# RESEARCH ON WEED DESTRUCTION MECHANIZED PROCESS BY FLAME CULTIVATION OF VEGETABLE AND ROW CROPS IN ORGANIC FARMING

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**Abstract.** The transition to organic farming systems requires the development of environmentally safe and effective methods of weed control without the use of herbicides. One of the promising approaches is flame cultivation, which provides thermal destruction of weeds while minimising chemical impact on agroecosystems. The aim of this study was to investigate the mechanised process of thermal weed destruction during flame cultivation of vegetable and row crops and to substantiate the technological parameters ensuring selective thermal treatment of weeds under organic farming conditions. The study combined theoretical, laboratory and field investigations. A generalized non-stationary mathematical model of heat transfer in plant stems was developed based on the heat conduction equation in cylindrical coordinates with convective boundary conditions. The model considers thermophysical properties of plants, stem diameter, flame temperature, gas pressure, burner height and machine operating speed. Dimensionless similarity criteria, including the Fourier and Biot numbers, were applied to evaluate the selectivity of thermal effects on weeds and cultivated plants. Experimental studies were conducted on carrot, maize, sunflower and tomato crops using prototype flame cultivators developed in cooperation with A3TECH-Ukraine Ltd. Laboratory and field tests determined the dependence of soil surface temperature on burner operating modes and established optimal parameters for flame cultivation. The obtained results confirmed the consistency between the theoretical model and experimental data. It was established that thermal treatment at temperatures up to 70 °C ensures effective weed destruction without significant negative impact on soil microbiological activity. Up to 98% of weeds at the "thread" stage were destroyed during pre-emergence flame cultivation, while in later growth stages the efficiency reached 80-90% depending on weed height and crop conditions. The study demonstrated that the selectivity of flame treatment is determined mainly by differences in stem diameter, density and thermal diffusivity between weeds and cultivated plants. The proposed mathematical model and experimentally validated technological parameters can be used for the design and optimisation of flame cultivators for organic farming systems. The developed technology provides an environmentally safe alternative to herbicide-based weed control and supports sustainable production of vegetable and row crops.

**Keywords:** flame cultivation, weed control, organic farming, thermal treatment, heat transfer, thermal conductivity, flame weeding, row crops, vegetable crops, thermophysical properties.

## Introduction

Modern agriculture faces serious environmental challenges associated with the intensive use of chemical herbicides. Long-term application of herbicides contributes to soil degradation, contamination of agricultural products and groundwater, reduction of biodiversity in agroecosystems, and the emergence of herbicide-resistant weed species. These problems are especially relevant in vegetable and row crop production systems, where weed competition significantly reduces crop yield and quality.

The global area of organic farming is steadily increasing due to growing demand for environmentally safe food products and sustainable agricultural technologies. Since the use of synthetic herbicides in organic farming is prohibited or significantly restricted, the development of effective non-chemical weed control methods has become an important task in agricultural engineering. Weed control remains one of the most labour-intensive technological operations in organic crop production.

Traditional mechanical methods of weed control often fail to provide sufficient effectiveness in crop rows and protective zones, while repeated tillage may damage crop root systems and worsen soil structure. Among alternative non-chemical methods, thermal technologies have attracted considerable attention. Flame weeding is based on the short-term thermal effect of burners on plant tissues, resulting in irreversible damage to cellular structures and physiological processes in weeds without environmental contamination.

Studies conducted in different countries have confirmed the effectiveness of flame cultivation during pre-emergence and post-emergence weed control. However, the processes of heat transfer between the burner flame and plant tissues, as well as the conditions ensuring selective thermal destruction of weeds without damaging cultivated plants, remain insufficiently investigated.

Therefore, the aim of this study was to investigate the mechanized process of thermal weed destruction during flame cultivation of vegetable and row crops and to substantiate the technological parameters ensuring selective thermal treatment under organic farming conditions.

