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## Evaluation of technological parameters of convective drying of pumpkin seeds with vibro-ozonation intensification of the process

Igor Palamarchuk\*

Doctor of Technical Sciences, Professor  
National University of Life and Environmental Sciences of Ukraine  
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine  
<https://orcid.org/0000-0002-0441-6586>

Mikhailo Mushtruk

PhD in Technical Sciences, Associate Professor  
National University of Life and Environmental Sciences of Ukraine  
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine  
<https://orcid.org/0000-0002-3646-1226>

Natalia Mushtruk

Postgraduate Student  
National University of Life and Environmental Sciences of Ukraine  
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine  
<https://orcid.org/0000-0002-3292-9063>

**Abstract.** Thermal and mechanical effects commonly pose challenges during the heat and mass transfer treatment of seed products. Consequently, drying methods utilising a vibratory fluidised bed, which minimise these effects on plant-based products, remain relevant. This study aimed to enhance the driving force and, consequently, the efficiency of the dehumidification process for thermolabile plant raw materials by employing vibro-mechanical activation of seed material movement, increasing electro-osmotic pressure to improve moisture diffusion conditions, and achieving disinfection during processing. The research methodology included experimental investigations conducted using a vibratory bed system with an ozone-air drying agent. The study examined the influence of vibration frequency, ozone concentration, and temperature regime

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\*Corresponding author



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on drying kinetics, heat and mass transfer rates, disinfection levels, and energy efficiency. Based on the results, a process flow diagram for convective drying of grain and cereal materials was developed, incorporating vibratory and ozonising means to intensify the process. The proposed process flow diagram ensured the necessary disinfection of the product, improved heat transfer conditions, maintained consistent hydraulic resistance along the entire rarefaction chamber, and ensured uniform drying. It also reduced energy consumption, enhanced the durability, reliability, and productivity of the process, and prevented overheating of the material, thereby enabling the drying of thermolabile products. Research findings demonstrated that filtration drying with vibro-ozonation reduced the processing time for pumpkin seeds by a factor of 1.67 and decreased energy consumption by a factor of 1.71 compared to conventional convective methods. The highest drying rate was achieved with filtration vibratory drying, which proved to be 1.68 times more efficient than convective drying. The practical significance of this research lies in the development of drying equipment that ensures uniform drying, mitigates the risk of overheating, and improves the longevity and productivity of the process. The obtained results can be implemented in industrial settings for the efficient processing of thermolabile agricultural products

**Keywords:** dehumidification processes; ozone; vibration; fluidised bed; heat carrier; thermolabile products; heat and mass transfer processes

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### Introduction

In modern drying technologies, vibration methods of technological impact on plant raw materials are becoming increasingly in demand in the processes of food and processing industries due to factors such as increased equipment productivity, shortened production cycles, and improved product quality; intensification of heat and mass transfer processes. W. Zhang *et al.* (2021) proved the feasibility of such technological measures in the processes of dehumidification and drying of seed and fruit-vegetable material. When creating low-frequency vibrations in a bulk mass of the product, the adhesion between the particles of the technological load weakens, which leads to the emergence of a fluidisation state in the system. In the research of I. Palamarchuk *et al.* (2023), it was proved that such a state of the processed medium contributes to the effective mixing of the mass due to an increase in the contact interaction area. At the same time, this allows for a reduction in the cost of bubbling the heat carrier through the material flow, since the magnitude of internal friction decreases.

An interesting aspect is the development of combined physical-mechanical and vibrational methods for moisture removal from raw materials in the food and processing industries. In the scientific studies of M. Mohamed *et al.* (2021), the main characteristics of vibrational electro-osmotic dehumidification of pectin-rich food raw materials, particularly beet pulp, were investigated. The authors proved that it is possible to increase the driving force of the dehumidification process by applying centrifugation with rotor rotation, superimposing low-frequency vibrations on the working container, creating an electro-osmotic effect under conditions of one-sided diffusion, and filtering the medium through perforations in the rotor.

Research by M. Capece & J. Larson (2022) established that the combination of these physicomachanical factors in the dehumidification process significantly enhances technical and economic parameters. Specifically, the specific energy consumption for removing 1 kg of moisture is reduced by a factor of 2.7 compared to traditional convective drying. Thus,

the proposed processes and equipment facilitate the intensification of dehydration and improve the efficiency of production technologies. I. Rogovskii *et al.* (2020) demonstrated that the application of wave and pneumodynamic processes for treating grain and cereal products substantially enhances the contact interaction between the product and the air environment. These technological approaches create favourable conditions for storage operations, optimise the microclimate in grain storage facilities, and promote intensive agitation of bulk material masses. The implementation of such methods was found to significantly improve the quality of stored products by ensuring uniform moisture distribution and reducing the risk of adverse processes in grain storage, such as the formation of stagnant zones or overheating.

