sea buckthorn of the "Galerit" variety, chokeberry of the "Chornooka" variety, parsley, and mint, as well as meat and vegetable semi-finished products (ground beef with the addition of pumpkin paste of the "Perlyna" variety). Experimental samples were prepared taking into account the type of raw materials, in particular, fresh agricultural raw materials were pre-ground in a blender until a homogeneous puree mass was obtained. Paste-like semi-finished products were pre-boiled for 85 seconds at a temperature of 65 ° C in a rotary film apparatus.

The preservation of the BAS content was carried out under the conditions of using standardized international methodologies, taking into account the thermolabile properties of the experimental raw materials and different experimental consistencies (fresh raw materials, pasty, and dried fraction). Vitamin C in apples was determined by HPLC (ISO 6557-2:2017, ascorbate) using a C18 column and detection (254 nm). In carrots, β-carotene was determined by HPLC (ISO 17932:2021, carotenoids) on a reversed-phase column with detection (450 nm). The anthocyanin content in chokeberry was determined by HPLC (ISO 20752:2014, C3G eq.), expressed in cyanidin-3-glucoside equivalents (520 nm). The content of B vitamins (B_1, B_2, B_6) was determined by HPLC (ISO 13903:2005; EN 14122:2014) with detection (270...290 nm), and the protein content was determined by the Kjeldahl method (ISO 1871:2009). The content of polyphenols was determined using the Folin-Ciocalteu reagent, expressing the results in percentage of preservation relative to the initial level. Chlorophylls in parsley were determined by the UV-Vis spectrophotometric method (Arnon, 645 and 663 nm). The antioxidant activity of meat-vegetable semi-finished products with the addition of pumpkin paste was determined by the DPPH and ABTS methods, recording the percentage of radical suppression at (517 and 734 nm). The scientific and practical assumptions adopted in the course of our study were based on the compliance of the homogeneity and moisture content of the initial semi-finished products with the necessary technological requirements. For example, vegetables and fruits (5...8 mm), spicy and aromatic raw materials – 10 mm (layer), and for cassette-geometric modules – 20...30 mm. The proposed experimental dimensions allowed us to take into account the uniformity of the heat flow across the entire working plane of the universal conveyor belt with replaceable modules of the model dryer design.

Kinematic data of the drying process of agricultural raw materials and semi-finished products of mixed composition on an improved functional-modular model of a belt dryer based on a film-like electric heater of the radiant type (FEhRt) and Peltier elements. The design model is additionally equipped with autonomous fans, a system for recovering exhausted warm air, a unified conveyor belt, a solar collector, and a photovoltaic panel with a battery for autonomous operation in field conditions. Temperature and humidity control in the working chamber was carried out by digital sensors with parameter display on the control unit with a Wi-Fi module for remote control and monitoring. Scientific and practical testing of the improved model was carried out in the operating temperature range of 35...65°C and an adjustable speed of a universal conveyor belt with replaceable modules of 0.2...1.5 m/min.

During the research, the energy consumption, uniformity of the temperature field and uniformity of dehydration across the width of the universal conveyor belt with variable modules were monitored. Energy consumption was measured using a wattmeter during the drying process cycle. The uniformity of the heat flux distribution was determined by thermocouples placed at five points of the cross-section of the working chamber of the apparatus. The uniformity of dehydration was assessed by the residual moisture in three transverse zones of the universal conveyor belt. Statistical processing of experimental data was carried out by the method of variance analysis with a significance level of $p < 0.05$. At the same time, when determining the reliability of the differences between the mean values, the Tukey criterion was used with the marking of reliable differences with the letters (a, b, c) in the table, and identical letters confirmed the absence of statically significant differences. The experiments were repeated in triplicate, and the results are represented as mean values with corresponding standard deviations.

5. Determining the effectiveness of solutions in improving a functionally modular IR belt dryer

5. 1. Construction of an improved model of a functionally modular IR belt dryer with Peltier elements, autonomous ventilation, recuperation, and a solar collector

The improved model of a functionally modular IR belt dryer for drying organic agricultural raw materials and semi-finished products of mixed composition is shown in Fig. 1.