## Materials and methods

For cultivation of vegetable and row crops in organic farming systems, effective weed control methods and technical means for their implementation must be employed. An effective method of weed control is thermal treatment, both in the inter-rows and in the buffer zones and rows of these crops. To ensure the ecological safety of this method for beneficial microorganisms in the soil, a microbiological analysis of the soil was carried out before and after flame cultivation on carrot crops using generally accepted methods.

For complex physical processes, which include heat transfer from the flame of the flame cultivator to the plants, the key parameters can vary significantly in space and time; therefore, establishing a relationship between these parameters is very difficult. In such cases, a method from mathematical physics proves useful, which assumes that the time interval is limited and only an elementary volume is considered from the entire space. This allows, within the confines of the elementary volume and the selected small time interval, the variation of certain parameters characterising the process to be neglected, thereby significantly simplifying the relationship between the parameters [1-3].

During laboratory and field studies on the “moving belt” test rig, an experimental design methodology was used to determine the temperature dependencies on the surface [4].

## Results and discussion

Currently, global production volumes of organic produce, including vegetables, are increasing; however, the transition to an organic production system presents certain difficulties for commercially oriented enterprises due to the lack of sophisticated and widely tested mechanised vegetable production technologies on farms.

Research into modern mechanised vegetable production technologies within the organic farming system has established that weed control is the most labour-intensive process, particularly during the pre-sowing and post-sowing periods. It is important to implement all field-proven agronomic weed control measures during the soil preparation stages for growing vegetable crops [5-7].

With the development of the organic farming sector, thermal weed control methods have gained prominence, as they ensure environmental safety and reliability of the production process.

A3TECH-Ukraine Ltd, under the leadership of the Managing Director M. Mints and the Design Engineer V. Galay, and with scientific support from the staff at the Institute of Agricultural Mechanisation of the National Academy of Agrarian Sciences of Ukraine, has developed and commenced production of flame cultivators for thermal control of weeds in open ground on row crops and vegetable crops [8-9]. Figure 1 shows a prototype of the FIGHTER thermal soil treatment cultivator for weed control using flame.

Fig. 1. **Fighter thermal soil treatment cultivator**

When the flame cultivator is in operation, the temperature of the topsoil can be varied over a wide range. For the complete destruction of weeds at the “thread” stage the flame from the gas burners acts on them for a fraction of a second, and the heating temperature at the soil surface does not exceed the permissible limits, which leads to irreversible damage to proteins in weed plants, disruption of metabolism and inhibition of the synthesis reaction. High temperatures can kill the living cells of more developed plants within a short time.

The development of a prototype flame cultivator was preceded by a study of the impact of elevated temperatures on the natural soil ecosystem during post-harvest treatment of table carrot crops. During laboratory and field studies, researchers from the Institute of Agroecology and Natural Resource Management of the National Academy of Agrarian Sciences of Ukraine – S. Mazur, I. Gumenyuk and A. Levishko – took soil samples immediately after treating the soil surface with an experimental prototype of a flame cultivator (Fig. 2).

The results of the studies showed that the use of flame cultivation significantly influences the direction of soil processes and the structure of the main ecological-trophic groups of microorganisms. It was established that the use of a moderate temperature treatment regime (around 70 °C) ensures effective weed suppression, whilst simultaneously activating soil microbiological activity and promoting the intensification of nutrient accumulation processes. Such changes indicate the advisability of introducing flame cultivation as an alternative method of weed control not only in traditional agricultural technologies but also in organic farming systems, where it is important to maintain the ecological balance of agrocenoses [10].

The percentage of weeds destroyed by flame in rows of row crops and vegetable crops is influenced by the developmental stages of the cultivated plants and weeds at the time of treatment, their moisture content, bulk density, etc. The greater the temperature difference between the burner flame and the object being heated, the greater the heating intensity and the more intense the heat exchange.

Fig. 2. **Laboratory and field studies of the flame cultivation process during post-emergence treatment of table carrot crops**

*Theoretical basis for the process of thermal weed control*

The degree of heat effect on plants depends on the flame temperature and the duration of its exposure to the plant (Fig. 3).

