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AN INTEGRATED SOLUTION: A CASCADE FLUIDIZER DRYER; DRYING FOR NEW GENERATION PRODUCTS

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This study considers the process of drying raw materials (fruit, grain, mixed, dairy, and vegetable-fat) in an improved prototype of a cascade fluidization dryer, compared to the basic (control) model without Peltier elements and film-like electric heaters. The task addressed is to enable stable fluidization, resource saving, and preservation of the quality characteristics of raw materials during drying.

The proposed structure includes autonomous fan systems, warm air recirculation channels, air heating up to 75°C, and zoned temperature regime: sections A1 (68…75°C), A2 (58…65°C), and A3 (48…55°C) with temperature adjustment using Peltier elements. The raw material moves by gravity through inclined channels, enabling consistent drying with humidity and air velocity control (2.3…2.6 m/s), which supports effective fluidization.

Experimental studies on apples, oatmeal, muesli, and lactose mixture have shown that the technology provides a reduction in drying time (from 22 to 60 min) while preserving nutrients and moisture uniformity (standard deviation up to 0.9…1.6%). Air recirculation (35…42%) and autonomous control over process parameters improve resource efficiency without compromising quality.

The results confirm the versatility of the improved cascade fluidized bed dryer for resource-saving drying of various types of food raw materials under optimized temperature conditions and automated process control. The devised technology could be implemented in the food industry for making high-quality dried products while maintaining functional properties

Keywords: cascade dryer, fluidization, low-temperature electric heater, Peltier element, adaptive control, inclined channels

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1. Introduction

Under current conditions of food and resource-saving instability, the improvement of innovative technologies for processing agri-food raw materials with a simultaneous focus on resource efficiency and preserving the quality of the final product is of particular importance [1]. One of the priority areas is to design resource-saving dryers of a new generation, capable of providing not only intensive dehydration but also the preservation of biologically active components of raw materials.

The relevance of research area related to developing modern systems for drying and post-harvest processing of agricultural raw materials is due to the global challenges of food security, the need to preserve nutritional value, and minimize losses at the stages of the production and logistics chain. Special attention is given to the segment of small and medium-sized producers, farms, agro-processing cooperatives, which often do not have access to high-tech solutions and are forced to work with outdated equipment [2]. It is this link in agricultural production that most urgently needs affordable technical means for post-harvest processing of agricultural raw materials with a high degree of readiness for consumption. Under current conditions of agricultural sector transformation, caused by the consequences of war and global challenges, the implementation of resource-efficient management and innovations in the production of high-quality food products is of particular importance. The issues of food security, product quality management, and integration of raw material processing technologies are of significant scientific interest, which are reflected in recent studies [3, 4]. Under conditions of post-war recuperation, the development of transparent, anti-crisis management solutions in the food sector is particularly relevant.

The design of an innovative drying device and the corresponding technology for its application is not only a technical but also a socio-economic challenge that meets modern European trends in the formation of short food chains according to the “from field to fork” model [5, 6]. This approach involves the integration of agricultural production with local processing, reducing logistics costs, minimizing quality losses, and increasing the added value of products directly on the ground. Thus, the proposed technical solutions are aimed at forming the foundations of technological independence of regional producers, contributing to the development of sustainable agriculture and strengthening food security within the framework of a pan-European strategy.

Research into devising innovative resource-saving drying technologies for agri-food raw materials, combining resource efficiency and preserving the biological value of the product, is a key area for developing modern food engineering and agro-processing. Their implementation is an urgent need to improve the efficiency of the agricultural sector, especially under conditions of food instability, post-war recuperation, and the development of local agricultural production.

2. Literature review and problem statement

In [7], the emphasis is on innovative approaches to improving the energy efficiency of fluidized bed drying, but the authors note that the level of usable heat is only 55...60% while 40...45% is lost to the environment through the ventilation system. At the same time, structural solutions of a cascade structure with air recirculation, which could potentially significantly reduce these losses, remain outside the scope of their analysis. This is explained by the complexity of implementing a multi-stage recuperation system and the need to integrate zone heating with heat recuperation processes, which requires more in-depth design development.

In [8], it is shown that at an initial raw material humidity of 50%, the energy efficiency of the fluidized bed dryer system was only 28.8%, which is explained by significant heat costs for heating the air environment. At the same time, possible design solutions for reducing losses were not considered – in particular, the use of thermal insulation or integrated IR heaters. This emphasizes the feasibility of designing improved structures based on film-like IR heaters with thermal insulation, which would significantly minimize heat loss and increase the energy efficiency of the drying process.

One of the solutions is reported in [9] by modeling moisture diffusion during rice drying while determining the diffusion coefficient and activation energy. However, the work does not take into account temperature control at the final stages of the technological process and does not take into account Peltier elements to stabilize the temperature range at the final stages of maintaining the target temperature regime.

Paper [10] emphasizes the importance of CFD modeling for optimizing design solutions, but it is noted that most experimental works lack the practical implementation of hybrid film IR heaters or Peltier modules. The reason is the difficulties with integrating electric heating and thermoelectricity into existing structures.