Research by A. Tuncer *et al.* (2020) has established that the process of drying pumpkin seeds using an ozone-air mixture has a dual technological effect. In the initial drying period, ozone enters into oxidation reactions on the surface of the grain with organic and inorganic substances, providing a cleaning effect on the surface of the grain material. At the same time, part of the surface moisture interacts with the formed ozonides, which further intensifies the moisture removal process. As noted by D. Delfiya *et al.* (2021), the ozone-air mixture, used as a drying agent, not only contributes to reducing moisture but also provides a disinfecting effect on the surface microflora due to the reactive action of ozone. The effectiveness of this effect depends on the ozone concentration and the drying temperature regime, which underlines the importance of precise control of these parameters in the technological process.

According to the research of D. Wang *et al.* (2021), the application of vibration technologies contributes to the optimisation of technological processes, particularly through reduced energy consumption, which is an important aspect in the context of current trends towards energy efficiency and rational resource use. The

authors claim that their application allows for the efficient execution of dehumidification, drying, mixing, and separation processes with minimal heat losses and significantly lower energy costs. Such an approach contributes not only to reducing production costs but also to increasing the competitiveness of the final product on the market. Vibrational processes ensure uniform processing of materials, making them promising for widespread implementation in the food and processing industries.

One of the significant advantages of modern technologies is their environmental friendliness. As noted by S. Şevik *et al.* (2019), the use of an ozone-air mixture for drying pumpkin seeds provides a high level of disinfection without the need for chemical preservatives. Research results have shown that ozone, as a powerful oxidant, effectively destroys the cells of bacteria, fungi, and other microorganisms, while preserving the natural properties of the product. Such an approach is particularly important in the production of organic products, where minimising the use of chemical additives is a top priority. Thanks to this, the ozonation method is finding increasingly widespread application, combining effective treatment with environmental safety.

The combination of these advantages makes vibration technologies an important component of modern production processes in the food and processing industries. Their widespread implementation not only improves the quality and safety of food products but also makes the production process more environmentally sustainable and economically viable. Thus, vibration technologies represent a promising direction for research and implementation in industries focused on innovation, efficiency, and environmental responsibility. The aim of the presented scientific research was to increase the productivity of the pumpkin seed dehumidification process and to improve its technological qualities through the use of mechanical vibrations to increase the contact area

with the heat carrier flow, activate electro-osmotic diffusion of moisture, and disinfect the plant product with ozone.

### Literature Review

The development of energy-efficient and high-quality methods for drying biological materials occupies a leading place in modern scientific research due to the need to ensure high productivity and minimise the loss of nutrients. One of the promising directions is the application of low-frequency vibrations, which create additional mechanical heat and mass transfer effects. R. Gomez *et al.* (2023) noted that the creation of a vibrated fluidised bed not only increases the total contact area between the bulk material and the drying agent but also contributes to a uniform temperature distribution throughout the volume of the material. In their experiments, the authors showed that at optimal parameters (vibration amplitude 1.5-2 mm, frequency 50-60 Hz), there is a significant reduction in drying time while maintaining quality indicators. The research of Á. Calín-Sánchez *et al.* (2020) covered the features of drying vegetables in a vibrated fluidised bed with additional radiant heating. The authors established that the combined use of methods allows for reducing heat losses due to more effective penetration of heat into the material. This ensures not only the preservation of nutritional properties but also a significant reduction in energy consumption.

In the study of R. Ilyas *et al.* (2019), the processes of sugar crystallisation under various vibration frequencies were analysed in detail. In particular, it was established that at frequencies of 30-70 Hz, crystallisation accelerates by 2.5-9 times, which is explained by the activation of internal moisture transfer in the material. The author emphasised the need for optimal coordination of the frequency and amplitude of vibrations to minimise energy consumption. R. Aslam *et al.* (2021) investigated the influence of alternating dynamic loads on the rheological

properties of beet pulp. The results showed that with an increase in the shear rate, the viscosity of the process mass decreases significantly, which, in turn, contributes to the faster removal of moisture through capillaries and pores. The author's contribution also includes the development of mathematical models for predicting these processes in real production conditions.

L. Bal-Prylypko *et al.* (2022) in their scientific article argue that vibrational impact during the drying of granulated sugar in a vibrated fluidised bed allows reducing the time required to transition to the period of falling drying rate. The authors' experiments also showed that the maximum intensity of the process is observed at an amplitude of 2 mm and a frequency of 50 Hz. S. Moscatello *et al.* (2023) and V. Vasylyv *et al.* (2021) investigated the effectiveness of lowfrequency vibrations in the second period of beet pulp drying and found that additional mechanical impact during this period allows avoiding the formation of excessively dried zones, which ensures uniform quality of the final product.

I. Palamarchuk *et al.* (2023) made a significant contribution to the development of equipment for drying bulk materials, creating a series of installations for vibro-filtration drying. The authors described in detail its operating principle, noting that although it provides a high level of productivity, its complex design can lead to excessive energy consumption and non-uniform drying due to the hydraulic resistance of the layer. I. Rogovskii *et al.* (2020) developed a dryer for grain and oilseed crops, which includes a labyrinthine working zone. The authors proved that such a design contributes to improving the movement of the drying agent through the material layer. However, they noted that the single use of the drying agent and difficulties in regulating the modes limit the potential of this technology.