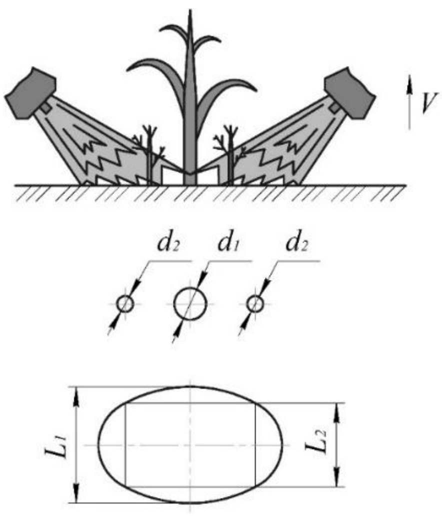


Fig. 3. **Determining exposure of the flame to weeds and cultivated plants**

Thermal weed control during flame cultivation occurs as a result of the brief action of the burner flame on the plant stem. In the “thread” phase, the plant is approximated by a homogeneous isotropic cylinder of radius (1):

$$R_i = \frac{d_i}{2}, \quad (1)$$

where $d_i$ – diameter of the stem (of the weed or cultivated plant).

The heating process is considered to be unsteady and axisymmetric. Air movement and the influence of wind flow are not taken into account; the wind speed is assumed to be zero ($v = 0$). Heat transfer occurs exclusively due to thermal conductivity within the stem and convective heat transfer at its surface.

The temperature field in the stem is described by the equation of unsteady heat conduction (2):

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \lambda_i \left( \frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r} \frac{\partial T_i}{\partial r} \right), \quad (2)$$

where $a_i = \frac{\lambda_i}{\rho_i c_i}$ – thermal conductivity coefficient of the plant $i$;
$\lambda$ – thermal conductivity, W·(m·K)$^{-2}$;
$\rho$ – density (bulk weight), kg·m$^{-3}$;
$c$ – specific heat capacity, J·(kg·K)$^{-1}$.

The classical derivation of the thermal conductivity equation is not given here, as it is described in detail in the literature on heat and mass transfer [1-3; 11-15].

The initial temperature of the plant is assumed to be uniform (3):

$$T_i(r, 0) = T_0. \quad (3)$$

At the centre of the stem, the condition of axial symmetry holds (4):

$$\frac{\partial T_i}{\partial r} |_{r=0} = 0. \quad (4)$$

On the surface of the stem ($r = R_i$), heat transfer with the flame is described by a third-order boundary condition (5):

$$-\lambda_i \frac{\partial T_i}{\partial r} |_{r=R_i} = h\,(T_f - T_s), \quad (5)$$

where $h$ – heat transfer coefficient;
$T_f$ – flame temperature near the soil surface;
$T_s$ – stem surface temperature.

The flame temperature is determined by the operating parameters of the cultivator (6):

$$T_f = T_f(P, V, H), \quad (6)$$

where $P$ – gas supply pressure, MPa;
$V$ – machine speed, m·s$^{-1}$;
$H$ – burner height, m.

The duration of thermal exposure to an individual plant is determined by the length of the flame and the unit's speed (7):

$$t_e = \frac{L_f}{V}. \quad (7)$$

To generalise the calculations, dimensionless similarity criteria have been introduced – the Fourier number and the Biao number (8):

$$Fo_i = \frac{a_i t_e}{R_i^2} \text{ and } Bi_i = \frac{hR_i}{\lambda_i}. \quad (8)$$

Taking into account the geometric and kinematic relationships (9)

$$R_i = \frac{d_i}{2},\ t_e = \frac{L_f}{V}, \quad (9)$$

we obtain the expression for the Fourier number (10):

$$Fo_i = \frac{4\lambda_i L_f}{\rho_i c_i d_i^2 V}. \tag{10}$$

Irreversible thermal damage to tissues occurs when a critical temperature is reached at the centre of the stem (11):

$$T_i(0, t_e) \geq T_{cr}, \tag{11}$$

where $T_{cr} = 60\text{-}70$ °C.