In [11], the specific energy consumption for different technologies was estimated – from 3.9 to 44.7 MJ/kg depending on the type of installation. However, the study did not analyze how a cascade design with recuperation could reduce the specific energy consumption within 10...15 MJ/kg. One of the structural solutions is to use a design with recuperation and IR heating.

In [12], a hybrid corn drying technology combining fluidized bed and infrared heating was investigated; a mathematical model of simultaneous heat and mass transfer was built. However, no solution was proposed for scaling the technology to an industrial level, and no aspects of heat reuse or automated process control were considered. This may be due to the focus on the laboratory scale and CFD modeling, without taking into account the practical implementation of a complex system. One solution is to integrate a cascade system with Peltier elements for heat reuse, as well as PLC control to stabilize operating parameters for industrial air-bed dryers.

The practical use of a fluidized bed dryer based on infrared heating [13] increases the effective diffusion coefficient to 30%, thereby reducing the drying time by 58% compared to convective fluidized models. However, the effect of air recuperation in a zoned temperature regime was not taken into account, although this may lead to resource savings and improved drying quality.

In [14] it was found that due to heat recuperation, the resource efficiency of the process increased by 17%, while without recuperation, the productivity decreased by half. However, the proposed experimental design without external Peltier modules is limited in fine temperature control at the final stages of drying, confirming the relevance of research in this direction.

In [15], a combination of solar and biomass thermal systems was considered: the temperature of the drying chamber is maintained at 50...55°C, heat transfer efficiency up to 85%. But Peltier integration or zoned technological control was not proposed since it is advisable to use it in a combination of several heating technologies, thereby confirming the feasibility of using cascade dryers.

For example, in [16], fluidization with microwave heating was considered, while the drying rate increased to 80%, but the control of the internal temperature field remained inaccurate due to local hot zones. Here, a combination of infrared heating with zoned heating and thermoelectric control and the possibility of air recirculation could help for optimal resource efficiency of the technological process.

In [17], ANN models for predicting drying rate and humidity stability were considered. However, automated sensor control with PLC and thermocouples was not considered, although this approach is aimed at increasing the reliability of the technological process as a whole and its resource efficiency. This may be due to the narrow spectrum of research, which is mostly used without practical implementation of research, although research with practical simultaneous testing provides competitive data.

In [18], a pulse rice dryer was analyzed under conditions of cyclic air supply in order to reduce the energy consumption of the heat and mass transfer process by 25...30%. However, the structural implementation of the exhaust air regeneration was ignored, which may be partly due to the complexity of the practical implementation of the process under conditions of air purification, distribution in the zones of working chambers, etc. However, the practical implementation of an effective structural approach to the recuperation of the air environment in cascade dryers would allow for the beneficial use of thermal energy, but this requires detailed research.

In [19], it is shown that the optimal drying temperature of carrots is 55°C, while the drying efficiency drops above 75°C. However, the structures of devices without Peltier elements are structurally incapable of reducing the temperature in the final drying phase without risks, which inevitably leads to a decrease in resource efficiency and the quality of the obtained raw materials. This is partly due to the complexity of precise temperature control over operating parameters in fluidized bed dryers since a pre-prepared air mixture is used that passes through a heater.

In [20], drying at reduced pressure was analyzed, which contributed to a 40% reduction in drying time, but this leads to a structural complication of the device and control of the final humidity. One of the solutions is the use of additional control systems: PLC, non-contact sensors of technological parameters, including the use of thermoelectric Peltier elements to improve control over the temperature range at important technological stages, contributing to an increase in the practical efficiency of using the dryer.

A similar solution was considered in [21], in which a thermoelectric dryer was investigated, combining an air heater and a cooler from thermoelectric converter plates based on the Peltier effect, a fan, a drying chamber with a lattice base, a condensate drain pipe and a diffuser for optimal air distribution. It is shown that air cooling through Peltier elements below the dew point allows for condensation and air dehumidification. However, the designed structure has not yet been integrated into cascade sections of dryers, although it is an effective engineering and technological solution, confirming the relevance of research in this area.

In particular, in [22], modern innovative technologies for drying solid particles were studied, in particular combined (hybrid) methods, new structures of contact drying media and increasing energy efficiency while enabling product quality. However, no specific technical solution was proposed for the integration of air-bed systems with IR heating, PLC control, or heat recuperation. The reason is that the topic is covered within the framework of a review article, which is focused on general technological trends without detailed technical structures or designs of specific dryer configurations. The solution is to design cascade dryers for solid materials with a combination of fluidization + IR heating + heat recuperation and PLC control in cascade modules with Peltier elements to improve energy efficiency and automated control.

In [23], the drying of potato slices under a forced convection mode with air recirculation was investigated; an experimental analysis of the influence of temperature, air velocity, and recirculation modes on the humidity level and energy consumption was conducted. A significant reduction in heat loss and improvement in drying quality were obtained when partial recirculation was used. However, no structural or automated solution was proposed for the industrial implementation of recirculation with adaptive control or integration of IR heating and heat recuperation. One of the reasons is the focus of the research on laboratory tests and analysis of the influence of individual drying parameters, without a detailed consideration of scaling or process automation. One of the solution options is to design a hybrid drying system with adaptive air recirculation, integration of IR heating, Peltier elements for heat recuperation, and PLC control to increase resource efficiency in industrial production.