Convective dryers are one of the most common for processing bulk materials. To improve them, rotary dryers were developed, which

allow for effective mixing of the material, ensuring uniform drying. For example, researchers such as Y. Li *et al.* (2022) and others studied the influence of rotation speed and blade design. In addition, dryers with a fluidised bed have been developed, which provide high heat and mass transfer efficiency. Infrared dryers allow for reducing drying time and energy consumption. It was important to develop combined systems that combine infrared radiation with convective heating. Scientific works, for example, by D. Huang *et al.* (2021), are aimed at modelling the energy distribution in the infrared field.

Microwave drying provides rapid heating due to the penetration of energy deep into the material. One innovation is the combination of microwave drying with vacuum technologies, which minimises thermal loading. Engineers from the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine have worked in this direction. Vibrational dryers intensify the drying process due to the mixing of particles, preventing the formation of zones with reduced heat transfer. Vibro-ozonation technologies, proposed in the research of A. Niveditha *et al.* (2021), allow for the treatment of materials not only by drying but also by the oxidation of microorganisms. The introduction of electro-osmosis allows for reducing moisture in capillaryporous materials by creating an electric field. Research in this direction is actively conducted in EU countries, as well as in Ukraine, particularly at the Institute of Biosystems Energy.

Combining different methods (such as convective, infrared, and microwave drying) allows for achieving a synergistic effect. Scientists D. Elustondo *et al.* (2023), M. Awad *et al.* (2024), and Y. Mao & S. Wang (2023) demonstrate the latest achievements in the field of dryer design. For example, dryers with adaptive control involve the use of artificial intelligence systems and sensors to optimise the process in real-time. Energy recovery drying units use the heat of the exhaust air to preheat new

batches of material. Compact mobile dryers are designed for local use, especially in agricultural cooperatives.

The future of equipment for drying bulk materials is linked to the development of environmentally friendly technologies with minimal impact on the environment; technologies focused on reducing energy consumption; and universal dryers capable of adapting to different materials and conditions. These works not only reveal the mechanisms of heat and mass transfer processes but also open up new perspectives for the integration of vibration and ozonation methods on an industrial scale. In the future, special attention should be paid to combining energy-efficient technologies with ensuring the quality of the finished product.

## Materials and Methods

Moisture measurement of pumpkin seeds being dehydrated in a drying chamber was carried out using an indirect method, taking into account the ability of the drying agent to absorb moisture when passing through a layer of product, leading to a change in its relative humidity. Knowing the initial moisture content of the product, the relative humidity of the drying agent at the inlet and outlet of the drying chamber, as well as the flow rate of the drying agent, the moisture content was determined using H-d diagrams, where H is the enthalpy of atmospheric air (in kJ/kg of dry air), and d is the moisture content of the air (in %).

The flow rate of the drying agent was calculated using the formula (1):

$$L = 3,600 \cdot \gamma \cdot v \cdot F, \quad (1)$$

where L is the flow rate of the drying agent, kg/h;  $\gamma$  and  $v$  are the density (in  $kg/m^3$ ) and velocity (in  $m/s$ ) of the drying agent, which depends on the moisture content and barometric pressure in the air duct;  $F$  is the cross-sectional area of the air duct,  $m^2$ .

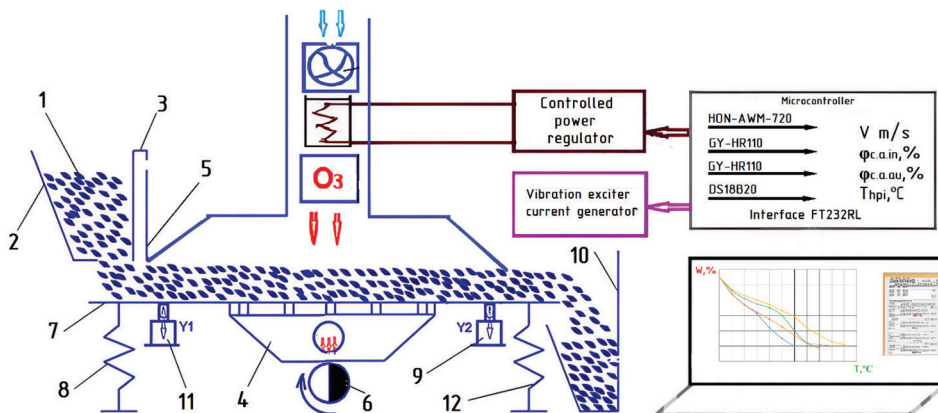
The density of the drying agent was determined from the relationship (2):

$$\gamma = 2 \cdot 10^{-3} \cdot (B / (273 + t)) \cdot ((1,000 + d) / (622 + d)), \quad (2)$$

where  $B$  is the barometric pressure,  $Pa$ ;  $t$  is the temperature of the drying agent,  $^{\circ}C$ ;  $d$  is the moisture content of the drying agent,  $g/kg$ .

