CHAPTER 7

Innovative approaches to the storage technology of dehydrated meat semi-finished products using natural antioxidants

Liudmyla Kiurcheva
Mykyta Semenov
Serhii Holiachuk

Abstract

The monograph is devoted to the study of innovative approaches to the storage of dehydrated meat semi-finished products from chicken and pork. The combination of convective dehydration modes and treatment with natural antioxidants of meat raw materials during long-term storage was studied.

To preserve the quality and nutritional value of dehydrated raw materials, trans-ferulic acid was used as a natural antioxidant capable of influencing oxidative processes and structural indicators of products. The results of experimental studies on the influence of antioxidant treatment on the dynamics of changes in quality indicators during storage are presented. The optimized parameters of preliminary convective dehydration are considered as a technological possibility of forming a stable product structure to extend the shelf life.

The results of the study can be used by scientists, meat processing industry technologists and food industry specialists in the development of modern technologies for storing dehydrated products and preserving consumer properties.

Keywords

Dehydration, meat semi-finished products, trans-ferulic acid, convective drying, drying kinetics, product quality.

7.1 Introduction

An important task of the modern food industry is the production of long-term semi-finished meat products with high organoleptic indicators and a guaranteed level of safety. Given the high biological value of meat as a source of complete protein,

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essential amino acids, minerals and vitamins, ensuring its stability during storage is one of the priority areas of scientific research. The relevance of this task is enhanced by the need to implement energy-saving and resource-efficient technologies that meet the principles of sustainable development and minimize the ecological burden on the environment.

Among modern methods of preserving meat raw materials, dehydration is considered a promising method for extending the shelf life of products by reducing the mass fraction of moisture and water activity, which helps to slow down microbiological and oxidative processes [1]. Reducing water activity significantly limits the development of microflora and the intensity of enzymatic reactions, ensuring increased microbiological stability of the product during storage.

During the drying process of meat raw materials, complex physicochemical changes occur, namely: protein denaturation, structural transformations of muscle tissue, color changes and lipid oxidation. As a result of such changes, the quality of dehydrated meat products deteriorates, signs of foreign taste and smell appear, and nutritional value decreases, which leads to a reduction in shelf life. In this regard, an urgent scientific and practical task is to improve the technology of dehydration of semi-finished products by optimizing drying modes taking into account moisture removal parameters. A promising direction is the use of natural antioxidant compounds.

Trans-ferulic acid, which belongs to phenolic compounds of plant origin, is characterized by pronounced antioxidant activity and the ability to influence lipid peroxidation processes [2]. Its use in drying technologies for meat raw materials can help preserve organoleptic characteristics and increase the nutritional value of products during storage without the use of synthetic preservatives. However, the use of trans-ferulic acid requires scientific justification and confirmation of safety, compliance with current regulatory requirements for food ingredients

Thus, the use of natural antioxidants in combination with the optimization of drying regimes of meat raw materials is a rather relevant area of research and will have practical significance for the production of dehydrated meat semi-finished products for long-term storage and expanding the range of functional food products.

7.2 Natural antioxidants in meat systems

The key task of the technology for the production of dehydrated meat semi-finished products, storage of meat and meat products is to control the oxidation of lipids and proteins, which determines the degree of stability of food products during long-term storage. Therefore, the main technological problem is the intensification of oxidative reactions in lipid and protein fractions. Thus, changes in taste, aroma, color and texture are largely associated with the formation of primary and secondary products of lipid peroxidation under the influence of oxygen and thermal factors. Such reactions can lead to the formation of aldehydes, ketones and other volatile compounds, which negatively affect the physicochemical properties and quality characteristics of the product. To reduce the intensity of these processes, natural supplements are used that can inhibit the formation of free radicals and affect the oxidation reaction [3].

Antioxidant substances of plant origin are characterized by the ability to inhibit the oxidation processes of food products, stop spoilage and positively affect the nutritional value of raw materials, therefore they make it possible to use them to replace synthetic additives [4]. Thus, flavonoids, tocopherols, carotenoids, phenolic and other substances include antioxidant compounds capable of neutralizing some forms of oxygen, thus affecting oxidative reactions and processes of lipid and protein oxidation [5].