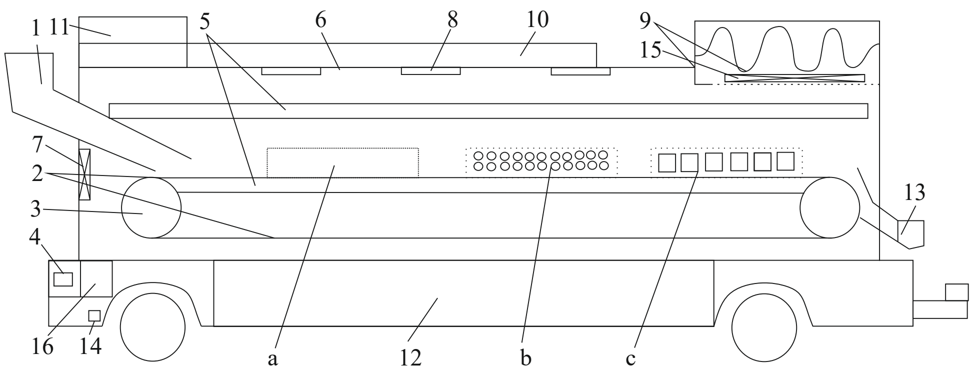

Fig. 1. Diagram of an improved model of a functionally modular IR belt dryer based on autonomous fans connected to Peltier elements, using a recuperation system and a unified conveyor belt with replaceable modules: 1 – feed dispenser; 2 – universal conveyor belt with replaceable modules (*a* – flat Teflon module; *b* – perforated module (metal / polymer); *c* – cassette-geometric module); 3 – shaft (drive); 4 – drive shaft speed regulator; 5 – film-like electric heater of the radiant type (above and below the belt); 6 – thermally insulated housing with sheet aluminum; 7 – pressure fans; 8 – Peltier elements; 9 – exhaust secondary air recovery system; 10 – solar air collector for autonomous heating of primary air; 11 – solar photovoltaic panel; 12 – battery; 13 – unloading weighing hopper; 14 – Wi-Fi module for remote control; 15 – autonomous exhaust fan; 16 – control unit

In the course of scientific and practical research, organic agricultural raw materials and semi-finished products of mixed composition are fed by nutrient dispenser 1 onto the working surface of a universal conveyor belt with replaceable modules 2. The functionality of the improved design involves mounting three types of replaceable modules on the conveyor belt to ensure IR drying of raw materials of various consistencies. The flat Teflon module (a) is intended for grain crops, fractionally cut vegetables, fruits, and berries. The perforated module (b) with a cell diameter of 2...5 mm in a polymer or metal version is intended for finely dispersed agricultural raw materials, including spicy and aromatic raw materials, chopped vegetables and berries. Cassette-geometric module (c) with cells 20...50 mm – for blended pastes and meat-vegetable semi-finished products with the addition of pumpkin paste (other natural fillers can also be used).

The movement of the universal conveyor belt with replaceable modules 2 is carried out by shaft 3, which is driven by an electric motor equipped with speed regulator 4. This, in turn, makes it possible to adjust the operating range of the universal conveyor belt speed on control unit 15 within the range from 0.2 m/min to 1.5 m/min in accordance with technological needs.

Combined low-temperature heating of the improved model of the functionally modular IR belt dryer is implemented by using a film-like electric heater of the radiant type 5. The design provides for the installation of the upper FEhRt above the belt to form the radiation-convective component of drying and under the belt (lower) for conductive heat exchange. The total power of FEhRt (1.8…2.2 kW) under low-temperature processing conditions in the range of 35…65°C to preserve BAS and organoleptic properties.

The improved model of the IR belt dryer has the form of a complex frame made of steel anti-corrosion profiles fixed on aluminum guide profiles with a length of 2 to 4 m. To adjust the size and reduce the weight and metal content of the structure, it is additionally covered with heat-insulating sheet aluminum foam 6, while the side supports are made in the form of scissors for simplified transportation, for example in front-line regions. The overall geometric dimensions of the improved structure during transportation are 2.5 × 1.2 × 1.5 m and it requires 30…40 min for preparation for the technological cycle in the agricultural sector by 2 engineers.

The structure is equipped with a ventilation system based on two injection fans 7, operating under an autonomous mode by converting the secondary thermal energy of the dryer body by Peltier elements 8 into a low-voltage supply voltage (15…30 W). This, in turn, contributes to the saving of energy resources of the electric drive of classic fans, which is especially relevant under the conditions of the mobility of the device and use in front-line regions. The improved functionally modular IR dryer provides for the recovery of secondary warm air in the built-in heat exchanger 9 for preheating the "input" air by 12…18°C and increasing the resource efficiency of the technological cycle. The basis of the IR dryer power supply system is mains (220 V), solar air collector 10 – for partial preheating of the "primary" air and solar photovoltaic panel 11 for powering the fans and charging the battery 12. In turn, equipping the mobile structure with a battery facilitates the use of the device in field conditions for 6…8 kWh or limited energy resources, and therefore 6…8 hours of autonomous operation of the dryer in field conditions. Mounting of an alternative power supply system: solar air collector based on a transparent polycarbonate coating (with a capacity of 1.5….2.0 kW) and a photovoltaic panel is carried out on the roof of the device at an angle of 30…35° for optimal reception of solar energy.

During IR drying in the improved structure, the final product moisture content is achieved within 5...8% due to the installation of humidity and temperature sensors in the chamber, a weight control system for dried raw materials in bunker 13 with automatic weight measurement. The exhaust secondary air is removed by an exhaust fan. Additional equipment of control unit 16 with the ability to digitally transmit technological data via Wi-Fi module 14 provides operational control over the final moisture content for different types of raw materials. The innovative engineering and technological solutions implemented in the improved structure could contribute to the universal use of the IR dryer for a wide range of organic agricultural raw materials and semi-finished products of mixed composition in the "from field to table" system. The basic parameters of the improved functionally modular IR belt dryer are given in Table 1.