The velocity of the drying agent was determined using a vane anemometer. The measurement of the relative humidity of gases is traditionally carried out using psychrometers,

the main components of which are dry and wet thermometers. To measure and regulate the parameters of the studied heat and mass transfer processes, ensuring guaranteed compliance with the parameters of the intensive drying process of pumpkin seeds with vibro-ozonation activation, a design, software, and a microcontroller system were developed and manufactured (Fig. 1).



**Figure 1.** Installation for drying bulk materials with vibro-ozonation technological impact and a system for adaptive control of the dehydration process

Source: authors' development

The developed system allowed for the determination of the temperature and humidity of the heat carrier, as well as the velocity of the drying agent. This enabled the calculation of its flow rate and, consequently, the acquisition of comprehensive data for the continuous calculation of the moisture content of the seeds within the drying chamber. The equipment also functioned as a timer, automatically recording the current temperature and humidity data. This enabled the presetting and recording of time stamps with an accuracy of one minute. The data and control point memory were, however, power-dependent. The accumulated and current information about the dehydration process parameters was transmitted to a computer via an interface for further analysis, processing, and calculation.

When connected to a computer, the microcontroller's clock was automatically synchronised with the computer's clock.

The calculation of the current moisture content of the product was performed using a computer and the given formulas (1) and (2), utilising the moisture content values of the drying agent obtained from the microcontroller and the input constants characterising the process. The research involved considering the following technological impacts on pumpkin seeds: filtration drying with vibro-ozonation activation; filtration heat exchange with vibration activation; filtration drying itself; and convective drying of the product in a stationary state. To implement these technological measures, an experimental setup was developed, the scheme of which is presented in Figure 1.

The experimental setup consists of a hopper 2 (Fig. 1) on which gate 3 is placed to regulate the height of the layer of wet material 1. Below hopper 2, there is a vacuum chamber 4 connected to a vibration exciter 6, on which a perforated bottom of the working chamber 7 is fixed. The latter is installed on elastic supports 8 and 9. Below the bottom 7, two symmetrically placed variable-angle electromagnets 11 and 12 are mounted. A drying chamber 5 is installed above the vacuum chamber, with an unloading hopper 10 located in its lower part.

During the operation of the experimental model, a heating agent is supplied to the drying chamber 5. From hopper 2, using slide gate 3, the wet material 1 enters the upper part of the perforated bottom 7 and moves along its surface under the action of low-frequency vibrations generated by the vibration exciter 6 in the direction of the unloading hopper 10. Due to the created vacuum in chamber 4, the heating agent is filtered through a layer of wet material, which, due to intensive mixing under conditions of low-frequency vibrations, has high porosity and, accordingly, low hydraulic resistance, which allows for a significant intensification of the drying process and a reduction in energy consumption.

## Results and Discussion

The mechanism of the investigated process of convective drying with vibro-ozonation activation occurs as follows. When ozone is directed onto the surface of plant material, free radical processes arise, which rapidly spread into the internal tissues. In essence, this amounts to the transfer of energy, which is released at the molecular levels of the upper layer of the grain or food product, into the internal tissues. Moreover, part of the excess energy is spent on physicochemical transformations, as a result of which the structure of cell membranes, redox potential, ionic permeability, and other cell properties change. Part of the energy is converted into heat, accelerating the development

of the studied heat and mass transfer processes of dehumidification.

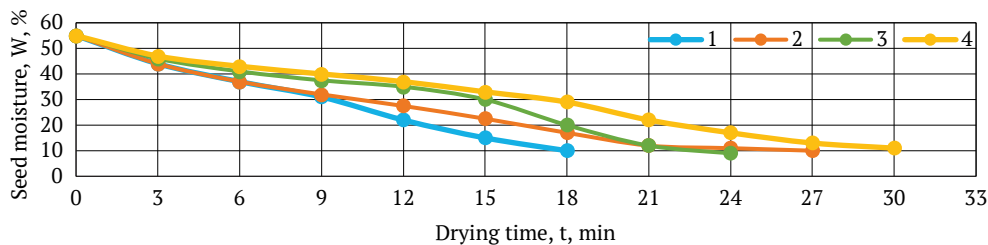
As ozone passes through the grain mass, it decomposes into molecular and atomic elements,  $O_2$  and  $O$ , releasing heat equivalent to 142 kJ/mol. Atomic oxygen binds moisture around itself in the form of droplets, which are carried away by the airflow. After the removal of surface moisture, ozone affects the permeability of cell membranes, and the presence of atomic oxygen promotes the movement of moisture outwards. The next stage of drying involves the removal of sorption-bound moisture, using the amount of heat released during the decomposition of ozone, as well as the presence of atomic oxygen and ions of different polarities. Under the influence of electromagnetic interaction forces, the dipole bonds of water molecules with the pumpkin seed cells are weakened, which significantly affects the increase in the drying rate of the grain during this period. The introduction of low-frequency vibrations into the technological mass of the product ensures both an increase in the contact area between the material and the heat carrier flow and an improvement in the efficiency of the aforementioned chemical interaction reactions.