Phenolic substances of plant origin have the ability to reduce the level of lipid peroxidation in meat raw materials during processing and long-term storage [6], as a result, extending the shelf life of the product while maintaining the qualitative indicators of nutritional value. Thus, the use of plant extracts, such as rosemary extract, grape seed and green tea, demonstrated a positive antioxidant effect on meat raw materials, a decrease in the formation of oxidative products and an improvement in organoleptic properties were observed [7].

Recently, the use of trans-ferulic acid, which is characterized by its ability to affect the charges of the phenolic ring and free radicals, thereby stabilizing oxidative processes in meat raw materials during heat treatment and long-term storage, has attracted particular interest.

When dehydrated, the use of antioxidant substances for the production of semi-finished meat products has a complex meaning: it allows to reduce the negative impact on oxidation processes during the drying process itself; helps reduce the course of these processes during storage of the finished product and has a positive effect on organoleptic indicators and prolonging the shelf life [3]. However, the effectiveness of the use of such antioxidants depends on the method of their introduction, concentration, conditions and parameters of long-term storage, which necessitates further research in this direction.

7.3 Dehydration of raw meat

Dehydration of meat raw materials is one of the preservation methods based on reducing the mass fraction of moisture, as a determining factor in inhibiting the development of microorganisms. The effect on water activity leads to a decrease in enzymatic processes, inhibition of lipid and protein oxidation processes, which ensures an extension of the shelf life of products [1].

Meat raw materials are a complex multicomponent system in which water has different forms of bonding (adsorbed, osmotic and capillary). Thus, each form is characterized by its own strength and specific effect on the processes of processing and storage of meat products. The removal of moisture from meat raw materials is accompanied by structural changes in the protein-lipid complex, which affects the diffusion processes. The drying process depends on the water-binding capacity and the rate of moisture removal from the depth of the material to the surface. Effective heat and mass transfer in food raw materials is possible only under optimal drying conditions: temperature, air flow rate, product thickness [8].

The choice of technology and drying method is determined by the need for a balance between the speed of dehydration, energy efficiency of the process and the preservation of the organoleptic and structural-mechanical properties of the product. Convective, vacuum, sublimation and combined drying methods are used in the food industry.

Convective drying is based on the removal of moisture by the action of a stream of heated air. At the initial stage of the process, the rate of dehydration is determined by the conditions of external heat and mass transfer. An increase in temperature affects the process of moisture removal, but can cause protein denaturation and acceleration of lipid peroxidation reactions. This is especially critical for meat raw materials, since such processes affect the formation of color, taste and aroma of the product [1].

Vacuum drying removes moisture from raw materials at low temperatures by evaporation under vacuum, which allows dehydration to be carried out at lower temperatures. This process helps to reduce the thermal load on protein structures and preserve pigments and volatile aromatic substances. However, the need to use sealed chambers, vacuum pumps and systems for precise control of process parameters significantly affects production efficiency.

Freeze drying involves pre-freezing the raw material with subsequent removal of ice by sublimation in a vacuum. This method ensures minimal structural damage to tissues and a high ability of the product to rehydrate, which is associated with the formation of a porous structure after the removal of ice crystals. However, the energy intensity and technological complexity of the process limit its use mainly for the production of specialized high-value products.

In the food industry, with the use of innovative technologies, combined approaches are becoming increasingly important, which involve combining different methods of dehydration or using preliminary preparation of raw materials in order to change their structural and functional properties [9, 10]. Such solutions allow controlling the kinetics of drying and reducing the negative impact of thermal treatment. The combination of optimization of convective drying modes with the use of natural antioxidants aimed at increasing the oxidative stability of the product is especially promising [2].

Thus, the choice of the method and method of drying meat raw materials depends on a comprehensive approach to the physicochemical characteristics of the product, the requirements for its quality and shelf life, as well as the economic feasibility of production. Given the technological availability and the ability to regulate the process parameters, convective drying remains the basic dehydration method for the production of meat semi-finished products with a long shelf life, which can be improved by optimizing the regimes and using antioxidant components.

7.4 Analytical drying models

Mathematical description of the dehydration process is a key stage in the scientific justification of the drying parameters of meat raw materials, as it allows quantitatively characterizing the kinetics of moisture removal, establishing the limiting stages of mass transfer and predicting the duration of the technological cycle. For muscle tissue, which has a complex capillary-porous and protein-lipid structure, internal moisture transfer is limited by diffusion mechanisms, as well as the degree of water binding to the proteins of the myofibrillar complex.