The results of the numerical calculation of the temperature at the centre of the stem are shown in Fig. 4.

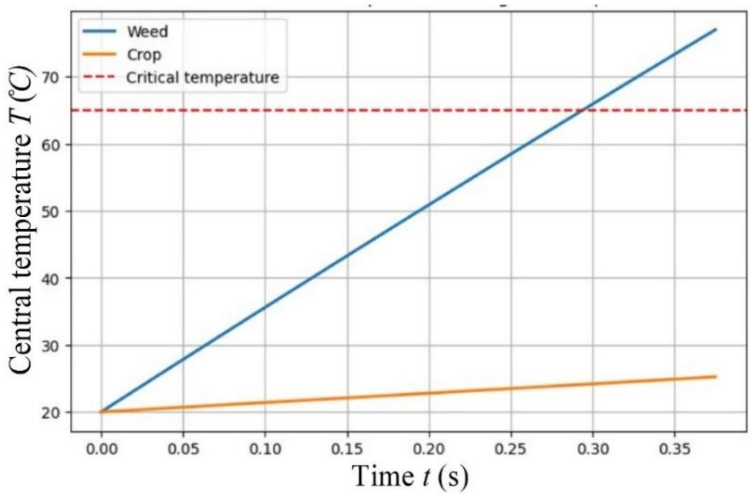


Fig. 4. **Calculated dependence of the temperature at the centre of the weed and crop plant stems on the duration of thermal exposure**

Thus, weed destruction is determined by the fulfilment of the condition: $Fo_{weed} \geq Fo_{crop}$, selectivity ensured if $Fo_{weed} > Fo_{crop}$, or, taking into account the obtained expression for the Fourier number,

$$\frac{\lambda_w}{\rho_w c_w d_w^2} > \frac{\lambda_c}{\rho_c c_c d_c^2}.$$

Since the moisture content of cultivated plants and weeds is similar, the thermal conductivity coefficients $\lambda_i$ differ only slightly. The determining factor for selectivity is the difference in the bulk density $\rho_i$ and stem diameters $d_i$, which accounts for the difference in thermal conductivity coefficients $a_i$.

Thus, the resulting differential equation of heat conduction with the corresponding boundary conditions allows the temperature field within the plant stem to be determined depending on the cultivator's operating modes and the plants' thermophysical characteristics. The resulting selectivity criterion serves as the analytical basis for selecting the technological parameters of flame cultivation.

The thermal conductivity coefficient is a physical parameter of a substance. Whilst the thermal conductivity coefficient characterises the ability of bodies to conduct heat, the thermal diffusivity coefficient is a measure of a body's thermal inertia properties. That is, the rate of temperature change at any point in the body will be greater the higher the thermal diffusivity coefficient.

The value of the thermal conductivity coefficient is determined by the denominator ($c\rho$). The bulk densities of maize, sunflower and tomato seedlings obtained at the time of the experimental test are, on average, 20.0-25.0% higher than the bulk density of weeds at the "thread" stage; therefore, the thermal conductivity coefficient of the aforementioned crops will be lower.

Thus, the thermophysical characteristics of maize and tomato seedlings allow for flame treatment to be carried out in the protective zone between rows, and lead to the conclusion that a prerequisite for flame treatment between rows is a significant difference in the thermophysical characteristics and stem diameters of cultivated plants compared to weeds.

As a result of a series of laboratory and field studies conducted on the "moving belt" stand, the relationship between the surface temperature and the speed of movement and gas pressure in the burner was determined for different burner angles and burner heights above the soil surface, and the optimal working zone for flame cultivation was identified to ensure effective and high-quality thermal weed control. The experimental dependencies obtained (Fig. 5) confirm the functional relationship $T_f = T_f(P, V)$, used in the mathematical model, ensures the consistency of theoretical and experimental results.