In the investigated process, using the aforementioned technological methods, an evaluation was conducted based on parameters such as seed moisture content, moisture removal rate, and temperature of the pumpkin seed material, which can be explained by the peculiarities of the physicochemical processes occurring within the seed and its shell (surface) and the seed mass itself (Fig. 2).

At the initial stage (moisture content of 54-30%), the mixing effect was uneven due to the sticking of seeds to each other and to equipment parts. Partially due to the formation of a crust, the transparency of the perforated bottom was impaired, which hindered the supply of the drying agent. Therefore, heating of the seed mass occurred gradually, mainly due to conductive heat transfer. The moisture removal

process was ensured by the evaporation of free moisture from the seed surface and the filtration of unbound surface moisture in the direction of natural flow “seed layer – perforated bottom”. The pressure difference was found

to be excessive above the seed layer due to the injection of heated and ozone-enriched drying agents and the rarefaction in the sump-diffuser space, which significantly activates the dehydration process at relatively low temperatures.



**Figure 2.** Dependence of pumpkin seed moisture content  $W$ ,

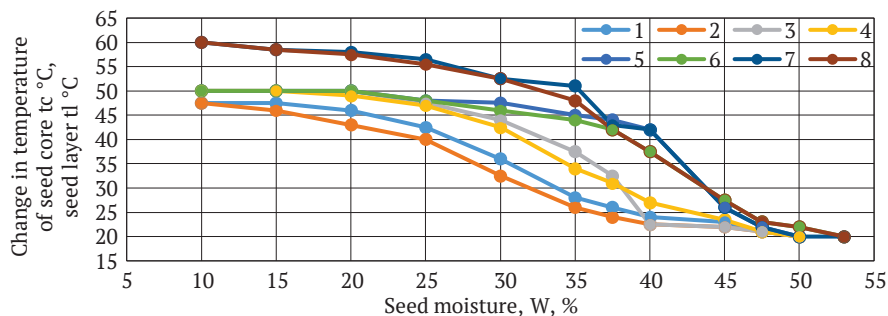
% on drying time  $\tau$  (in min) for different drying methods

**Note:** 1 – filtration with vibro-ozonation activation; 2 – filtration with vibration activation; 3 – filtration; 4 – convective in a stationary bed. The drying agent temperature for the pumpkin seed moisture content range of 54-35% was 30°C and within the range of 35-10% – 50°C

**Source:** authors' development

The next stage of moisture removal (moisture content of 30-15%) is characterised by a deterioration of the adhesive and cohesive properties of the seeds, which contributed to the activation of the mixing process, forming “fountaining” areas. The continuous film of moisture is removed, and the liquid phase moves from the pores and capillaries of the shell to the outer surface of the seed, from which it evaporates. Moreover, voids free of

liquid phase are created and spread within the shell. Moisture is also transferred from the seed surface by concentration diffusion. Due to the increased influence of the convective component, an increase in the temperature of the seed mass is observed. The results of studies determining the effect of the drying agent temperature on the heating of the core and shell of pumpkin seeds with changes in seed moisture content are shown in Figures 2 and 3.



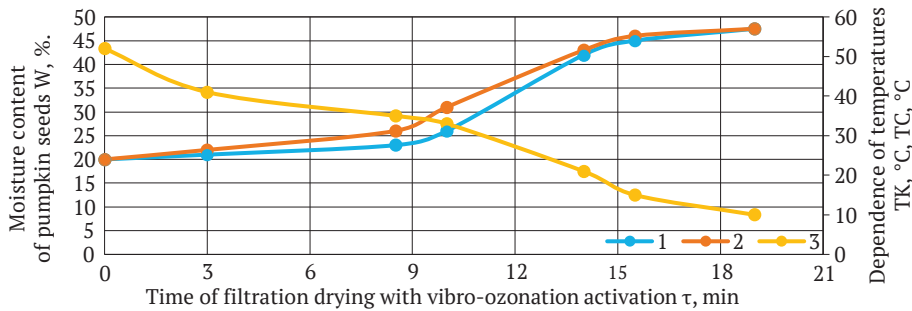
**Figure 3.** Changes in the temperature of the seed kernel (embryo)  $t_k$  (°C), seed coat  $t_c$  (°C) during filtration drying of pumpkin seeds at different seed moisture content values  $W$ , % and drying agent temperature

**Note:** at ( $W < 38\%$ ):  $Tda_{1f}$  – 30°C;  $Tda_{2f}$  – 40°C;  $Tda_{3f}$  – 50°C;  $Tda_{4f}$  – 50°C; at ( $W > 38\%$ ):  $Tda_{1c}$  – 50°C;  $Tda_{2c}$  – 50°C;  $Tda_{3c}$  – 50°C;  $Tda_{4c}$  – 60°C