In [24], a three-stage hybrid drying of potato slices was studied, combining solar drying, microwave heating, and sorption drying. An analysis of energy consumption, CO_2 emissions, and drying kinetics was carried out; the hybrid system showed the highest efficiency and the lowest emissions compared to single-stage methods. However, no technical solution was proposed for automated control over the drying process or heat reuse (e.g., through heat recuperation or Peltier elements). The reason is the focus on experimental comparison of stages and environmental performance, without detailed development of the engineering implementation of the system. One solution is to integrate PLC control with heat recuperation systems to improve accuracy and stability on an industrial scale.

In [25], a small-sized solar dryer with phase change materials (PCM) was investigated to preserve heat and continue drying during the dark period. Temperature stabilization and efficiency improvement were experimentally proven. However, no automated control or scalable solution for industrial application was proposed. The reason is the focus on a small-sized design for domestic conditions. One of the solution options is the integration of PLC and recuperators for stable control of drying in large systems.

In [26], anti-crisis measures and mechanisms for enabling sustainable development of the regional economy after COVID-19 were considered. However, the issues of energy efficiency and technological solutions for the agricultural sector, in particular product drying, were left out of attention. For a cascade fluidized bed dryer, it is advisable to integrate these management approaches with technical innovations (IR heaters, Peltier), which would make it possible to combine economic sustainability and technological modernization.

In [27], the risks of food security in Ukraine were investigated and forecasts of the development of the situation were proposed. The aspects of post-harvest processing and preservation of raw material quality through drying technologies were not sufficiently disclosed. In a cascade fluidized bed dryer, these risks could be minimized through a controlled thermal regime (50...65°C, air speed 1.5...2.5 m/s), which enables the stability of food safety.

In [28], an integrated food quality management system and methods for its implementation were considered. However, engineering and technological solutions for improving drying devices that directly affect quality were ignored. A cascade fluidized bed dryer with multi-level heating and automated humidity control could become a practical way to implement integrated quality management.

In [29], the need for transparent resource management is indicated, which is the key to effective agricultural policy.

In [4], the emphasis is on technologies for processing plant raw materials into food semi-finished products using protein concentrates while in [30], it is on increasing the energy efficiency of agricultural enterprises. However, the authors do not propose comprehensive engineering solutions that would combine resource saving, controlled drying, and preservation of raw material quality.

Thus, the reviewed studies are mainly focused on technological, economic, or management individual aspects (resource saving, recuperation, heaters). At the same time, there are no integrated solutions with temperature zoning, the use of film IR heaters, Peltier elements, PLC control, and air recirculation. The main reason is the technical complexity of integrating such components into a compact housing with precise control over operating parameters.

3. The aim and objectives of the study

The aim of our study is to devise an integrated solution that combines an improved structure of a cascade fluidized bed dryer and an optimized drying technology aimed at increasing the resource efficiency of the process and preserving the biological value of agri-food raw materials. The implementation of such technical solutions will contribute to the development of local agro-processing capacities in the format of mini-shops, farms, and cooperatives, corresponding to the modern European model "from field to fork", enhancing food security and forming the basis for preserving the health of the nation by expanding access to new generation products.

To achieve the goal, the following tasks were set:

– to propose guidelines for improving the structure of a cascade fluidized bed dryer with film-like electric heaters of the radiant type and Peltier elements to stabilize the temperature regime and increase the resource efficiency of the process;

– to experimentally substantiate an innovative drying technology focused on preserving biologically active substances and forming the quality characteristics of new generation products.

4. The study materials and methods

The object of our study is the process of drying raw materials (fruit, grain, mixed, dairy, and vegetable-fat) in an improved prototype of a cascade fluidization dryer, compared to the basic (control) model without Peltier elements and film-like electric heaters.

Research hypothesis assumes that the improved structure of the dryer and innovative drying technology could increase the quality of finished products (preservation of biologically active substances) and reduce energy consumption. This will contribute to the development of local production, mini-shops, and agro-processing cooperatives, which is an important step for integration into the modern European model "from field to fork", thereby enabling food security and health of the nation.

Assumptions adopted: local raw materials are representative of the region; autonomous control over parameters ensures process stability.

Simplifications accepted: the movement of raw materials is considered simple (gravity-air), quality assessment is limited to the main components (vitamin C, protein, β-glucans), air recirculation is fixed at 35...42%, and drying modes are constant.