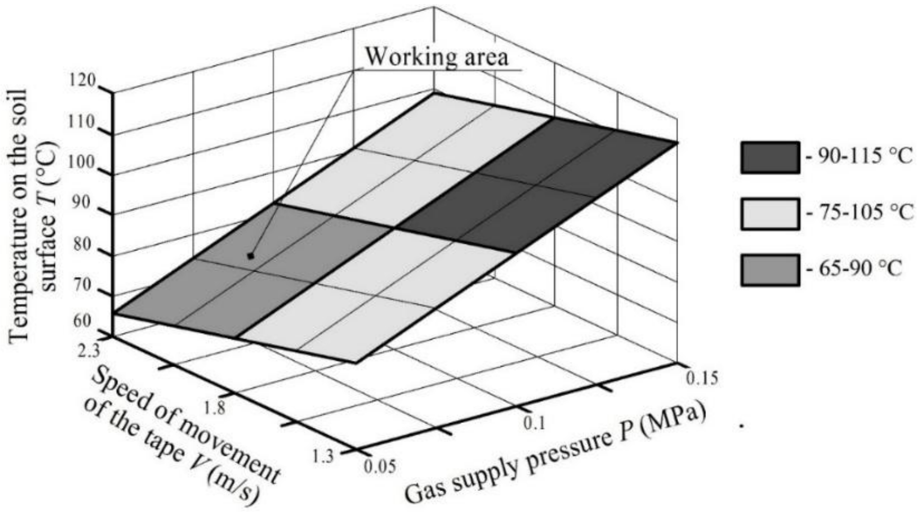


Fig. 5. **Dependence of the soil surface temperature on the belt speed and gas supply pressure**

Taking the above into account, laboratory and field studies were conducted on continuous pre-emergence flame cultivation using an experimental rig with burners manufactured by "A3TEKH-Ukraine" on table carrot crops and in rows of maize, sunflower and tomato seedlings, when weeds are in the "thread" stage and their diameters are significantly smaller than the diameters of the stems of the cultivated plants (Fig. 6).

It has been established that, under conditions of an acceptable temperature of 70 °C, up to 98% of weeds are destroyed at the "thread" stage; in rows of tomato seedlings, "fire" treatment should be carried out when the height of the weeds does not exceed 5 cm; then up to 90% of weeds are destroyed, and at a height of 10-12 cm – 80% (Fig. 7).

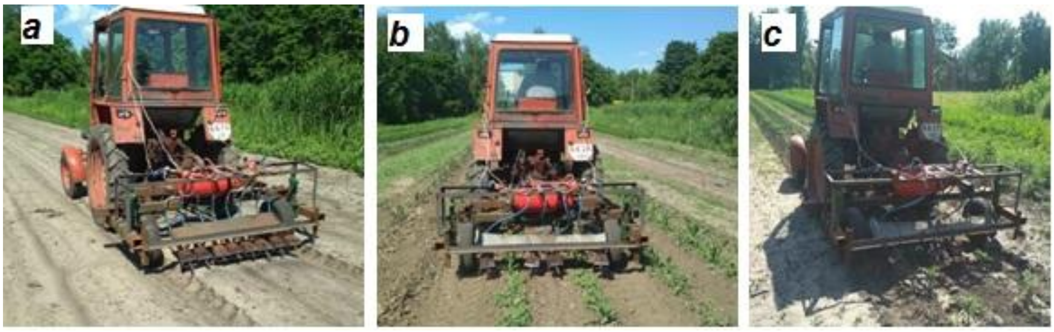


Fig. 6. **General views of the units for flame cultivation operations:** a – continuous full-width flame cultivation on table carrot crops; b – flame cultivation in rows on maize crops; c – flame cultivation in rows of tomato seedlings

The experiments were conducted in triplicate. The results were analysed using methods of variational statistics at a significance level of $p \leq 0.05$.

The cultivation of maize and tomato seedlings without the use of herbicides or manual labour on the experimental field plots (Fig. 8) confirmed the feasibility of using flame cultivation to control weeds in these crops.