In the case of thin-layer convective dehydration (slice thickness 7 mm, temperature 70°C), the process is usually characterized by the absence of a long period of constant speed and the predominance of the decreasing stage of drying. This indicates diffusion control of the process, which is consistent with the literature data [11].

For such systems, it is advisable to use both phenomenological (based on mass transfer equations) and empirical thin-layer models.

To unify experimental results, the dimensionless parameter Moisture Ratio (MR) is used, which is defined as

$$MR = \frac{M_t - M_e}{M_o - M_e},$$

where M_o – initial moisture content; M_t – moisture content at time t; M_e – equilibrium moisture content.

Under the condition that $M_e \ll M_t$, for thin samples the following simplification is commonly accepted:

$$MR \approx \frac{M_t}{M_o} \text{ or } MR \approx \frac{m_t}{m_o},$$

where m_t – current sample mass; m_o – initial sample mass.

Phenomenological model based on Fick's second law [12, 13]. For a slab of thickness 2*L*, the solution of Fick's second law for unsteady-state diffusion is expressed as

$$MR \approx \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff}^{t}}{4L^2}\right),$$

where D_{eff} – effective moisture diffusivity, m²/s; *t* – drying time, s; *L* – half-thickness of the sample, m.

For long drying times, the series solution can be approximated by its first term

$$MR \approx \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}^{t}}{4L^2}\right).$$

The estimation of D_{eff} makes it possible to quantitatively compare the intensity of internal mass transfer under different formulation conditions, particularly when trans-ferulic acid is incorporated.

For practical analysis of the drying kinetics of semi-finished meat products, empirical thin-layer models are widely used, as they provide high accuracy in approximating experimental drying curves [14].

Model Page.

$$MR = \exp\left(-kt^n\right),$$

where *k* – drying rate constant; *n* – process nonlinearity exponent.

The Page model is a modification of the simple exponential relationship and adequately describes the diffusion-controlled stage of dehydration of biological materials, including meat raw materials [15].

Henderson-Pabis model.

$$MR = A\exp\left(-kt\right),$$

where *A* – empirical constant; *k* – drying rate coefficient [16].

A comparative analysis of the Page and Henderson–Pabis models make it possible to determine the degree of agreement with experimental data and to establish the influence of formulation factors on process kinetics [17].

Criteria for evaluating model adequacy [18].

The goodness of fit was assessed using the coefficient of determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pred,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{\mathrm{exp}}\right)^2},$$

and the root mean square error (RMSE)

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pred,i}\right)^2},$$

where N – number of experimental data points.

For food systems, the values of $R^2 > 0.90$ are considered acceptable, while $R^2 > 0.95$ indicates a high correspondence of the model to the experimental data.

Within the framework of this work, the model was applied to describe the kinetics of convective dehydration of meat semi-finished products at a temperature of 70°C and a slice thickness of 7 mm. Special attention was paid to assessing the effect of the introduction of trans-ferulic acid on the parameters k, n, and D_{eff}.

It is assumed that the antioxidant can affect the structural and mechanical properties of muscle tissue, change the degree of moisture binding and, accordingly, the kinetics of internal mass transfer. Comparison of the values of the effective diffusion coefficient and activation energy allows to quantitatively assess the structural changes of the system under the action of the functional additive.

Thus, the combination of a phenomenological approach (based on Fick's second law) and empirical thin-layer models provides a comprehensive interpretation of the dehydration process and creates a scientific basis for optimizing technological regimes.

7.5 Experimental implementation of convective dehydration of meat raw materials using trans-ferulic acid

The object of the study is the process of convective dehydration of meat raw materials under the conditions of the prescription introduction of a natural antioxidant compound – trans-ferulic acid (FA). The subject of the study is the kinetic patterns of moisture removal and quality indicators of dehydrated meat semi-finished products depending on the type of raw material and the presence of an antioxidant additive.

The purpose of developing the recipe is to increase the antioxidant properties of dehydrated semi-finished meat products (pork meat, chicken meat) by treating them with trans-ferulic acid (FA) in a minimum concentration to ensure an effect on oxidative processes without negative changes in the organoleptic and safety indicators of the product.