Practical testing of hardware and technological solutions was implemented in the front-line Kharkiv oblast at the scientific and educational center "Innovative resource-saving technologies for processing organic products", the State Biotechnology University (Kharkiv, Ukraine). The research was carried out on a model of a cascade fluidization dryer with three sections equipped with film-like electric heaters and Peltier elements in the last section. The dimensions of the model structure of CFD: diameter of the working chamber – 0.5 m, height of each section – 0.3 m, fluidization area – 0.2 m^2. The tests were carried out with the following raw materials available for the Kharkiv front-line region; fruit – apples of the "Symyrenko" variety (humidity 86 ± 2%, mass fraction of vitamin C – 11.5 mg/100 g, sugar content – 9%) from local orchards in 2024; grain – oat flakes of domestic production (β-glucan content – 3.8 ± 0.3%), obtained from grain in the Kharkiv oblast; mixed – muesli of our own preparation with the composition: oat flakes of local production (composition of oat flakes, wheat of the Aurora variety, barley of the Lubystok variety, dried berries (cranberries, mountain ash) and walnuts) from the region; protein-fat – lactose mixture of Kharkiv production for baby food (protein content – 3.2 ± 0.1%, fat – 3.8 ± 0.1%) adapted to the needs of the local market.

CFD drying modes: temperature, air speed, time in sections were set individually for each type of raw material. The movement of raw material was carried out by gravity and air flow. Process control was provided by temperature sensors of the PT100 type (Ukrainian production), humidity sensors HMT337 (Switzerland production), and ultrasonic air velocity sensors DTF100 (Japan production). Data from the sensors were processed by a Siemens S7-1200 PLC system equipped with an interface for integration with local telecommunication networks for reliable remote monitoring under conditions of unstable communication. Ultrasonic air velocity sensors are protected from dust and moisture, which is relevant for work in the agro-industrial environment of the Kharkiv region. Air velocity was controlled by ultrasonic air velocity sensors of domestic production (model UD-100).

The drying process included standard preparatory operations: calibration, grinding, and cleaning (if necessary, in accordance with technological requirements). Drying was carried out in an improved cascade fluidized dryer by feeding raw materials into the upper section (A_1) by a screw feeder. Section A_1 provided intensive initial moisture evaporation at a temperature of 68...75°C with the formation of a fluidized layer to intensify heat and mass transfer. The middle section (A_2) executed the main drying phase at a temperature of 58...65°C, and the lower section (A_3) enabled humidity stabilization at 48...55°C using Peltier elements for smooth regulation of the heat balance. Each section had an autonomous ventilation system with fluidization parameter control. Up to 35...42% of air was recirculated through the heat exchange unit, which increased resource efficiency. The dried raw materials were discharged after the PLC controller reached the target humidity values (3.7...12.0% dry matter). Comparison of results with the control group (basic CFD without improvements). Efficiency assessment included moisture measurement by gravimetric method (DSTU ISO 712:2010). Vitamin C – by titrimetric method (DSTU 4954:2008). Protein – by Kjeldahl method (DSTU ISO 937:2005). β-glucans – by enzymatic method (AACC Method 32-23.01).

Statistical processing of the results is based on a series of 5 independent experiments; analysis was performed in the Statistica 13.3 program. The mean values, standard deviations, and significance of the difference ($p < 0.05$) were evaluated.

5. Improving the structure of the cascade fluidized dryer and the results of experimental studies

5. 1. Design and parameters of the cascade fluidized dryer for stable thermal conditions and resource-saving drying

The structure of the cascade fluidized dryer (CFD) at the stage of improvement consists of three sequentially arranged sections (Fig. 1). The internal contour of each section is covered with a film-like electric heater of the radiant type. The outer surface of the structure is thermally insulated, which makes it possible to minimize heat losses to the environment and improve the energy efficiency of the drying process.

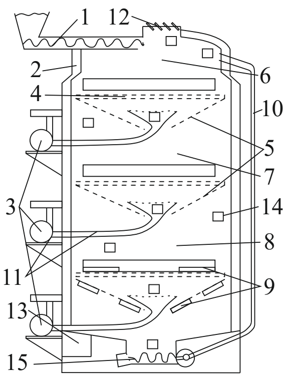

Fig. 1. The improved structure of a cascade fluidized-bed dryer (CFD): 1 — screw blower of raw materials; 2 — radiant film electric heater arranged on the walls of the sections; 3 — fan (for each section); 4 — fluidized bed (perforated bottom) through which air is supplied for fluidization; 5 — inclined channels for moving raw materials between sections; 6 — section A_1 — upper module of intensive evaporation (68...75°C); 7 — section A_2 — middle module of stable drying (58...65°C); 8 — A_3 — lower module of delicate drying with Peltier elements (48—55°C); 9 — Peltier elements with cooling radiators; 10 — technical air recirculation channel with cyclone filter; 11 — discharge fans with heating pipeline for preheating; 12 — air outlet for recirculation or discharge to the environment; 13 — PLC-based control system; 14 — humidity and temperature sensors; 15 — pipe with a screw for discharging dried raw materials

The raw material is loaded by screw blower 1 into upper section 6 (A_1), the temperature of which is maintained within 68...75°C. The raw material is evenly distributed over fluidization bed (perforated bottom) 4 with a fluidization area of 0.2 m^2 using an autonomous ventilation system. Each section (A_1, A_2, A_3, 6–8) has its own fan 3, which supplies air from below through a filter, providing a directed flow with specified parameters. Before being fed into the drying zone, the air first passes through discharge fans 11 with a heating pipeline based on radiant film electric heater 2 for preheating the air with subsequent dispersion through the dryer sections. In addition, the inner surface of each section is covered with film-like electric heater of the radiant type 2. Heater 2 generates a uniform thermal field and infrared radiation, which contributes to the effective heating of the raw material. The sections of CFD (6–8) are connected by inclined channels 5, through which the raw material under the influence of gravity and the aerodynamic flow formed by the fan system moves to discharge pipe 15.

