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IMPLEMENTATION OF ENERGY-SAVING MODES FOR ELECTRO-RADIATION DRYING OF OIL-CONTAINING MATERIAL USING AUTOMATION TOOLS

Borys Kotov[1], Roman Kalinichenko[2], Serhii Stepanenko[3], Vasyl Lukach[2], Volodymyr Hryshchenko[2], Alvian Kuzmych[3], Yurii Pantsyr[1], Ihor Garasymchuk[1], Volodymyr Vasylyuk[2]

[1]Higher Educational Institution "Podillia State University", Kamianets-Podilskyi, Ukraine, [2]National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine, [3]Institute of Mechanics and Automation of Agricultural Production, Hlevakha, Ukraine

Abstract. *For industrial processing of oil-containing plant material, it is necessary to reduce its moisture content to 6–8%. The use of convective, energy-intensive dryers for drying seeds to low moisture levels is inefficient. The aim of the work is to improve the mathematical description of dynamic modes of grain drying in infrared energy supply systems and, based on this, to develop an automatic control system. The main method of researching the static and dynamic characteristics of the grain processing process using infrared radiation is the analytical method followed by experimental verification of the obtained mathematical description. To intensify the process of achieving the desired moisture content of the raw material, it is proposed to use contactless heating with infrared radiation. In this case, the issue of preventing overheating and scorching of the material is resolved by using vibration transportation with particle mixing and automating surface temperature control and its stabilization by adjusting the movement speed. Based on the dependencies, it can be concluded that an increase in the temperature of the grain due to distributed power input enhances the intensity of heating and stabilizes the temperature of the grain material. This leads to a reduction in the time required for the development of moisture gradients within individual grains and speeds up the evaporation of moisture from the surface of the grains. The paper clarifies the mathematical model of thermal processes of infrared processing of oilseeds, on the basis of which an automatic control system was developed for the implementation of energy-saving grain drying modes. The research results showed that the introduction of an automated infrared drying mode allows for a reduction in specific energy consumption by 30-40%.*

Keywords: electro-radiation heating, oil-containing seed material, infrared energy supply, automatic control

WDRAŻANIE ENERGOOSZCZĘDNYCH TRYBÓW SUSZENIA ELEKTRORADIACYJNEGO MATERIAŁÓW ZAWIERAJĄCYCH OLEJ PRZY UŻYCIU NARZĘDZI AUTOMATYZACJI

Streszczenie. *Przemysłowe przetwarzanie materiałów roślinnych zawierających olej konieczne wymaga zmniejszenia ich wilgotności do 6–8%. Wykorzystanie konwekcyjnych, energochłonnych suszarni do suszenia nasion do niskiego poziomu wilgotności jest nieefektywne. Celem pracy jest udoskonalenie matematycznego opisu dynamicznych trybów suszenia ziarna w systemach zasilania energią promieniowania podczerwonego i, w oparciu o to, opracowanie automatycznego systemu sterowania. Główną metodą badania statycznych i dynamicznych charakterystyk procesu przetwarzania ziarna za pomocą promieniowania podczerwonego jest metoda analityczna, a następnie eksperymentalna weryfikacja uzyskanego opisu matematycznego. Aby zintensyfikować proces osiągania pożądanej wilgotności surowca, proponuje się zastosowanie bezkontaktowego ogrzewania promieniowaniem podczerwonym. W tym przypadku problem zapobiegania przegrzaniu i przypaleniu materiału rozwiązuje się poprzez zastosowanie transportu wibracyjnego z mieszaniem cząstek oraz automatyzację kontroli temperatury powierzchni i jej stabilizację poprzez regulację prędkości ruchu. Na podstawie zależności można stwierdzić, że wzrost temperatury ziarna spowodowany rozłożonym poborem mocy zwiększa intensywność ogrzewania i stabilizuje temperaturę materiału ziarnistego. Prowadzi to do skrócenia czasu potrzebnego do powstania gradientów wilgotności w poszczególnych ziarnach i przyspiesza odparowywanie wilgoci z powierzchni ziaren. W artykule wyjaśniono model matematyczny procesów termicznych przetwarzania nasion oleistych za pomocą promieniowania podczerwonego, na podstawie którego opracowano automatyczny system sterowania służący do wdrażania energooszczędnych trybów suszenia ziarna. Wyniki badań wykazały, że wprowadzenie automatycznego trybu suszenia za pomocą promieniowania podczerwonego pozwala na zmniejszenie zużycia energii o 30–40%.*