**Source:** authors' development

The final stage of drying (seed moisture content 17-8%) occurred in a mode of active mixing in a vibrofluidised bed, facilitated by a significant mass loss and cleaning of the seed surface. The moisture transfer mechanism is characterised by a deepening of the evaporation front into the seed kernel. Swelling moisture, as well as condensation from the surface of the kernel, moves through the developed system of capillaries and pores of the coat and evaporates at the phase transition boundary. Further, the

phase transition front moves into the depth of the kernel, and moisture enters the coat in the form of vapour. This stage is characterised by significant heating of the seed mass due to intensive exchange of its surface and contact with the drying agent. At values of  $T_{da_{4f}} > 50^{\circ}\text{C}$ , a crust is formed in the layer of pumpkin seed moisture, making the seed layer virtually impermeable to the filtration of the drying agent. Therefore, studies in mode No. 4 were conducted at  $T_{da_{4f}} = 50^{\circ}\text{C}$  (Fig. 4).



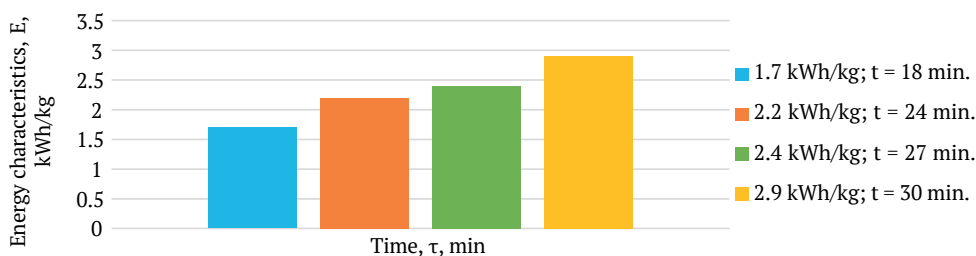
**Figure 4.** Dependence of the seed kernel temperature  $TK$ ,  $^{\circ}\text{C}$  (line 1), pumpkin seed moisture content  $W$ , % (line 2), and seed coat temperature  $TC$ ,  $^{\circ}\text{C}$  (line 3) on the filtration drying time with vibro-ozonation activation  $\tau$  (in min)

**Source:** authors' development

Results of studies on the heating of the seed kernel (embryo) and the outer seed coat, depending on the drying agent temperature, allowed the determination of the maximum permissible temperatures at which the seed's conditioning characteristics, in particular its germination and germination energy, are preserved. According to the obtained data, the maximum heating temperature of the protein components of the embryo should not exceed  $t_k = 42^{\circ}\text{C}$  to ensure optimal germination and germination energy indicators. In cases where the temperature of the drying agent exceeds  $t_c$ , the maximum permissible temperatures for maintaining sowing qualities are  $47^{\circ}\text{C}$  and  $t_{da} = 50^{\circ}\text{C}$  at a specific energy consumption of  $Q = 4.23 \text{ MJ/kg}$  of relative humidity. Thus, the conducted studies allow for a clear definition of temperature limits for safe drying, taking into

account the quality of the seeds and the energy efficiency of the process.

To optimise the technological and energy parameters of vibro-ozonation drying of pumpkin seeds in a vibrofluidised bed, a comparative analysis of the efficiency of drying processes carried out using the developed microcontroller system was performed (Fig. 2, 3, 4, 5). According to the experimental results, the use of the latest system allowed for a significant improvement in drying parameters compared to traditional methods. In particular, the increase in drying rate was from 1.12 to 1.68 times, indicating a significant increase in process efficiency. Specific energy consumption decreased by 1.21-1.71 times, and processing time decreased by 1.21-1.67 times, which significantly reduces energy costs and increases drying productivity.



**Figure 5.** Energy characteristics of the studied convective methods of drying pumpkin seeds

**Note:** 1 – filtration with vibro-ozonation activation; 2 – filtration with vibration activation; 3 – filtration; 4 – convective in a static product bed. The drying agent temperature for the product moisture content range of 54–35% was 30°C and within the range of 35–10% – 50°C

**Source:** authors' development

Particularly high results were achieved using filtration drying with vibro-ozonation activation, which demonstrated the highest efficiency in reducing seed processing time and energy consumption. This phenomenon is explained by a significant decrease in internal friction within the seed mass and a significant increase in the contact area between the seeds and the heat carrier. Such improvement allows for a significant acceleration of the drying process due to more intensive heat transfer, which in turn contributes to a decrease in energy consumption. In particular, the highest drying rate was recorded for filtration vibration drying (Fig. 5), which confirms its high efficiency compared to other methods.

Filtration drying with vibro-ozonation activation showed the best characteristics in minimising the processing time of pumpkin seeds and energy consumption for the process, which is explained by the greatest reduction in internal friction in the product mass and the largest contact area of seed coverage by the heat carrier flow. The highest drying rate was observed for filtration vibration drying (Fig. 5).