The implemented technical solution for the heater location, for section A_1 the temperature stabilized within 68...75°C at an air velocity of 2.4 m/s, enabling intensive evaporation of moisture from the raw material. In the middle section A_2 the temperature was 58...65°C, and in the lower A_3 – 48...55°C, respectively.

The set air flow rate for a fluidization area of 0.2 m^2 was maintained at 250...350 m^3/h to form a state of fluidization and uniform mass and heat transfer. Additional preheating in the air channel in front of the sections is aimed at reducing the duration of the system reaching a stable thermal regime by 15...20%. The involvement of an air recirculation system with the selection of zone A_3 and return to section A_1 after filtration reduces the proportion of "fresh" outside air to 40...45% thereby contributing to the increase of resource efficiency of the technological cycle as a whole. Recirculation air through channel 10 was returned at a temperature of about 42...45°C to reduce the thermal load on the heating elements of the incoming air. The combination of local IR heating, preheating in the channel, and recirculation reduces the drying time by 18...22% without significant losses in the quality of the finished product (in particular, the color, aroma, and shape are preserved in the case of drying apple raw materials to 12% moisture).

The air temperature during the implementation of technological processes did not exceed 75°C, and the flow velocity should exceed the settling velocity of particles (approximately 2.3...2.4 m/s). This ensures the phenomenon of fluidization – a state of suspension of particles in the air, which significantly increases the blowing area and intensifies mass and heat transfer.

After the initial stage of intensive evaporation in section A_1, the partially dried raw material passes into the second section (A_2) under a temperature regime of 58...65°C. In section A_2, the main drying continues with constant monitoring of temperature and humidity to achieve the specified quality indicators. From there, the raw material enters the third section (A_3) through an inclined channel, where the temperature is maintained within 48...55°C.

Section A_3 provides for the installation of 4...6 pcs. of Peltier elements 9 in the upper part of the side walls to stabilize the temperature regime. One side of Peltier element 9 is cooled, the other is heated; at the same time, low-voltage current is generated for autonomous operation of the exhaust fans. Radiators are installed on the hot side of the Peltier elements to remove heat into the surrounding air environment, thereby contributing to the stable operation of the cold side of the element to maintain the temperature in the 50°C zone. Such a smooth decrease in temperature in the final drying phase makes it possible to preserve the functional components, color, and shape of the finished product. The cascade dryer is also equipped with an air recirculation system: part of the air from the outlet of section A_3 is returned to section A_1. Before reusing, the air passes through a filtration system (filters or a cyclone trap) to clean it of dust and microparticles. Recuperation is possible if the temperature difference between the outlet air and the external environment is more than 25°C. Each section is equipped with sensors 14 for temperature (accuracy ±0.5°C), humidity, and flow rate for precise control over the drying process parameters.

When the residual moisture of the raw material reaches the technological level (for example, 12% for apples or 4.3% for oatmeal), the system completes the cycle automatically. Data reading and output is carried out via a PLC controller with a display 13 and could also be transmitted via Wi-Fi or RS-485 interfaces. The dried raw material is discharged through the lower screw dosing nozzle of cascade fluidization dryer 15.

A feature of CFD operation is to enable fluidization in each section depending on the type of raw material, which was investigated experimentally and summarized in Table 1.

Table 1

Fluidization conditions of cascade fluidized bed dryer by sections for different raw materials

Experimental raw materials	CFD section	Process temperature, °C	Average air speed, m/s	Fluidization effect and stability (visual/actual)	Practical observation
Apple (dried)	A_1	72	2.1	Unstable – raw material clumping	Requires drying of the previous layer
	A_2	63	2.5	Uniform fluidization	Optimal speed and temperature
	A_3	52	2.3	Smooth finish, slight hang-up	Peltier element maintains stability
Oatmeal	A_1	70	2.6	Intensive suspension	Well distributed
	A_2	60	2.3	Stable	Without clumping
	A_3	50	2.1	Clear fluidized zone	Recommended for final drying
Muesli	A_1	73	2.2	Uneven component lift	Fractional stratification (grain/fruit)
	A_2	63	2.5	Partial stabilization	After speed correction
	A_3	52	2.3	Uniform hovering	Peltier element improves structure
Lactose mixture	A_1	68	2.4	Easy suspension, dust-like lifting	Pre-granulation recommended
	A_2	58	2.6	Stable fluidization	Best mode
	A_3	48	2.4	Final drying without scattering	Peltier stabilized

Fruit raw material (apple) at 72°C and 2.1 m/s in section A_1 had unstable fluidization due to clumping; stabilized in A_2 (63°C, 2.5 m/s) and A_3 (52°C, 2.3 m/s) using Peltier elements. Oat flakes demonstrated stable fluidization at all stages (70…50°C; 2.6…2.1 m/s), without delamination or clumping. Muesli had uneven rise in A_1 (73°C, 2.2 m/s) due to fractionation; stabilization was achieved in A_2…A_3 (2.5…2.3 m/s) after adjusting the air flow rate. Lactose mixture showed dusting in A_1 (68°C, 2.4 m/s), granulation is recommended; optimal fluidization was observed in A_2…A_3 (58…48°C; 2.6…2.4 m/s) with the support of Peltier elements. In general, stable fluidization is achieved at a speed of 2.3…2.6 m/s and a zoned temperature of 48…75°C, taking into account the type of raw material and the application of corrective measures.