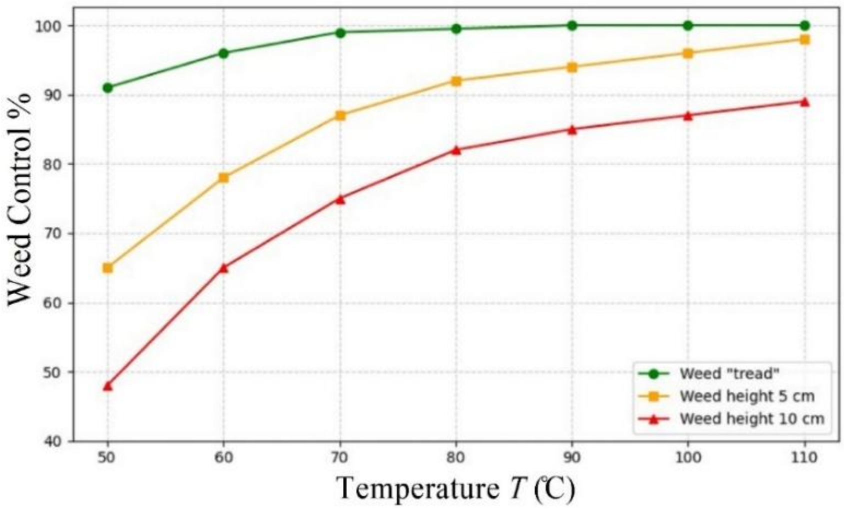


Fig. 7. **Percentage of weeds destroyed after flame weeding at different stages of development**

Fig. 8. **Experimental field plots of maize and tomatoes after flame cultivation**

Thus, the data from the presented studies on the application of thermal treatment in cultivation of organic vegetable crops indicate that it is a universal method for controlling weeds at the “thread” stage, both in continuous pre-emergence cultivation of crops and in the rows of row crops and vegetable crops, the thermophysical characteristics of which stems are superior to those of weeds.

## Conclusions

1. A generalised non-stationary mathematical model for the thermal destruction of weeds has been developed, based on the heat conduction equation in cylindrical coordinates with a convective boundary condition and taking into account the thermophysical characteristics of plants ($\lambda$, $\rho$, $c$), stem diameter and flame temperature, which are determined by the operating modes of the flame cultivator (gas pressure, speed of movement, flame geometry).
2. An analytical criterion for the selectivity of flame treatment has been derived, which establishes that the effectiveness of weed control is determined by the ratio of the parameter $\lambda \cdot (\rho c d)^{-2}$ for weeds and cultivated plants. It has been shown that, due to their lower density and stem diameter, weeds in the “thread” stage are characterised by a higher thermal conductivity coefficient, which ensures their more intensive heating.
3. The functional relationship between the flame temperature at the soil surface and the cultivator’s operating modes has been experimentally confirmed, which is consistent with the theoretical model. At a treatment temperature of up to 70 °C, up to 98% of weeds in the early stages of development are destroyed.
4. It has been established that the use of a moderate temperature regime does not cause a statistically significant negative impact on soil microbiological indicators ($p \leq 0.05$), confirming the environmental safety of the technology for organic farming systems.
5. The practical implementation of the research results has led to the creation and introduction of industrial prototypes of flame cultivators, the parameters of which can be reasonably determined based on the proposed mathematical model.

6. Unlike known approaches, this study has, for the first time under flame cultivation conditions, established an analytical relationship between the thermophysical characteristics of plants and burner operating modes, which allows for the prediction of conditions for selective thermal weed control without the use of herbicides.