Słowa kluczowe: ogrzewanie elektroradiacyjne, materiał nasienny zawierający olej, dostarczanie energii podczerwonej, automatyczne sterowanie

Introduction

The technology for extracting plant oils from seed material involves not only mechanical but also moisture-thermal treatment, specifically thermal dehydration, which is necessary to provide the raw material with the required physicochemical properties. Convective heat supply to the initial raw material has become widely used [3]. However, convective drying units, with an efficiency coefficient of up to 40%, are ineffective for the thermo-treatment and drying of low-moisture (initial moisture content of oilseeds 12–14%, final 6–8%) oilseed material [4, 7].

To dehydrate oil-containing raw materials with increasing demand, processes with infrared energy supply, such as electro-radiation heating and drying, are used. Infrared irradiation, as an intensive thermal treatment method for oilseed material before oil extraction, ensures the inactivation of anti-nutritional substances – trypsin inhibitor and urease enzyme [8].

However, increased energy consumption in existing drying-thermal units limits the widespread use of this equipment.

One of the reserves for reducing the energy intensity of the process and the specific power of the equipment is to bring the infrared radiation source closer to the irradiated material (minimizing the height of the emitter installation). However, this may lead to overheating and scorching of parts of the material's surface, resulting in losses of dry matter.

To avoid technological and energy contradictions, it is advisable to use air-cooling of the material's surface. This increases the thermal transfer potential (temperature difference between the radiation and the material surface). To implement the proposed method, temperature control of the material surface and corresponding adjustment of airflow are required. This can practically achieved through the automation of the irradiation mode control process.

To create an automatic control system, a clearly formulated mathematical model of the dynamics of heating and dehydration processes of the material is necessary.

1. Analysis of literary sources and problem statement

It has been established that the unique properties of oil-containing crops result in significant demand for them in modern processing industries [3]. At the same time, the limited potential for intensifying heating and drying processes of oilseeds in convective energy supply drying units has been identified [4, 7]. In this context, the use of electrophysical methods for intensifying heat-intensive processes has become widespread [8]. The use of electromagnetic fields [13], indirect heating with heat pumps [11, 12], and resistive heating [6, 10] of the drying agent allows for a substantial intensification of convective drying processes [8, 9]. However, the drawbacks of convective heat exchange are not eliminated in this approach.

Significant opportunities and prospects are opened by the use of contactless heat transfer through infrared irradiation of oil-containing material [1, 5]. The rapid penetration of infrared rays into the depth of particles and their absorption by water [13) structural inclusions intensifies the conversion of water into vapor and its pressurized removal, but there is a potential for overheating of surfaces. Therefore, studies [1, 5] suggest using vibrational mixing of the material.

Studies have addressed [2] the creation of mathematical descriptions of infrared drying processes for grain materials. However, to utilize these descriptions for the synthesis of a control system, the dynamics of the object need to be represented by transfer functions. The issues of automating infrared drying have not been clearly reflected in the analyzed works.

The aim of the work is to improve the mathematical description of dynamic modes of grain drying in infrared energy supply systems and, based on this, to develop an automatic control system.

2. Materials and methods

The main method of researching the static and dynamic characteristics of the grain processing process using infrared radiation is the analytical method followed by experimental verification of the obtained mathematical description. To intensify the process of achieving the desired moisture content of the raw material, it proposed to use contactless heating with infrared radiation. In this case, the issue of preventing overheating and scorching of the material is resolved by using vibration transportation with particle mixing and automating surface temperature control and its stabilization by adjusting the movement speed. To achieve the described results, the following methods are proposed. Modeling and Optimization of Process Technological Parameters: Utilizing mathematical modeling to analyze heat and mass transfer processes and determine the optimal intensity of infrared radiation; Developing algorithms for automatic temperature regulation based on PID controllers or adaptive control systems; Integrating programmable logic controllers (PLCs) to manage the conveyor speed and the intensity of infrared radiation; Employing intelligent control systems based on machine learning to adapt parameters in real time depending on the condition of the grain; Exploring the feasibility of using renewable energy sources (e.g., solar energy) to power the infrared emitter; Reducing heat loss through the use of insulating materials and heat recovery systems.

3. Results and discussion

In the study, the primary method for investigating the static and dynamic characteristics of the grain processing process using infrared radiation is an analytical method, followed by experimental validation of the obtained mathematical description.