Key design improvements compared to the basic apparatus are integration of film-like electric heaters of the radiant type on the inner walls of the sections, zoning of drying with differentiated temperature regimes in sections, use of Peltier elements in the final section, air recirculation with partial heat recuperation, preheating of air in the supply line, and an improved automated control system based on PLC.

5. 2. Experimental justification of parameters for the innovative technology for drying new generation products

In the process of experimental and practical research of a cascade fluidized bed dryer with zoning, film electric heaters of the radiant type and Peltier elements, approaches to the production of new generation products were optimized. Drying technology is aimed at maximum preservation of biologically active substances, increasing resource efficiency, and enabling versatility in terms of the type of raw material undergoing heat treatment.

The movement of raw materials between sections occurs gravitationally or using an air flow controlled by sensors in the working space of the dryer.

After drying, the finished product is packaged in accordance with the specified storage conditions, further use, or sale. According to the results of experimental research, the operating parameters of the improved cascade fluidized bed dryer (Table 2) for different types of experimental raw materials were summarized. Among the studied samples, three main groups were identified: fruit, grain/mixed, and protein-fat raw materials within the framework of the proposed resource-saving technology.

Table 2

Operating parameters of an improved cascade fluidized bed dryer during drying of various types of experimental raw materials

Indicator	Basic CFD	Improved CFD (for different raw materials)			
		Apple	Muesli	Oatmeal	Lactose mixture
Initial humidity, %	analogous	84.6	14.5	13.2	12.0
Final humidity, %	12.0…4.0	12.0	4.8	4.3	3.7
Total drying time, min	73.0 ± 3	60.0	21.0	22.0	26.0
Temperature of intensive evaporation section, A_1, °C	75 ± 2 (one-level)	72…75	70…72	72…75	68…70
Temperature of the stable drying section, A_2, °C	–	62…65	60…62	62…64	58…60
Temperature of the delicate drying section, A_3, °C	–	50…55 (+Peltier element)	50…52 (+Peltier element)	52…54 (+Peltier element)	48…50 (+ Peltier element)
Average air speed, m/s	2.3 ± 0.3	2.3	2.5	2.4	2.4
Duration distribution by sections (A_1 / A_2 / A_3, min)	none (one-level drying)	25.0 / 20.0 / 15.0	8.0 / 7.0 / 6.0	9.0 / 7.0 / 6.0	12.0 / 8.0 / 6.0
ΔT temperature in A_3, °C	± 2.0	± 0.4	± 0.5	± 0.5	± 0.4
PEVT power, kW	1.1	0.9	0.8	0.85	0.75
The operation of Peltier elements	none	Active in A_3	Active in A_3	Active in A_3	Active in A_3
Recuperation	none	Up to 40%	Up to 35%	Up to 38%	Up to 42%

Note: recuperation depends on the temperature difference in the exhaust duct and the inlet flow.

The results confirm the effectiveness of the improved cascade fluidized bed dryer for different types of raw materials. The longest drying time was for apples – 60 min at an initial moisture content of 84.6% and a final moisture content of 12.0%. The shortest cycle was observed for muesli – 21 min (from 14.5% to 4.8%), due to the fractional structure and stable fluidization at 2.5 m/s.

Oat flakes were dried for 22 min (from 13.2% to 4.3%) with a stable temperature across sections (A_1: 72...75°C, A_3: 52...54°C) and high moisture uniformity. The lactose mixture had the lowest final moisture content – 3.7%, the total drying time was 26 min, optimal temperature stability ($\Delta T = \pm 0.4$°C) and the highest air recuperation – up to 42%. Peltier elements were active in all experiments at stage (section) A_3, providing gradual cooling and stable delicate drying of the experimental raw materials. The power of PEVT varied within 0.75...0.9 kW. Air recuperation reached 35...42% depending on the temperature difference, which improved the energy efficiency of drying without loss of product quality. Compared with the basic (single-temperature) CFD, the improved structure provides a decrease in the average drying temperature by 5...8°C at the same final humidity; a reduction in drying time by 18...22%; increased temperature stability in the A_3 zone (±0.4...0.5°C versus ±2°C in the basic one); recuperation of up to 40% of the air flow and a decrease in heat consumption by 10...15%.