Table 1

Technical parameters of the experimental model of the IR belt dryer for organic agricultural raw materials and semi-finished products of mixed composition

Parameter	Value
Working area of a universal conveyor belt with interchangeable modules	0.8…1.2 m^2
Interchangeable module structures	a – flat Teflon, b – perforated (metal / polymer), c – cassette-geometric
Working speed range of universal conveyor belt	0.2…1.5 m/min
Low temperature working ranges of drying	35…65°C
Power of upper film-like electric heater of radiant type	0.8…1.2 kW
Power of the lower film-like electric heater of the radiant type (FEhRt)	0.8…1.2 kW
Ventilation system	Supply fan (2 pcs.) + exhaust fan
Ventilation system performance	50…80 m^3/h
Low voltage from Peltier elements	15…30 W (for fan)
Air recovery efficiency (temperature increase)	12…18°C (preheating)
Main energy sources	220 V mains, solar collectors / battery
Battery capacity	6…8 kW·h
Thermal power of the solar collector	1.5…2.0 kW
Working dimensions (maximum)	4.0 × 1.5 × 2.2 m
Working dimensions (during transportation)	2.5 × 1.2 × 1.5 m
Duration of preparation for the technological cycle in the agricultural sector	30…40 min

After determining the design and functional features of the improved model of the mobile IR dryer, it is advisable to proceed to the experimental substantiation of the effectiveness of the proposed combined solutions.

5. 2. Comparing the efficiency of drying and preservation of bioactive substances in the basic and improved dryer

The results of experimental data processing are shown in Fig. 2, 3.

The drying duration, depending on the type of test sample (raw material), has the following data: wheat of the "Podolyanka" variety (grain) is reduced from 85 min to 60 min; carrots of the "Shantane" variety (vegetable) – from 70 min to 50 min. Apple of the "Gala" variety (fruits/berries) – from 75 min to 50 min, respectively. Leaf parsley (spicy and aromatic) – from 40 min to 25 min and minced beef with the addition of pumpkin paste of the "Perlyna" variety (meat and vegetable semi-finished product) – the duration is reduced from 60 min to 40 min. This was made possible by the combined use of FEhRt, autonomous fans connected to Peltier elements, a secondary exhaust air recovery system, a unified conveyor belt with replaceable modules, and a solar collector.

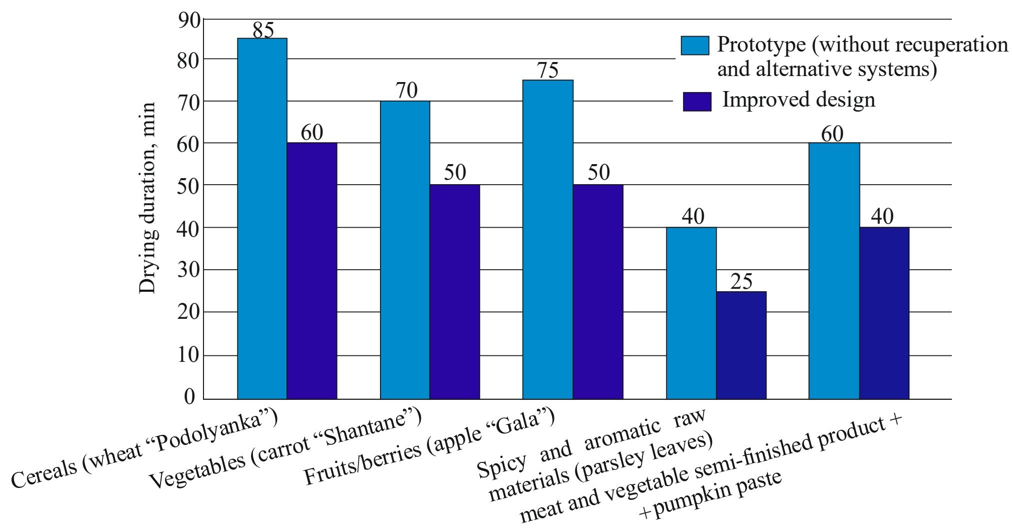

Fig. 2. Comparison of IR drying duration of raw material samples in a basic and improved IR belt dryer