When describing the physical aspect of the process of grain heat treatment using infrared (IR) radiation and the design features of the electro-thermal radiation installation, the following assumptions and simplifying presumptions were used. The temperature of the surface elements of the installation is equal to the temperature of the air, and losses through the surface are neglected. Since vibrational movement is used, heat transfer to the supporting surface is disregarded. The effects of backward and direct radiation, as well as heat conduction in the media, are accounted for in the heat transfer coefficients, which are independent of temperature and do not change over time. Heating of the grain is considered non-gradient. The rate of moisture evaporation (in the case of using wet raw material) is proportional to the rate of material heating and is determined by the Rebinder equation: $Rb = cd\theta/rdU$.

To eliminate the nonlinearity of the radiative component of the thermal balance, the following relation is used:

$$Q_v = c_n(T_1^4 - T_2^4) = c_n(T_1^4 - T_2^4)(T_1 + T_2)(\theta_1 - \theta_2) = = \alpha_v(\theta_1 - \theta_2) \quad (1)$$

where $T_1, (\theta_1), T_2, (\theta_2)$ are the temperatures of the bodies (media) exchanging energy; c_n, α_v the effective emission coefficient and the linearized radiative heat transfer coefficient.

The initial system of linearized differential equations describing the unsteady process of complex radiative-convective heat exchange between the emitter 1, the grain layer 2, and the air 3 circulating in the chamber is as follows:

$$m_1c_1\frac{d\theta_1}{d\tau} = P - \alpha_1F_1(\theta_1 - \theta_2) - \alpha_2F_2(\theta_1 - t) \quad (2)$$

$$m_2c_2\frac{d\theta_2}{d\tau} = A_1\alpha_1F_1(\theta_1 - \theta_2) - \alpha_3F_3(\theta_3 - t) - Gc_2(\theta_2 - \theta_1) \quad (3)$$

$$m_3c_3\frac{dt_v}{d\tau} = G_vc_p(t_1 - t_v) + \alpha_2F_2(\theta_1 - t_v) + \alpha_3F_3(\theta_2 - t_v) \quad (4)$$

where, θ_1, θ_2, t_v are the temperatures of the emitter, grain, and air, respectively; m_1c_1, m_2c_2, m_3c_3 the heat capacities of the emitter, grain, and air; G, G_v the mass flow rates of the grain and air; $\alpha_1, \alpha_2, \alpha_3$ the heat transfer coefficients; F_1, F_2, F_3 the heat exchange surfaces; A is the coefficient of radiant energy absorption by the grain.

When expressing the dynamic equations (2)–(4) in increments: $\theta_1 = \theta_1^0 + \Delta\theta_1$; $\theta_2 = \theta_2^0 + \Delta\theta_2$; $t_v = t_v^0 + \Delta t_v$; $G = G^0 + \Delta G$, by subtracting the static equations, neglecting second-order smallness terms, and converting the equations to canonical form, we obtain the following system of ordinary differential equations:

$$T_1\frac{d\Delta\theta_1}{d\tau} + \Delta\theta_1 = k_1\Delta P + k_2\Delta\theta_2 + k_3\Delta t_v \quad (5)$$

$$T_2\frac{d\Delta\theta_2}{d\tau} + \Delta\theta_2 = k_4\Delta\theta_1 + k_5\Delta t_v - k_6\Delta G_2 + k_7\Delta\theta_{21} \quad (6)$$

$$T_3\frac{d\Delta t_v}{d\tau} + \Delta t_v = k_8\Delta t_1 + k_9\Delta G_3 + k_{10}\Delta\theta_1 + k_{11}\Delta\theta_2 \quad (7)$$

In the equations, T_1, T_2, T_3 are time constants that characterize the dynamics, while $k_1, \dots, k_{11}$ are constant coefficients expressed through the design and technical parameters of the object: $k_1 = (\alpha_1F_1 + \alpha_2F_2)^{-1}$; $k_2 = \alpha_1F_1k_1$; $k_3 = \alpha_2F_2k_1$; $k_4 = K'A\alpha_1F_1$; $K' = (A\alpha_1F_1 + \alpha_3F_3 + c_2G_2)^{-1}$; $k_5 = K'\alpha_3F_3$; $k_6 = c_2\theta_2^0K'$; $k_7 = c_2G_2^0K'$; $k_8 = c_3G_3^0K''$; $k_9 = (c_3t_1^0 - c_3t^0)K''$; $k_{10} = \alpha_2F_2K''$; $k_{11} = \alpha_3F_3K''$; $K'' = (\alpha_2F_2 + \alpha_3F_3 + G_3^0c_3)^{-1}$; $T_1 = m_1c_1k_1$; $T_2 = m_2c_2K'$; $T_3 = m_3c_3K''$.