Our experimental data include indicators of drying duration (Fig. 2), preservation of nutrients (Fig. 3), and uniformity of moisture distribution over the volume of raw materials (Fig. 4). The study was conducted for four types of raw materials: fruit (for example, apples), grain (oatmeal), mixed (muesli: grains + dried fruits + nuts), and lactose mixture.

Fig. 2 demonstrates a tendency to reduce the drying time in the improved CFD with a difference of at least 35...60% depending on the type of raw material ($p < 0.05$). In particular, the drying of apples was reduced from 140 ± 5 min to 60 ± 3 min (–57%), oat flakes – from 32 ± 2 min to 21 ± 1 min (–34%), muesli – from 40 ± 2 min to 22 ± 1 min (–45%), lactose mixture – from 65 ± 3 min to 26 ± 2 min (–60%). Our results demonstrate a statistically significant advantage of the improved drying mode for all the studied options.

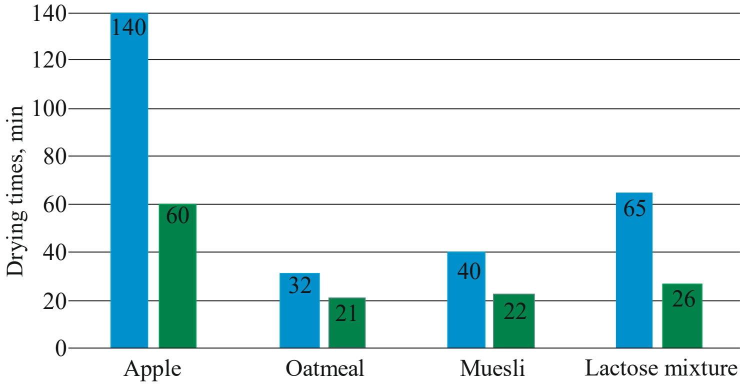

Fig. 2. Comparison of drying times for different types of raw materials in conventional (■) and improved CFD technology (■), min

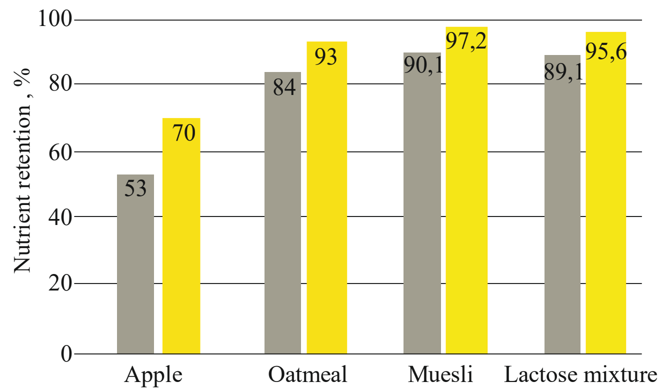

Fig. 3. Comparison of nutrient retention of different types of raw materials in conventional (■) and improved CFD technology (■), %

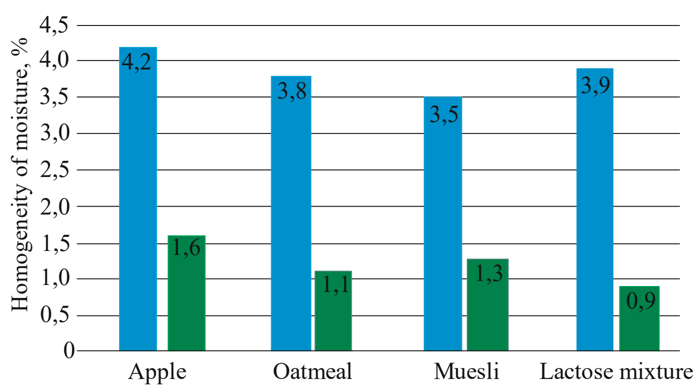

Fig. 4. Homogeneity of the distribution of residual moisture in different types of raw materials in conventional (■) and improved CFD technology (■), σ, (%)

The results confirmed that the use of improved drying technology provides a significantly higher level of nutrient preservation (improvement by 6...17% compared to conventional technology, $p < 0.05$). Thus, in apples, the content of vitamin C increased from 53 ± 1.5% to 70 ± 1.8% (+17%), in oatmeal – β-glucans from 84 ± 2% to 93 ± 2% (+9%), in muesli – protein from 90.1 ± 1.2% to 97.2 ± 1.1% (+7.1%). In the lactose mixture, the preservation of the protein component increased to 95.6 ± 1.0% compared to 89.1 ± 1.3% (+6.5%). This indicates a better biological value of the product after processing in improved CFD.

The moisture uniformity index has improved significantly: the standard deviation has decreased from 4.2–3.9% at conventional drying to 1.6–0.9% in the improved structure. This indicates a stable temperature regime, uniform blowing of the raw materials, and a high level of automated control over drying parameters.