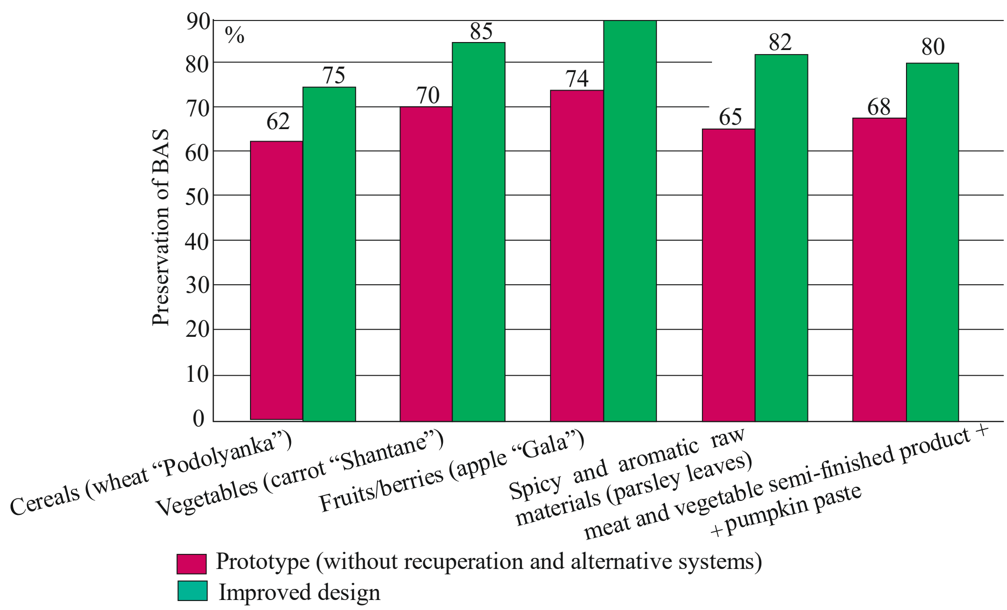

Fig. 3. Comparison of the level of preservation of bioactive substances of experimental raw material samples in a basic and improved IR belt dryer

For cereals (wheat of the "Podolyanka" variety), the preservation of BAS is observed from 62% to 75%. For vegetables, on the example of carrots of the "Shartane" variety, the level of BAS preservation was 70% in the prototype and 85% in the improved model. For fruits and berries, on the example of apples of the "Gala" variety – from 74% to 91%, respectively. The content of BAS in spicy and aromatic raw materials, on the example of leaf parsley, the level of BAS preservation is 65% in the prototype and 82% in the improved model. At the same time, in a meat and vegetable semi-finished product, on the example of beef with the addition of pumpkin paste of the "Perlyna" variety, the BAS content increases from 68% to 80%. The comparative analysis includes experimental samples taking into account the reflection of each group of organic agricultural raw materials and semi-finished products of mixed composition. Other experimental samples: beets of the "Bona" variety, pumpkin variety "Perlyna", sea buckthorn variety "Galerit", chokeberry variety "Chornooka" and mint are given in the general research Table 2. In addition, during the research of grain raw materials on the example of wheat variety "Podolyanka"), the protein content after IR drying in the basic apparatus (10.8 ± 0.3 g/100 g) and, accordingly, in the improved design was determined, which was: 12.2 ± 0.4 g/100 g. At the beginning of the research, it was established that the residual content of vitamins B_1...B_6 after IR drying in the improved apparatus was 0.61 ± 0.02 mg/100 g, which is approximately 13% higher than after drying in the prototype (0.54 ± 0.02 mg/100 g). Therefore, the overall indicator of increasing the preservation of the protein-vitamin complex is actually within +13%.

It was found that the improved device provides a reduction in drying time by an average of 30...35% compared to the prototype and increases the level of BAS preservation by 15...20% in the experimental samples. Wheat of the "Podolyanka" variety is characterized by a reduction in drying time (from 85 min to 60 min) and preservation of the protein-vitamin complex – 75% (62% in the prototype). Carrots of the "Shantane" variety have a reduction in drying time from 70 min to 50 min and a higher residual content of β-carotene: 87 ± 2 mg/100 g, while in the prototype – 70 ± 3 mg/100 g. Beetroot of the "Bona" variety and pumpkin of the "Perlyna" variety are characterized by a reduction in drying time by 27% and 25%, respectively, and preservation of the level of carotenoids up to 86%. Apple of the "Gala variety", sea buckthorn of the "Galerit variety" and chokeberry of the "Chornooka" variety are characterized by a residual content of vitamin C and anthocyanins within 90...92%, exceeding the data of the prototype. In parsley and mint, the content of chlorophylls, essential oils and polyphenols is preserved 1.2...1.3 times higher than in the base dryer. Meat and vegetable semi-finished products are characterized by the preservation of antioxidant activity: 84%, as opposed to 72% obtained in the prototype.

During the research of the improved model, thermodynamic equilibrium was observed in the working chamber: $\Delta T =$ 12...18°C with air circulation within 50...80 m^3/h. It was established that the temperature deviation in the cross-section of the drying chamber did not exceed ±1.5°C, and the difference in residual humidity between the extreme points was < 5%, which confirms the stability of the thermal regime and a high level of resource saving.

Under the conditions of dehydration uniformity along the working width of the belt is 95 ± 2%, thereby preventing local overheating of thermolabile raw materials, and therefore maximum preservation of BAS. The total energy consumption during IR drying by the improved model design was 1.8 ± 0.2 kW, according to the results of experimental and practical studies (prototype – 2.4 ± 0.2 kW), thereby confirming the ability of the device to operate autonomously from a battery (6...8 kWh) or a solar air collector (1.5...2.0 kW) under field conditions, which makes the device an effective resource-saving low-temperature solution for agricultural enterprises, modular lines, and craft production within the "From field to table" concept.