To the equations (5)–(7), the equation for moisture content change, obtained from experimental data, should be added:

$$T_4\frac{d\Delta u}{d\tau} + \Delta u = k_{12}\Delta\theta_2 + k_{13}\Delta u_1 \quad (8)$$

where, $\Delta u_1, \Delta u$ are the change in the initial and current moisture content of the grain; k_{12}, k_{13} the empirical coefficients; T_4 is the time constant obtained from the grain drying curve.

By applying Laplace transforms to equations (5)–(8), we obtain analytical expressions for the transfer functions for the channels connecting the grain temperature at the output with its input temperature, the emitter temperature and its power, as well as the parameters of the air in the chamber. The transfer functions of the inertial elements in the thermal regime control system for heat treatment have been obtained for the main channels in the following form:

$$W_1(p) = \frac{\Delta\theta_1}{\Delta P} = \frac{k_1}{T_1p+1};\ W_2(p) = \frac{\Delta\theta_1}{\Delta\theta_2} = \frac{k_2}{T_1p+1};$$

$$W_3(p) = \frac{\Delta\theta_1}{\Delta t_v} = \frac{k_3}{T_1p+1};\ W_4(p) = \frac{\Delta\theta_2}{\Delta\theta_1} = \frac{k_4}{T_2p+1};$$

$$W_5(p) = \frac{\Delta\theta_2}{\Delta t_v} = \frac{k_5}{T_2p+1};\ W_6(p) = \frac{\Delta\theta_2}{\Delta G_2} = \frac{k_6}{T_2p+1};$$

$$W_7(p) = \frac{\Delta\theta_2}{\Delta\theta_{21}} = \frac{k_7}{T_2p+1};\ W_8(p) = \frac{\Delta t_v}{\Delta t_1} = \frac{k_8}{T_3p+1};$$

$$W_9(p) = \frac{\Delta t_v}{\Delta G_3} = \frac{k_9}{T_3p+1};\ W_{10}(p) = \frac{\Delta t_v}{\Delta\theta_1} = \frac{k_{10}}{T_3p+1};$$

$$W_{11}(p) = \frac{\Delta t_v}{\Delta\theta_2} = \frac{k_{11}}{T_3p+1};\ W_{12}(p) = \frac{\Delta u}{\Delta\theta_2} = \frac{k_{11}}{T_4p+1};$$

$$W_{13}(p) = \frac{\Delta u}{\Delta u_1} = \frac{k_{12}}{T_4p+1}$$

In accordance with the obtained equations (5)–(8) and the transfer functions of the elementary elements, a mathematical model of the dynamic regimes of the infrared heating process for grain has been developed in the form of a structural diagram (Fig. 1).

The task of the automatic control system for the heat treatment process is to stabilize the material temperature at a level that ensures the maximum absorptive capacity of the grain material, and to adjust the grain flow by changing its transportation speed along the vibrating conveyor. In this process, disturbances in moisture content are compensated by adjusting the speed of material movement. The grain temperature is regulated by adjusting the amount of air filtered through the grain layer.

The functional diagram of the electro-radiation dryer with an automatic control system for drying mode is shown in Fig. 2. In Fig. 3 shows the change in temperature (a) and humidity (b) of grain during infrared drying, where 1 is constant power; 2 – distributed.

The dashed lines on the diagram indicate the contours of the automatic control system for the infrared drying process.