The materials of the study: muscle tissue of chicken meat (breast fillet without skin; initial mass fraction of moisture 74–76%); muscle tissue of pork meat (tenderloin; initial mass fraction of moisture 72–74%).

Trans-ferulic acid with a mass fraction of the main substance ≥ 98% was used as a functional additive. In order to ensure uniform distribution in meat samples, the antioxidant additive was previously dissolved in food alcohol (96%).

The marinade composition (per 100 g of raw material) included:

– sodium chloride – 1.2%;
– dried paprika – 0.5%;
– ground black pepper – 0.3%;
– trans-ferulic acid – 0.1% (in the form of an ethanol solution).

This formulation allows to simulate the conditions of production of dehydrated meat semi-finished products with a spicy-salt profile and at the same time minimize the influence of extraneous ingredients on the drying kinetics.

The selected concentration of FA (0.1%) is technologically appropriate considering the combination of antioxidant efficiency and sensory properties. Lowering the concentration may be insufficient to inhibit lipid peroxidation, while increasing it can potentially affect the flavor profile of the product.

The functional role of the marinade components: salt for osmotic effect and flavor formation; paprika acts as a natural colorant and a source of phenolic compounds; black pepper for aroma formation; trans-ferulic acid serves as the antioxidant aimed at inhibiting lipid oxidation chain reactions and stabilizing the pigment system. Thus, the prescription composition forms a multicomponent antioxidant background, where FA performs a dominant stabilizing function.

The study was conducted according to a two-factor experimental design considering:

Factor A – type of meat raw material:

A_1 – chicken meat;

A_2 – pork meat.

Factor B – formulation composition:

B_1 – control sample (without FA);

B_2 – experimental sample (FA at a dose of 0.1 g per 100 g of raw material, i.e., 0.1%).

In total, four experimental variants were formed:

A_1B_1 – chicken meat, control;
A_1B_2 – chicken meat + FA;
A_2B_1 – pork meat, control;
A_2B_2 – pork meat + FA.

The introduction of trans-ferulic acid was carried out by its preliminary dissolution (0.1 g FA in 10 ml of ethanol 96%) with subsequent introduction into the marinade and thorough mixing. The prepared samples were marinated for 60 min at a temperature of 4–6°C with periodic mixing to ensure the diffusion of salt, spices and antioxidant compounds into the thickness of the muscle tissue. After the completion of marinating, the surface of the samples was dried with filter paper to remove excess moisture.

Drying was performed in a laboratory dehydrator with forced air circulation. The process parameters were as follows: drying agent temperature – 70°C; slice thickness – 7 mm; air velocity – approximately 2 m/s; drying duration – 8 hours.

The choice of temperature 70°C is due to the need to ensure sufficient moisture removal intensity while preserving the organoleptic properties of the raw material and limiting thermal denaturation of proteins. The thickness of 7 mm corresponds to the conditions of a thin layer, which is methodologically correct for the further application of analytical models of drying kinetics.

Before the start of the process, the samples were weighed to determine the initial mass (m_o). Control weightings were carried out after 2, 4, 6, and 8 hours (t_o, t_1, t_2, t_3, t_4). After the dehydration was completed, the samples were cooled to 25°C, packed in sealed polymer bags and stored at 20 ± 2°C.

The results obtained (**Table 7.1**) indicate that under the same dehydration conditions, the introduction of trans-ferulic acid at a dose of 0.1% does not cause statistically significant differences in total mass losses after 8 h of drying. This gives grounds to believe that the antioxidant additive does not have a significant effect on the overall degree of dehydration (**Fig. 7.1**), and possible differences are mainly associated with changes in the kinetics of the process at individual stages.