6. Results of research on an improved model IR belt dryer: discussion and summary

An improved model of a functionally modular IR belt dryer has been designed (Fig. 1). This was made possible by using a film-like electric heater of the radiant type and Peltier elements. The structure is additionally equipped with autonomous fans, a system for recovering exhausted warm air, a unified conveyor belt, a solar collector, and a photovoltaic panel with a battery for autonomous operation under field conditions.

Table 2

Comparison of experimental and practical drying results in the prototype and improved IR belt dryer (mean ± *SD*, $n = 3$)

Raw material type / example	Drying duration, min (prototype)	Drying time, min (advanced IR design)	Preservation of bioactive substances, % (prototype)	Preservation of bioactive substances, % (advanced IR design)	Main indicators of chemical analysis after drying	Ret., % (prototype)	Ret., % (advanced IR design)	Dehydration uniformity across the width of the tape, %	Power consumption, kW
Cereals (wheat variety «Podolyanka»)	85^a	60^b	62^a	75^b	Increased retention of protein and B vitamins (+13%)	62 ± 3^a	75 ± 3^b	96.2 ± 1.4	1.9 ± 0.1
Vegetables (carrots of the «Shantane» variety)	70^a	50^b	70^a	85^b	β-carotene 70 ± 3^a → → 87 ± 2^b mg/100 g	70 ± 3^a	87 ± 2^b	95.4 ± 1.8	1.8 ± 0.2
Vegetables (beetroot variety «Bona»)	75^a	55^b	68^a	84^b	Betanin 42 ± 3^a → → 53 ± 2^b mg/100 g; vitamin C 47 ± 3^a → → 59 ± 3^b mg/100 g	68 ± 3^a	84 ± 3^b	95.0 ± 1.6	1.8 ± 0.2
Pumpkin variety «Perlina»	80^a	60^b	69^a	86^b	Carotenoids 48 ± 2^a → → 61 ± 2^b mg/100 g	69 ± 3^a	86 ± 3^b	95.8 ± 1.7	1.8 ± 0.2
Fruit («Gala» apple variety)	75^a	50^b	74^a	91^b	Vitamin C $68.0 \pm 2{,}5^a$ → → $82.0 \pm 3{,}1^b$ mg/100 g	74 ± 3^a	89 ± 4^b	94.7 ± 1.6	1.8 ± 0.2
Berries (sea buckthorn variety «Galerit»)	80^a	55^b	75^a	90^b	Carotenoids 55 ± 4^a → → 72 ± 3^b mg/100 g	75 ± 4^a	90 ± 3^b	95.2 ± 1.6	1.7 ± 0.2
Berries (chokeberry)	80^a	55^b	76^a	92^b	Anthocyanins 76 ± 4^a → → 92 ± 3^b mg/100 g	76 ± 4^a	92 ± 3^b	95.1 ± 1.7	1.7 ± 0.2
Spicy and aromatic raw materials (parsley leaf)	40^a	25^b	65^a	82^b	Chlorophylls 65 ± 5^a → → 82 ± 4^b mg/100 g	65 ± 5^a	82 ± 4^b	96.0 ± 1.3	1.6 ± 0.2
Spicy-aromatic (mint)	45^a	30^b	67^a	84^b	Essential oils 0.18 ± 0.02^a → → 0.25 ± 0.03^b%; polyphenols 56 ± 3^a → → 71 ± 3^b mg/100 g	67 ± 3^a	84 ± 3^b	95.9 ± 1.5	1.6 ± 0.2
Meat and vegetable (minced meat + pumpkin paste)	60^a	40^b	68^a	80^b	Antioxidant activity 72 ± 3^a → 84 ± 2^b%	72 ± 3^a	84 ± 2^b	94.8 ± 1.5	1.9 ± 0.2

They contribute to reducing the drying time by 30...35% (Fig. 2, Table 2) and provide a higher residual content of BAS by 15...20% compared to the prototype (without recovery and autonomous systems). For example, the experimental sample of the "Gala" apple variety is characterized by a residual vitamin C content of 82.0 ± 3.1 mg/100 g, while in the prototype this figure was: 68.0 ± 2.5 mg/100 g. For the "Shantane" carrot variety, the residual β-carotene content is 87 ± 2 mg/100 g, and in the prototype – 70 ± 3 mg/100 g, respectively. In chokeberry – 92 ± 3 mg/100 g of anthocyanins, and after drying in the prototype: 76 ± 4 mg/100 g. For leaf parsley, the retention of chlorophyll content is 82 ± 4 mg/100 g versus 65 ± 5 in the prototype. The meat-vegetable semi-finished product is characterized by an antioxidant activity of 84 ± 2%, while in the prototype this indicator is 72 ± 3% (Fig. 3, Table 2). The data presented confirm a higher level of preservation of vitamin C and other BAS after low-temperature drying in the improved device compared to the prototype, which confirms resource saving. For example, in work [9] the influence of heat transfer uniformity and ΔT on the quality of the drying process is indicated but, unfortunately, without determining the efficiency of using the recovery system. The proposed improved design contributes to an increase in the temperature of the incoming "cold" air by 12...18°C (Table 1) due to the recovery system, thereby contributing to a reduction in electricity consumption by 10...15%, which is important for the mobility of the device.