The conducted research demonstrates that the experimental model of a convective dryer with vibro-ozonation intensification has a significant advantage in terms of pumpkin seed drying efficiency. The intensive mixing of seeds during heat transfer results in rapid and uniform drying of the material. In particular,

traditional drying systems often face the problem of uneven heating: the seed surface may experience overheating, while the inner layers remain moist (Carter *et al.*, 2019). Such uneven drying leads to a decrease in the quality of the finished product and increases the overall processing time.

In the investigated model, vibratory mixing of the seeds allows for avoiding such problems, which is extremely important when processing seeds with a high moisture content at the initial stages of drying. For example, for sunflower seeds, which often require prolonged drying due to a thick husk, vibration technologies could also increase drying efficiency and allow for better preservation of nutrients, which is important for the food industry. Periodic drying methods, described in the research of N. Langenaeken *et al.* (2019), are characterised by the fact that the entire volume of seeds is processed simultaneously and remains stationary in the dryer until the process is complete, while the flow regime provides faster and more uniform moisture removal. Unlike such technology, the developed flow process ensures continuous movement of the seeds through the drying chamber. The ability to adjust the residence time of the seeds in the drying chamber allows the process to be adjusted according to the specific characteristics of the material.

In the developments of L. Roy *et al.* (2020), it was proven that a continuous process also

contributes to reducing equipment setup losses between batches, which is an advantage for mass production, where minimising downtime and cooling periods between batches is critical. For the proposed model, more humid or more heat-sensitive types of seeds may require a longer stay at lower temperatures, which is easily achieved in the proposed model.

To ensure the economic feasibility of drying and dehumidification processes in large enterprises, there is a growing demand for simple convective technologies (Sá-Caputo *et al.*, 2019). At the same time, every percentage of energy consumption significantly affects the final cost of the product, therefore, the introduction of vibration-filtration dryers will reduce costs and, accordingly, increase the competitiveness of products on the market. Filtration drying with vibro-ozonation activation has shown that overall energy consumption can be reduced by 1.71 times compared to the traditional convective drying method.

For small farms, the issue of ensuring minimal heat treatment duration is relevant both to save energy costs and to improve product quality and, consequently, demand for it; this requires increasing the drying rate of seeds before long-term storage and allows for significant time savings at a high processing rate without loss of product quality (Piddubnyi *et al.*, 2024). In this regard, the studied vibro-ozonation activation contributes to reducing internal friction between seed particles, which significantly improves heat and mass transfer conditions. Such an approach contributes to the rapid heating of the material with minimal heat consumption for the “internal” processing of the product, which explains the significant energy savings. According to the research results, filtration vibration drying showed a process speed that exceeds the traditional convective method by 1.68 times. Fast drying provides an increase in the number of batches processed in one cycle of the dryer operation, which leads to an increase in the productivity of production capacities.

The quality of the final product is a crucial indicator of drying efficiency, especially when it comes to food products. In traditional methods, where there is no active mixing, seed particles may be heated unevenly, leading to so-called “overheating” in the contact zone with the heat carrier; for example, when drying corn or wheat, overheating of the grain can cause damage to the outer coat, which impairs its germination during subsequent sowing, according to research (Akhlaq & Ali, 2020). The application of vibro-ozonation activation has made it possible to achieve a uniform temperature regime throughout the entire volume of the drying chamber, which minimises thermal and mechanical damage to the product structure and loss of its nutritional properties. Thanks to uniform mixing and gradual renewal of the moisture exchange surface, the proposed technology avoids such problems, preserving the integrity and quality of the seeds.

Heat treatment of plant raw materials in a static bed within stationary thermal chambers or cabinets requires a sufficiently high energy consumption to achieve an acceptable result, which is usually accompanied by significant heat losses (Sun & Seok, 2019; Singh & Agarwal, 2021). With such drying methods, the contact of seeds with the heat carrier is limited, which is why seed particles must be overheated to ensure effective heat and mass transfer (Wang *et al.*, 2020). When using the investigated model of a vibroconvective dryer with a fluidised bed of the product, under conditions of active surface renewal, it is possible to achieve the best results even at lower temperatures of the heat carrier, which also contributes to preserving quality.

In the production of organic products, preserving the biochemical properties of the material under convective heat exchange conditions is a significant challenge (Wathelet *et al.*, 2020). The proposed technology has significant potential for this industrial application, as it combines economic efficiency and high

drying speed with product quality preservation. Reduced energy consumption also has a positive impact on the environmental performance of production, as heat energy consumption is directly correlated with the level of emissions into the environment. The implementation of such technology in industrial lines would contribute not only to resource savings but also to reducing the overall environmental impact of production, which is an important factor in modern society.

In summary, the developed method of convective drying with vibro-ozonation intensification demonstrates several significant advantages over traditional methods. It provides a high speed of seed processing with a significant reduction in energy consumption, making it economically viable and environmentally sound. The uniformity of the temperature distribution, the ability to adjust the process parameters, the high quality of the final product, and the reduction of the negative impact on the environment make the proposed methodology attractive for implementation on an industrial scale.