Table 7.1 Moisture loss during convective drying (70°C, *n* = 1)

Sample variant	Mass, g					Mass loss, %
	(0 h)	(2 h)	(4 h)	(6 h)	(8 h)	
A_1B_1	71.9	52.7	41.2	32.9	25.8	64.1
A_1B_2	73.8	54.3	42.0	33.8	26.6	64.0
A_2B_1	74.2	57.8	46.9	40.1	32.8	55.8
A_2B_2	75.1	58.9	47.7	40.6	33.5	55.4

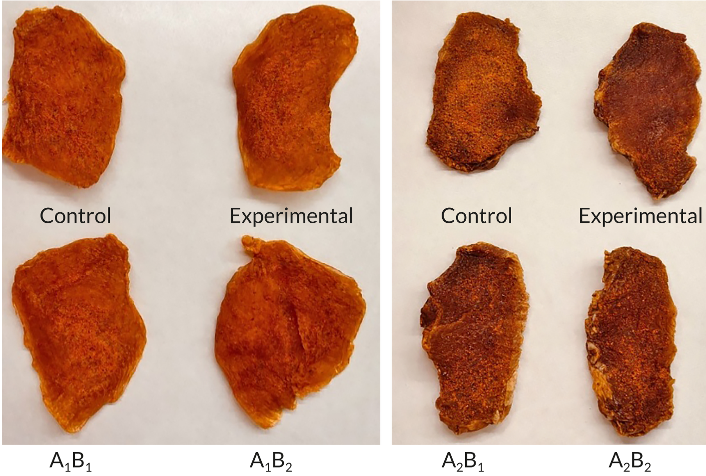


Fig. 7.1 Appearance of samples after drying (control and experimental)

The dimensionless moisture content was used to construct the kinetic curves (Moisture Ratio, MR)

$$MR = \frac{m_t}{m_o}.$$

Further mathematical processing of the experimental data was carried out by approximating the Page and Henderson-Pabis models, as well as determining the effective diffusion coefficient based on Fick's equation. The generalized parameters are presented in **Table 7.2**.

The Page model demonstrates higher approximation accuracy for all sample variants the coefficient of determination R^2 ranges from 0.9993 to 0.9998; the RMSE values do not exceed 0.0053.

Table 7.2 Approximation results

Sample variant	Henderson-Pabis A	Henderson-Pabis k, h^{-1}	R^2	RMSE	Page k	Page n	R^2	RMSE
A_1B_1	0.970	0.1261	0.9940	0.0175	0.1708	0.8560	0.9998	0.0029
A_1B_2	0.969	0.1258	0.9937	0.0179	0.1692	0.8612	0.9998	0.0028
A_2B_1	0.972	0.0999	0.9920	0.0175	0.1398	0.8427	0.9993	0.0053
A_2B_2	0.974	0.0993	0.9931	0.0162	0.1351	0.8575	0.9995	0.0044

For the Henderson-Pabis model, R^2 falls within the range of 0.9920–0.9940, which also indicates satisfactory agreement, though inferior to the Page model. The effect of FA on dehydration kinetics is minimal.

For pork samples, the drying rate constant k(H–P) values are: control – 0.0999 h^{-1}; FA – 0.0993 h^{-1}.

A similar trend is observed for chicken fillet: control – 0.1261 h^{-1}; FA – 0.1258 h^{-1}.

The difference does not exceed 1%, indicating no significant influence of the antioxidant on mass transfer intensity at 70°C.

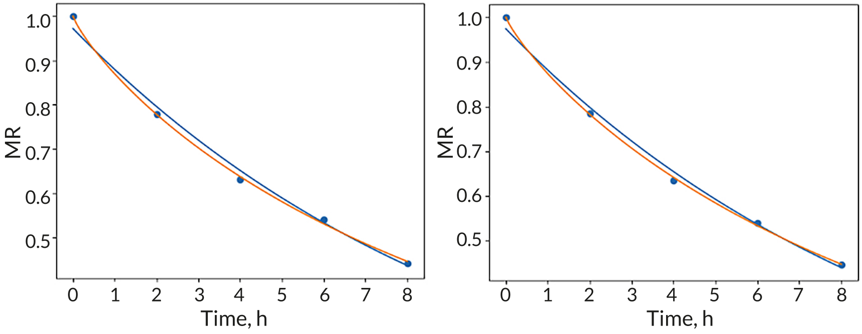
The type of raw material is the determining factor in drying kinetics.

Drying rate constants for chicken fillet are higher than for pork. This can be explained by the lower content of intramuscular fat, lower tissue density, and higher proportion of free moisture.

The graphical representation of the *MR*(*t*) relationships (**Fig. 7.2**, **7.3**) confirms the gradual decrease in relative moisture content, the absence of a constant-rate drying period, and the predominance of a diffusion-controlled mass transfer mechanism.