In [11], the combination of IR drying led to a reduction in energy consumption, which correlates with the data obtained from scientific and practical research (reduction to 1.8 ± 0.2 kW (Table 1), and in the prototype – 2.4 ± 0.2 kW, respectively). Compared with the hybrid solar-biomass system used in agricultural complexes [15], the proposed innovative improvements are characterized by a comparable resource-saving design in autonomous operation. In [25], during drying carrots, the preservation of the carotenoid content at 55°C was 80...85%, while the proposed solutions contribute to achieving a preservation level of 85...90% due to low-temperature IR drying under conditions of a stable temperature field.

The results of the implementation of the proposed solutions obtained in the course of scientific and practical research confirm their effectiveness and the formation of uniformity of dehydration across the width of the conveyor belt (95 ± 2%). The device operates in a low-temperature drying range (35...65°C) with variable thicknesses/shapes and consistency of raw materials under conditions of secondary air recovery ΔT = 12...18°C (Table 1). Any excess of these parameters will ensure overheating of the raw materials and loss of BAS of various heat-labile compounds. The practical effectiveness of the improvement of the drying device involves its use in mobile lines for processing organic raw materials, agricultural enterprises, farms in front-line regions and craft production for resource-saving processing and production of semi-finished products with a high degree of readiness. Further implementation is planned in the form of pilot laboratory installations with subsequent certification. The approximate capital costs for using the device are 8...15 thousand euros, which is 30...40% lower than the cost of imported analogues. And the potential niche of the Ukrainian market is estimated at 150...200 functionally mobile dryers per year with simultaneous entry into foreign markets after certification and compliance with the EU resource efficiency.

The limitation of the study is the testing of the improved design of the IR dryer on the specified types of raw materials and corresponding technological modes, which limits compiling generalized recommendations for using the device in a practical environment. Further research on the improved design may involve expanding the experimental base of prototypes under the conditions of parallel construction of a digital twin of the technological process for effective adaptation of the device to other types of raw materials with industrial testing.

7. Conclusions

1. A model of an improved IR belt dryer with combined heat supply (IR radiation and conductive heating) with a low-temperature gentle range of 35...65°C has been designed. A universal conveyor belt with replaceable modules (flat Teflon, perforated (metal / polymer) and cassette-geometric) provides drying of various types of organic agricultural raw materials and semi-finished products of mixed composition. Under conditions of secondary air recovery, an increase in the temperature of the "cold" air by 12...18°C is achieved, and autonomous ventilation is powered by low-voltage voltage (15...30 W), which is generated during the operation of Peltier elements. In addition to IR emitters, the dryer is additionally equipped with an alternative source of thermal energy – a solar air collector (1.5...2.0 kW) for preheating the "cold" air. As well as a solar photovoltaic panel, which provides charging of a battery with a capacity of 6...8 kWh. The belt drive is regulated by a drive shaft speed regulator within 0.2...1.5 m/min to achieve a final product humidity of 5...8%. The folding frame with aluminum guides (2.5 × 1.2 × 1.5 m in transport condition) requires 30...40 min to deploy and start the work cycle. The combination of engineering solutions (film-like electric heaters, secondary air recovery, autonomous ventilation due to Peltier elements, solar air collector, photovoltaic panel and battery) provides experimentally confirmed resource-saving of the drying process compared to the prototype.

2. The drying time in the improved structure has been confirmed to be reduced by 30...35% compared to the prototype (without recovery and alternative systems) with a simultaneous increase in the level of BAS preservation by 15...20%. For cereals, for example wheat of the "Podolyanka" variety, the drying time is reduced from 85 min to 60 min. For vegetables, for example carrots of the "Shantane" variety, the time is reduced from 70 min to 50 min; for fruits, for example apples of the "Gala" variety, from 75 min to 50 min. For herbs, for example parsley, respectively, from 40 min to 25 min; and for meat and vegetable semi-finished products with pumpkin paste, the time is reduced from 60 min to 40 min. Therefore, the proposed engineering solutions during the improvement of the IR dryer form low-temperature drying modes under which the residual content of BAS in most experimental samples is at the level of 75...92%, which corresponds to an increase in the level of their preservation by 15...20% compared to the prototype.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript under full human control.

Artificial intelligence was not used to create, process, or interpret scientific data, form conclusions or other elements of the scientific results of the paper.

Tool used: ChatGPT (OpenAI GPT-5, version 2025).