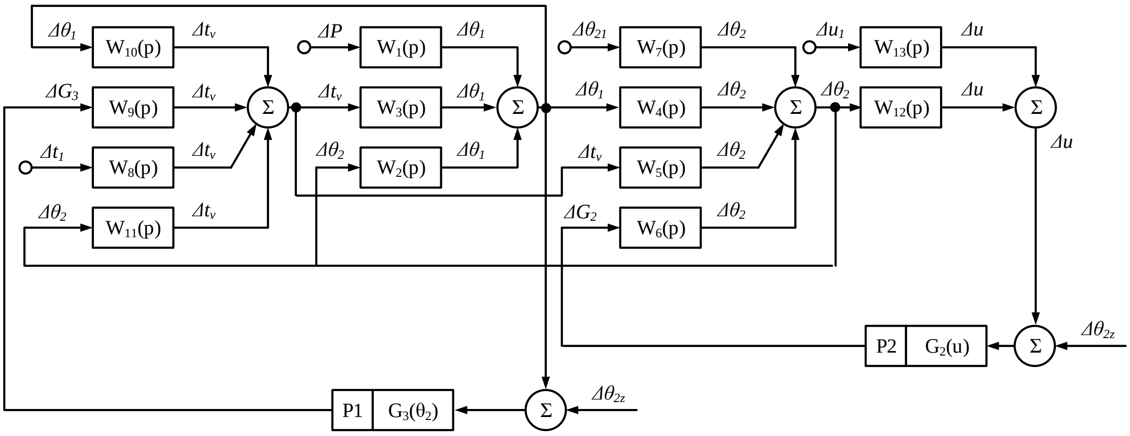

Fig. 1. The block diagram of the automatic control system for grain heat treatment modes: P1 – temperature controller; P2 – flow rate controller

Figure 3 shows the comparative thermograms of heating and drying kinetics of grain under stationary IR energy input (curve 1) and energy-efficient controlled IR drying (curve 2). From the presented graphical materials, the following conclusions can be drawn: the implementation of the proposed control for the electrothermal radiation unit allows for the dehydration process to be conducted in an isothermal mode, which prevents overheating of the thermolabile processed material; by achieving the maximum allowable temperature of the material more quickly and subsequently stabilizing it, the drying process is intensified, reducing the overall thermal drying exposure and specific energy consumption, and increasing the unit's productivity.

Analysing the dependencies obtained in Figure 3, it can be determined that the temperature of the grain with distributed power input increases the heating intensity and stabilizes the grain material temperature, which reduces the time for moisture gradient development within individual grains and accelerates the moisture evaporation from the grain surface. The conducted modelling allows for the evaluation of potential advantages of distributed power input.

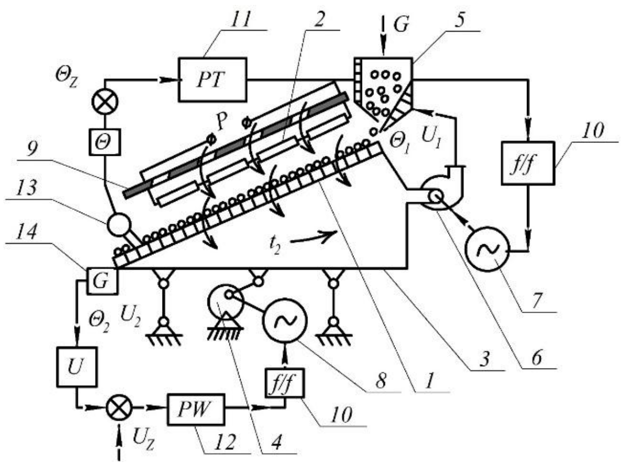

Fig. 2. Functional diagram of the electro-radiation grain dryer with automated drying mode control: 1 – vibroconveyor, 2 – infrared emitters, 3 – air intake box, 4 – vibration drive, 5 – ventilated grain hopper, 6 – fan, 7 – fan drive, 8 – vibrator drive, 9 – perforated screen, 10 – frequency converter, 11 – temperature controller, 12 – humidity controller, 13 – grain temperature sensor (pyrometer), 14 – grain moisture sensor

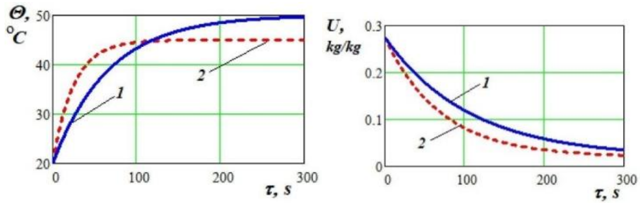

Fig. 3. Change in temperature (a) and moisture content (b) of the grain during infrared drying: 1 – constant power, 2 – distributed

4. Conclusions

1. An improved mathematical model of the dynamics of heat and mass transfer processes during infrared drying of oil-bearing materials has been developed, which takes into account the interaction of radiant, convective, and evaporative flows, as well as the dynamics of changes in the moisture content of the material. Based on this model, an automatic control system has been synthesized that ensures isothermal processing conditions by stabilizing the temperature through changes in the speed of vibratory material transport.