### Conclusions

As a result of the conducted scientific research, a design, software, and a microcontroller-based complex were developed for remote monitoring and computer interpretation of data with adaptive temperature control of thermolabile seed materials, namely pumpkin; which allowed measuring the temperature and humidity of the heat carrier, the speed of the drying agent, and indirectly – carrying out the current calculation of seed moisture, monitoring the heat and mass transfer process with the determination of rational process parameters.

The results of the studies conducted using the developed experimental model of a convective dryer with vibro-ozonation intensification of the seed processing process showed the following advantages of the proposed method: intensive mixing of seeds during heat transfer;

continuous flow moisture removal process; the ability to adjust the residence time of seeds in the drying chamber; equalisation of the material temperature throughout the entire volume of the drying chamber; intensive moisture removal with constant renewal of the moisture exchange surface; carrying out the process under rational regimes that ensure the current requirements for the final quality of the material and a significant reduction in specific energy consumption.

Filtration drying with vibro-ozonation activation demonstrated the best characteristics in minimising the processing time of pumpkin seeds: a 1.67-fold decrease compared to the convective heat transfer method and a 1.71-fold decrease in energy consumption for the process compared to traditional convective drying, which is explained by the greatest reduction in internal friction in the product mass and the largest contact area of the seed coverage with the heat carrier flow. The highest drying rate was shown for filtration vibration drying, which exceeded this indicator in the case of the convective method of processing by 1.68 times.

Promising directions for improving the studied technologies may include the use of vibrators with kinematic combined vibration excitation, which will significantly reduce the vibrating mass and, accordingly, energy consumption for the process; the implementation of a vibro-wave conveyor system, which makes it possible to both reduce energy consumption and metal consumption of drying equipment while maintaining the quality effects of the proposed technology.

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### Conflict of Interest

None.

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## Оцінка технологічних параметрів конвективного сушіння насіння гарбуза з віброозонуючою інтенсифікацією процесу

### Ігор Паламарчук

Доктор технічних наук, професор  
Національний університет біоресурсів і природокористування України  
03041, вул. Героїв Оборони, 15, м. Київ, Україна  
<https://orcid.org/0000-0002-0441-6586>

### Михайло Муштрук

Кандидат технічних наук, доцент  
Національний університет біоресурсів і природокористування України  
03041, вул. Героїв Оборони, 15, м. Київ, Україна  
<https://orcid.org/0000-0002-3646-1226>

### Наталія Муштрук

Здобувач  
Національний університет біоресурсів і природокористування України  
03041, вул. Героїв Оборони, 15, м. Київ, Україна  
<https://orcid.org/0000-0002-3292-9063>

**Анотація.** У процесі тепломасообмінної обробки насінневої продукції, як правило, виникають проблеми відносно наслідків термічної та механічної дії. Тому застосування методів сушіння з вібророзрідженим шаром продукції, що дозволяє мінімізувати механічний та термічний вплив на рослинну продукцію, не втрачають актуальності. Метою даної наукової роботи стало підвищення рушійної сили та відповідно ефективності процесу зневоложення термолабільної рослинної сировини за рахунок застосування вібромеханічної активації руху насінневого матеріалу, підвищення електроосмотичного тиску для поліпшення умов дифузії вологи, реалізація дезінфективного впливу у процесі обробки. Методологія дослідження включала експериментальні дослідження в установці з вібраційним шаром і озono-повітряним сушильним агентом. Досліджували вплив частоти вібрацій, концентрації озону та температурного режиму на кінетику сушіння, швидкість тепломасообміну, рівень дезінфекції та енергоефективність. За результатами дослідження розроблена схема конвективного сушіння зернового та зерно-круп'яного матеріалів з вібраційними та озонуючими засобами його інтенсифікації. Запропонована схема дозволила забезпечити необхідну дезінфекцію продукції, поліпшити умови теплопередачі; забезпечити однаковий гідравлічний опір вздовж всієї камери розрідження, рівномірність сушіння; зменшення енергетичних витрат на процес, збільшення його довговічності, надійності та продуктивності; виключення перегріву висушуваного матеріалу, що зробило можливим здійснювати процес сушіння термолабільної продукції. За результатами досліджень доведено, що фільтраційне сушіння з віброозонуванням скорочувало час обробки насіння гарбуза в 1,67 раза, зменшуючи енерговитрати в 1,71 раза порівняно з традиційним конвективним методом. Найвища швидкість сушіння була досягнута при фільтраційному вібраційному сушінні, яке виявилось ефективнішим за конвективне в 1,68 раза. Практична цінність роботи полягає у розробці конструкції сушильного обладнання, що забезпечує рівномірність сушіння, знижує ризик перегріву, підвищує довговічність і продуктивність процесу. Отримані результати можуть бути впроваджені у виробництво для ефективної обробки термолабільної сільськогосподарської продукції

**Ключові слова:** процеси зневоложення; озон; вібрація; псевдорозріджений шар; теплоносій; термолабільна продукція; процес тепломасообміну