The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

Authors' contributions:

Andriy Zagorulko: conceptualization, methodology, writing – initial version, supervision; **Iryna Voronenko:** conceptualization; validation; formal analysis; **Larysa Bal-Prylypko:** supervision; validation; writing – review and editing; **Maksym Ryabovol:** investigation, formal analysis, resources; **Mykhailo Marchenko:** methodology, software, visualization; **Tetyana Zheleva:** investigation; data curation; writing – preparation of results; **Serhiy Babayev:** investigation, visualization, data curation; **Eldar Bayram ogli Ibayev:** software, formal analysis, writing – review and editing.

References

1. Augustin, M. A., Riley, M., Stockmann, R., Bennett, L., Kahl, A., Lockett, T. et al. (2016). Role of food processing in food and nutrition security. Trends in Food Science & Technology, 56, 115–125. https://doi.org/10.1016/j.tifs.2016.08.005
2. Nowacka, M., Matys, A., Witrowa-Rajchert, D. (2024). Innovative Technologies for Improving the Sustainability of the Food Drying Industry. Current Food Science and Technology Reports, 2 (2), 231–239. https://doi.org/10.1007/s43555-024-00026-8
3. Venkateswarlu, K., Reddy, S. V. K. (2024). Recent trends on energy-efficient solar dryers for food and agricultural products drying: a review. Waste Disposal & Sustainable Energy, 6 (3), 335–353. https://doi.org/10.1007/s42768-024-00193-3
4. Chojnacka, K., Mikula, K., Izydorczyk, G., Skrzypczak, D., Witek-Krowiak, A., Moustakas, K. et al. (2021). Improvements in drying technologies - Efficient solutions for cleaner production with higher energy efficiency and reduced emission. Journal of Cleaner Production, 320, 128706. https://doi.org/10.1016/j.jclepro.2021.128706
5. Das, B., Singh, P., Kalita, P. (2025). Performance Evaluation of a Mixed-Mode solar dryer with PCM-based energy storage for efficient drying of Baccaurea ramiflora. Solar Energy, 288, 113279. https://doi.org/10.1016/j.solener.2025.113279
6. Huang, L., Bai, L., Zhang, X., Gong, S. (2019). Re-understanding the antecedents of functional foods purchase: Mediating effect of purchase attitude and moderating effect of food neophobia. Food Quality and Preference, 73, 266–275. https://doi.org/10.1016/j.foodqual.2018.11.001
7. Kiptelaya, L., Zagorulko, A., Zagorulko, A. (2015). Improvement of equipment for manufacture of vegetable convenience foods. Eastern-European Journal of Enterprise Technologies, 2 (10 (74)), 4–8. https://doi.org/10.15587/1729-4061.2015.39455
8. An, J., Xie, H., Yan, J., Wei, H., Wu, Y., Liao, X. (2024). A review of applications of energy analysis: Grain, fruit and vegetable drying technology. Energy Reports, 12, 5482–5506. https://doi.org/10.1016/j.egyr.2024.11.037
9. Majumder, P., Deb, B., Gupta, R., Sablani, S. S. (2022). A comprehensive review of fluidized bed drying: Sustainable design approaches, hydrodynamic and thermodynamic performance characteristics, and product quality. Sustainable Energy Technologies and Assessments, 53, 102643. https://doi.org/10.1016/j.seta.2022.102643
10. Haron, N. S., Zakaria, J. H., Mohideen Batcha, M. F. (2017). Recent advances in fluidized bed drying. IOP Conference Series: Materials Science and Engineering, 243, 012038. https://doi.org/10.1088/1757-899x/243/1/012038
11. Cherevko, O., Mikhaylov, V., Zahorulko, A., Zagorulko, A., Gordienko, I. (2021). Development of a thermal-radiation single-drum roll dryer for concentrated food stuff. Eastern-European Journal of Enterprise Technologies, 1 (11 (109)), 25–32. https://doi.org/10.15587/1729-4061.2021.224990
12. Zahorulko, A., Cherevko, O., Zagorulko, A., Yancheva, M., Budnyk, N., Nakonechna, Y. et al. (2021). Design of an apparatus for low-temperature processing of meat delicacies. Eastern-European Journal of Enterprise Technologies, 5 (11 (113)), 6–12. https://doi.org/10.15587/1729-4061.2021.240675
13. Zahorulko, A., Zagorulko, A., Kasabova, K., Shmatchenko, N. (2020). Improvement of zefir production by addition of the developed blended fruit and vegetable pasteinto its recipe. Eastern-European Journal of Enterprise Technologies, 2 (11 (104)), 39–45. https://doi.org/10.15587/1729-4061.2020.185684