## Author contributions

Conceptualization, V.A.; methodology, I.S. and P.R.; formal analysis, A.A. and V.A.; investigation, V.A., A.R. and I.S.; data curation, A.A., V.A. an I.S.; writing-original draft preparation, V.A.; writing-review and editing, A.A. and P.R.; visualization, P.R., A.R.; project administration, V.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

## References

[1] Bulyandra O. F. Technical Thermodynamics: Textbook/O. F. Bulyandra. Kyiv: Technika. 2001. 319 pp.
[2] Vasylenko S. M., Ukraintsev A. I., Olishevsky V. V. Fundamentals of Heat and Mass Transfer: Textbook/Edited by Academician of the Ukrainian Academy of Agrarian Sciences N. S. Guly. Kyiv: National University of Food Technologies, 2004. 250 pp.
[3] Barsukov S. I. Thermodynamics and Heat Transfer: Textbook/S. I. Barsukov, L. V. Knaub. 3rd ed., rev. Odessa: Astroprint. 2003. 608 pp.
[4] Boris A. M., Savchenko I. F., Rykhliivskyi P. A., Halai V. S. Investigation of the parameters and operating modes of burners in a flame cultivator/PROGRESSIVE RESEARCH IN THE MODERN WORLD/Proceedings of the VI International Scientific and Practical Conference, Boston, USA, 2–4 March 2023. pp. 266-271.
[5] Life hack for organic producers: fire cultivator. [online] [10.02.2026]. Available at: https://propozitsiya.com/news/layfkhak-dlya-vyrobnykiv-orhaniky-vohnevyy-kultyvator
[6] Flamethrower against weeds. [online] [10.02.2026]. Available at: https://infoindustria.com.ua/ognemet-protiv-sornyakov/
[7] Fire cultivators. What is this miracle? [10.02.2026]. Available at: https://agrostory.com/info-centre/agronomists/ognennye-kultivatory-chto-eto-za-chudo/
[8] Adamchuk V., Mints M., Boris A., Savchenko I., Hrytsyshyn M., Rykhlyvskyi P. et al. ‘Fire technology’ for weed control/Proposal. 2019. No. 12. pp. 132–135. https://propozitsiya.com/ua/vognyana-tehnika-dlya-borotby-z-buryanamy
[9] Adamchuk V. V., Mints M. L., Savchenko I. F., Boris A. M., Hrytsyshyn M. I., Rykhlyvskyi P. A., Kasprivych I. K., Halay V. S. Promising directions for the development and use of technical means for weed control in organic farming. Mechanisation and Electrification of Agriculture: National Collection of Scientific Papers/National Scientific Centre ‘IMESG’. Hlevakha, 2021. Issue 14(113). pp. 66-76. DOI: DOI: 10.37204/0131-2189-2021-14-7
[10] Levishko A., Gumeniuk I., Tsvigun V., Mazur S., Tkach Y., Demyanyuk O., Kovalenko T. The influence of fire cultivation on the soil microorganisms. International Journal of Ecosystems and Ecology Science; 13(2), 2023, pp. 91-96. DOI: 10.31407/ijees13.2
[11] Bergman T. L., Lavine A. S., Incropera F. P., DeWitt D. P. Fundamentals of Heat and Mass Transfer. 8th ed. Hoboken: John Wiley & Sons, 2019. 1072 p.
[12] Çengel Y. A., Ghajar A. J. Heat and Mass Transfer: Fundamentals and Applications. 6th ed. New York: McGraw-Hill Education, 2020. 992 p.
[13] Davidzon, M. Y. The first law of thermodynamics in vector form and convective heat transfer. American Journal of Physics and Applications, 6(6), 2018, pp. 147-153. DOI: 10.11648/j.ajpa.20180606.12
[14] Zhao N.-Y., Jin S.-X., Lin J.-H., Liu W.-H., Xu Z.-B., Chen Z.-J., Xu Y.-K. Multi-energy field-assisted plasticization for enhanced melt flow and heating efficiency. International Journal of Heat and Mass Transfer, 263, 2026, Article 128628. DOI: 10.1016/j.ijheatmasstransfer.2026.128628
[15] Fedosov S. V. and Bakanov, M. O. Method of ‘micro-processes’ for modeling heat and mass transfer in bodies of canonical form under Riemann–Newton boundary conditions. Smart Composite in Construction, vol. 2, no. 2, 2021, pp. 7-15.