6. Discussion of results regarding the effectiveness of the proposed hardware and technological solutions

The improved cascade fluidized dryer (CFD) using film-like electric heaters of the radiant type and thermoelectric

Peltier elements (Fig. 1) demonstrated resource efficiency in enabling a zoned temperature regime when drying various types of food raw materials. The use of sequential sections with an autonomous ventilation system and air recirculation helps reduce heat losses and increase the level of usable heat (55…60%). This significantly distinguishes the studied structure from conventional fluidized dryers, in which heat losses through the ventilation system reach 40…45% [7]. The proposed structure provides heat recuperation (35…42%), which makes it possible to increase the resource efficiency of the production cycle and reduce the environmental load. This makes it possible to increase the resource efficiency of the production cycle of target products. The integration of infrared heating using film-like IR heaters together with thermal insulation of the external surfaces of the sections minimizes heat loss under conditions of a stable and uniform thermal field to preserve the quality characteristics of the product.

In [8], the low energy efficiency of fluidized bed drying systems (approximately 28.8%) was noted because of the need for constant heating of large volumes of air. The proposed cascade structure with recirculation and the use of Peltier elements makes it possible to partially overcome this limitation through the stabilization of temperature regime at the final stage of drying and the reduction of external energy consumption. Our experimental results confirmed that stable fluidization is achieved at an air velocity of 2.3…2.6 m/s and a temperature of 48…75°C with flexible adaptation of parameters to the type of raw material (Tables 1, 2). This approach ensures the intensification of heat and mass transfer while preserving the structure and biologically active substances. In particular, fruit raw materials (apples) with high initial humidity require a gradual temperature decrease from 72°C to 52°C, which is achieved in a three-stage structure, with the use of Peltier elements for delicate control in the final stages. The homogeneity of humidity and stability of the temperature field make it possible to reduce the drying time compared to conventional methods. Thus, for apples, the drying time was reduced by almost half (from 140 to 60 min), and for other types of raw materials, in particular oatmeal, muesli, and lactose mixture, the time reduction is from 35% to 60% (Fig. 2). The results (Fig. 3) confirm the intensification of heat and mass transfer without loss of nutritional value.

Important advantages of the proposed solution are integration (cascade control + IR heating + Peltier elements + recuperation); versatility (the ability to dry fruit, grain, and protein-containing raw materials in one device); resource efficiency (thermal energy savings of 25–35% compared to known solutions [28–31]); and preservation of biologically active substances (an increase in the level of vitamin C in apples up to 70%, β-glucans in oatmeal up to 93%); automation of the process, which reduces the impact of the human factor.

In turn, alternative existing solutions include classic drum dryers, energy-intensive, which do not allow for precise temperature control and quickly dry fine-dispersed raw materials, as well as convective dryers without zoning that provide uniform heating but lose up to 45% of heat. Systems with microwave or IR heating without recirculation intensify the process but do not allow for delicate cooling of the product. Thus, our structure combines the advantages of known methods (IR heating, fluidization) and overcomes their limitations by combining technologies, recuperation, and automated control of modes. This allows for the production of new generation products with stable quality under resource-saving conditions.

The limitations of the study are related to the need for additional tests for industrial scaling, as well as the need to examine the impact of complex formulations on heat and mass transfer processes.

The disadvantages of our study are that it was conducted under limited conditions (small sample and short observation period), using simplified assumptions. This reduces the possibility of fully taking into account all external factors and limits the scaling of the results to other production or climatic conditions; however, the scale of the research is increasing at present.

Further research should focus on the integration of a complex recuperation system with automated control and the construction of mathematical models for predicting drying modes. The proposed cascade fluidization dryer with IR heating and thermoelectric Peltier elements demonstrates high potential for resource saving and preserving the quality of drying in the agri-food industry, meeting the modern requirements for sustainable development as well as the “from field to fork” concept.

7. Conclusions

1. The proposed areas for improving the cascade fluidized bed dryer include three consecutive sections with film-like infrared electric heaters and zoned temperature control based on PLC. Inclined channels between the sections enable continuous movement of raw materials under the influence of gravity and controlled air flow. To reduce energy consumption, partial air recirculation with heat recuperation up to 40% and preheating of air in the supply line are provided. The use of Peltier elements in the third section ensures temperature stabilization at 48…55°C, which is critical for preserving color, biologically active substances, and functional properties of dried products. Compared to the basic (single-temperature) CFD, our structure makes it possible to reduce the average drying temperature by 5…8°C at the same final humidity, reduce the drying time by 18…22%, increase the temperature stability in the A_3 zone (±0.4…0.5°C versus ±2°C), and reduce heat losses by 10…15%.

2. The innovative drying technology in the improved CFD ensured a high level of nutrient preservation and uniformity of the final product. Experimental studies have shown an increase in the residual content of vitamin C in apples up to 70%, β-glucans in oatmeal up to 93%, protein in muesli up to 97.2%, and minimal moisture heterogeneity ($\sigma = 0.9…1.6\%$). Our results confirm the effectiveness of zoned drying, the accuracy of automated parameter control, and compliance with the requirements for new generation products focused on functional nutrition. The proposed technical solutions contribute to increasing resource efficiency, the development of local agro-processing capacities in the format of mini-shops, farms, and cooperatives, which corresponds to the European “from field to fork” concept, strengthens food security, and creates a scientific and technical basis for expanding the population’s access to healthy food.

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 manus-cript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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