14. Zagorulko, A., Zahorulko, A., Kasabova, K., Chuiko, L., Yakovets, L., Pugach, A. et al. (2022). Improving the production technology of functional paste-like fruit-and-berry semi-finished products. Eastern-European Journal of Enterprise Technologies, 4 (11 (118)), 43–52. https://doi.org/10.15587/1729-4061.2022.262924
15. Mishra, L., Hauchhum, L., Gupta, R. (2022). Development and performance investigation of a novel solar-biomass hybrid dryer. Applied Thermal Engineering, 211, 118492. https://doi.org/10.1016/j.applthermaleng.2022.118492
16. Park, Y., Chang, Y.-S., Park, J.-H., Yang, S.-Y., Chung, H., Jang, S.-K. et al. (2016). Energy Efficiency of Fluidized Bed Drying for Wood Particles. Journal of the Korean Wood Science and Technology, 44 (6), 821–827. https://doi.org/10.5658/wood.2016.44.6.821
17. Waskale, H., Bhong, M. (2019). Forced Convective Drying Of Potato Chips with Air Recirculation. Available at: https://www.researchgate.net/publication/333338784_Forced_Convective_Drying_Of_Potato_Chips_with_Air_Recirculation
18. Rakshamuthu, S., Jegan, S., Joel Benyameen, J., Selvakumar, V., Anandeeswaran, K., Iyahraja, S. (2021). Experimental analysis of small size solar dryer with phase change materials for food preservation. Journal of Energy Storage, 33, 102095. https://doi.org/10.1016/j.est.2020.102095
19. Lee, D.-J., Jangam, S., Mujumdar, A. S. (2013). Some Recent Advances in Drying Technologies to Produce Particulate Solids. KONA Powder and Particle Journal, 30, 69–83. https://doi.org/10.14356/kona.2013010
20. Faure, E., Shcherba, A., Stupka, B., Voronenko, I., Baikenov, A. (2023). A Method for Reliable Permutation Transmission in Short-Packet Communication Systems. Information Technology for Education, Science, and Technics, 177–195. https://doi.org/10.1007/978-3-031-35467-0_12
21. Nejadi, J., Nikbakht, A. M. (2016). Numerical Simulation of Corn Drying in a Hybrid Fluidized Bed-Infrared Dryer. Journal of Food Process Engineering, 40 (2). https://doi.org/10.1111/jfpe.12373
22. Aviara, N. A., Onuoha, L. N., Falola, O. E., Igbeka, J. C. (2014). Energy and exergy analyses of native cassava starch drying in a tray dryer. Energy, 73, 809–817. https://doi.org/10.1016/j.energy.2014.06.087
23. Borel, L. D. M. S., Marques, L. G., Prado, M. M. (2020). Performance evaluation of an infrared heating-assisted fluidized bed dryer for processing bee-pollen grains. Chemical Engineering and Processing - Process Intensification, 155, 108044. https://doi.org/10.1016/j.cep.2020.108044
24. Lv, W., Li, D., Lv, H., Jin, X., Han, Q., Su, D., Wang, Y. (2019). Recent development of microwave fluidization technology for drying of fresh fruits and vegetables. Trends in Food Science & Technology, 86, 59–67. https://doi.org/10.1016/j.tifs.2019.02.047
25. Golmohammadi, M., Assar, M., Rajabi-Hamaneh, M., Hashemi, S. J. (2015). Energy efficiency investigation of intermittent paddy rice dryer: Modeling and experimental study. Food and Bioproducts Processing, 94, 275–283. https://doi.org/10.1016/j.fbp.2014.03.004
26. Aktaş, M., Khanlari, A., Amini, A., Şevik, S. (2017). Performance analysis of heat pump and infrared–heat pump drying of grated carrot using energy-exergy methodology. Energy Conversion and Management, 132, 327–338. https://doi.org/10.1016/j.enconman.2016.11.027
27. Ichise, T., Tatemoto, Y. (2022). Numerical analysis of drying characteristics of frozen material immersed in fluidized bed at low temperature under reduced pressure. Advanced Powder Technology, 33 (8), 103661. https://doi.org/10.1016/j.apt.2022.103661
28. Granaturov, V., Kaptur, V., Politova, I. (2016). Determination of tariffs on telecommunication services based on modeling the cost of their providing: methodological and practical aspects of application. Economic Annals-XXI, 156 (1-2), 83–87. https://doi.org/10.21003/ea.v156-0019
29. Potapskyi, O. V., Fesiun, S. V., Pylypenko, O. Yu., Babych, I. M. (2020). Pat. No. 147229 UA. Bahatozonalna termoelektrychna susharka. No. u202007428; declareted: 23.11.2020; published: 22.04.2021. Available at: https://sis.nipo.gov.ua/uk/search/detail/1589442/
30. Usama, M., Ali, Z., Ndukwu, M. C., Sathyamurthy, R. (2023). The energy, emissions, and drying kinetics of three-stage solar, microwave and desiccant absorption drying of potato slices. Renewable Energy, 219, 119509. https://doi.org/10.1016/j.renene.2023.119509
31. Zahorulko, A., Zagorulko, A., Mykhailov, V., Ibaiev, E. (2021). Improved rotary film evaporator for concentrating organic fruit and berry puree. Eastern-European Journal of Enterprise Technologies, 4 (11 (112)), 92–98. https://doi.org/10.15587/1729-4061.2021.237948