2. The proposed approach allows the implementation of energy-saving drying modes, reducing specific electricity consumption by 30–40% compared to traditional convective methods, preventing overheating and preserving the quality of thermolabile materials. The practical significance lies in creating the prerequisites for designing new generations of automated electric radiation dryers with higher productivity and lower energy consumption. Further research will be aimed at refining the thermophysical coefficients of the model for combined IR-convective drying and the specifics of using the model for different agricultural crops, as well as deepening the integration of the model with adaptive control algorithms.

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D.Sc. Borys Kotov
e-mail: eetsapk@pdatu.edu.ua

Doctor of Technical Sciences, professor, Institute of Higher Education "Podilskyi State University", Kamianets-Podilskyi, Ukraine. Scientific interests: substantiation of the scientific basis of intensification of heat and mass exchange processes during drying of plants, raw materials and grain; research on methods of increasing the energy efficiency of technological processes in industrial drying plants and aggregates for agricultural purposes.

https://orcid.org/0000-0001-6369-3025

Ph.D. Roman Kalinichenko
e-mail: rkalinichenko@ukr.net

Candidate of Technical Sciences, associate professor, National University of Bioresources and Nature Management of Ukraine, Kyiv, Ukraine.
Scientific interests: increasing the energy efficiency of processes of heat treatment and drying of grain materials.

https://orcid.org/0000-0001-9325-1551

D.Sc. Serhii Stepanenko
e-mail: stepanenko_s@ukr.net

Doctor of Technical Sciences, senior researcher, Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine, Glevakha, Ukraine.
Scientific interests: automation and robotics of post-harvest processing of grain; development of energy-saving technologies for processing and storage of grain and oil crops and methods of reducing their cost.

https://orcid.org/0000-0002-8331-4632

Ph.D. Vasyl Lukach
e-mail: vslukach@ukr.net

Candidate of Technical Sciences, Professor, National University of Bioresources and Nature Management of Ukraine, Kyiv, Ukraine.
Scientific interests: setting the parameters of working bodies of agriculture for energy- and nature-saving technologies

https://orcid.org/0000-0001-5715-9029

Ph.D. Volodymyr Hryshchenko
e-mail: vlgr@nubip.edu.ua

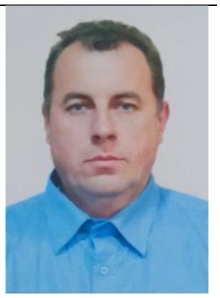
Candidate of Technical Sciences, Associate Professor, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine.
Scientific interests: modeling dynamic modes of typical technological objects in agro-industrial production; exploring methods to enhance energy efficiency in technological processes for maintaining microclimate conditions in agro-industrial facilities.

https://orcid.org/0000-0001-7789-3650

Ph.D. Alvian Kuzmych
e-mail: akuzmich75@gmail.com

Candidate of Technical Sciences, senior researcher, Institute of Mechanics and Automation of Agricultural Production of the National Academy of Agrarian Sciences of Ukraine, Hlevakha, Ukraine.
Scientific interests: increasing the efficiency of grain and oilseed harvesting processes

https://orcid.org/0000-0003-3102-0840



Ph.D. Yurii Pantsyr
e-mail: panziryuriy@gmail.com

Ph.D. in Technical Sciences, associate professor, Higher Educational Institution "Podillia State University", Kamianets-Podilskyi, Ukraine.
Research interests: automatic control systems for technological processes in agricultural production.

https://orcid.org/0000-0003-2969-1936

Ph.D. Ihor Garasymchuk
e-mail: igorgarasymchuk@gmail.com

Ph.D. in Technical Sciences, associate professor, Higher Educational Institution "Podillia State University", Kamianets-Podilskyi, Ukraine.
Research interests: energy saving and the use of electrical technologies in agricultural production.

https://orcid.org/0000-0002-4304-4447

Ph.D. Volodymyr Vasylyuk
e-mail: dekan.ae@ukr.net

Candidate of Technical Sciences, Associate Professor, National University of Bioresources and Nature Management of Ukraine, Kyiv, Ukraine.
Scientific interests: optimization of agricultural operations of post-harvest processing and processing of agricultural products

https://orcid.org/0000-0003-3840-5428