The analysis showed that the Page model more accurately approximates the experimental data (higher R^2 values and lower RMSE) compared to the Henderson-Pabis model. The addition of trans-ferulic acid (0.1%) did not affect the shape of the kinetic curves, indicating that it had no significant effect on the dehydration rate. Chicken meat is characterized by higher drying rate coefficients, indicating more intensive dehydration compared to pork.

The curves for the control and experimental samples are practically superimposed, which confirms the technological compatibility of FA with the convective dehydration process.



A_2B_1 A_2B_2

Fig. 7.2 Dehydration kinetics of pork

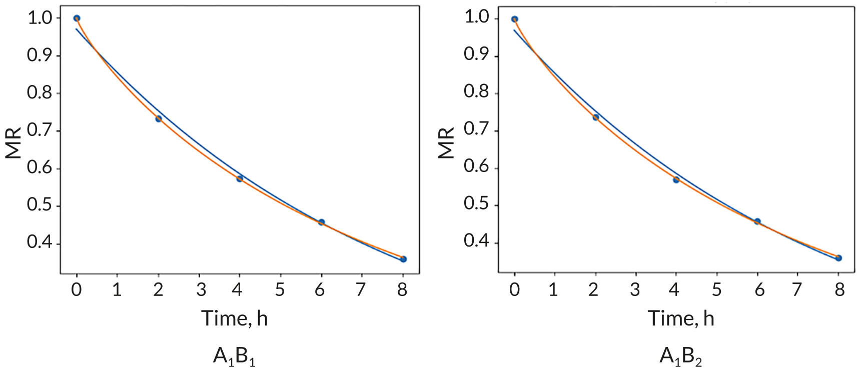


Fig. 7.3 Dehydration kinetics of chicken meat

A comparison of the model parameters allows the conclusion that the incorporation of FA at a concentration of 0.1% does not alter the shape of the kinetic curves; the parameters *k* and *n* change only slightly, and the overall degree of dehydration after 8 hours remains the same. Therefore, the antioxidant does not affect the heat and mass transfer characteristics of the system and does not require adjustment of the drying modes.

Organoleptic evaluation was carried out after cooling the samples to 25°C. The control and experimental samples were characterized by uniform dehydration, no signs of burning, elastic texture, typical aroma for the corresponding type of meat. The introduction of FA did not cause the appearance of foreign odor or taste. The color of the experimental samples remained stable and characteristic of thermally processed meat raw materials

7.6 Conclusions

A comprehensive analysis of experimental data showed that the dehydration kinetics for all samples is characterized by a predominantly decreasing drying rate, which confirms the diffusion mechanism of internal mass transfer. The process is adequately described by empirical models, with the Page model providing the highest accuracy of approximation of experimental data.

Comparison of control and experimental samples showed that the introduction of trans-ferulic acid at a concentration of 0.1% does not violate the heat and mass transfer conditions of the process, does not significantly affect the rate of moisture removal and does not require adjustment of drying modes at 70°C. At the same time, a tendency to a slight change in kinetic parameters (rate constant *k* and nonlinearity index *n*) was recorded, which may be associated with the structural features of the protein-water matrix and the degree of moisture binding.

It was found that chicken fillet is dehydrated more intensively compared to pork, which is due to morphological and compositional differences in the raw materials.

Therefore, the use of trans-ferulic acid at a dose of 0.1% is technologically justified and compatible with the convective drying process, does not worsen organoleptic characteristics and creates prerequisites for increasing product stability. At the same time, the results indicate the need for further statistical verification and investigation of oxidative stability to assess the overall effectiveness of the additive.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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The study was performed without financial support.

Data availability

The data that support the findings of this study will be made available by the authors on reasonable request.

Use of artificial intelligence statement

The authors used the AI assistant Perplexity (Grok 4.1, Perplexity AI) for translation and literature source selection. The authors bear full responsibility for the final manuscript. Generative AI tools are not credited and are not responsible for the final results.

Authors' contributions

Liudmyla Kiurcheva: Supervision, Conceptualization, Methodology, Writing – original draft, Investigation, Project administration.

Mykyta Semenov: Conceptualization, Methodology, Writing – original draft, Formal analysis, Investigation.

Serhii Holiachuk: Writing – original draft, Visualization, Formal analysis, Validation.

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