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IMPROVING THE MOBILE STRUCTURE OF A VERTICAL MODULAR SOLAR DRYER FOR THE AGRICULTURAL SECTOR "FROM FIELD TO FORK"

Andrii Zahorulko
Corresponding author
PhD, Associate Professor*
E-mail: zagorulko.andrey.nikolaevich@gmail.com

Iryna Voronenko
Doctor of Economical Sciences, Senior Researcher
Department of Information Systems and Technologies
National University of Life and Environmental Sciences of Ukraine
Heroyiv Oborony str., 15, Kyiv, Ukraine, 03041

Sofiia Minenko
PhD, Senior Lecturer
Department of Management, Business and Administration**

Andrii Pugach
Doctor of Public Administration Sciences, Professor, Dean***

Olena Nazarenko
PhD, Associate Professor
Department of Philology***

Olesya Lebedenko
PhD, Associate Professor
Department of Management, Public Management and Administration***

Eldar Ibaiev
PhD Student
Department of Processes and Equipment Food and Hospitality-Restaurant Industry named after M. Belaev
Kharkiv State University of Food Technology and Trade
Klochkivska str., 333, Kharkiv, Ukraine, 61051

Nataliia Tytarenko*
*Department of Equipment and Engineering of Processing and Food Production**
**State Biotechnological University
Alchevskykh str., 44, Kharkiv, Ukraine, 61002
***Dnipro State Agrarian and Economic University
Serhii Efremov str., 25, Dnipro, Ukraine, 49009

The object of this study is the radiation drying of local agricultural raw materials (Jerusalem artichoke of the "Kyivskyi bily" variety and apples of the "Williams" variety) in a mobile structure of a vertical-modular solar dryer. The study is aimed at improving the resource-saving drying of agricultural raw materials. The solar dryer has adjustable hemispherical air collectors (tilt angle 20…45°) and a heat-insulated chamber with a thermal accumulator (stone pebbles, size 50–80 mm), a backup infrared heater (600 W), and autonomous fans in a combination with Peltier elements. Drying of agricultural raw materials with a thickness of 4–12 mm and a heat carrier speed of 0.05–2.0 m/s was carried out in the summer-autumn decades of 2024. The drying duration of Jerusalem artichoke was 38.6–50 h, apples – 30.5…37 h; drying temperature – 22…50 °C. Moisture removal was 77.8 % for Jerusalem artichoke and 87.0 % for apples. Moisture removal when loading 6.0 kg of raw materials was 3.5 kg for Jerusalem artichoke (77.8 % moisture) and 4.2 kg for apples (87.0 % moisture) under drying conditions to a moisture content of 20.0 %. Losses of vitamin C during sun drying in Jerusalem artichoke were 2.17 times (versus 3.21 times during convective drying), and in apples – 2.26 times (versus 2.58 times). Dietary fiber in Jerusalem artichoke decreased by 2.29 times (versus 3.33 times), and in apples – by 2.25 times (versus 3.91 times). Losses of β-carotene in Jerusalem artichoke during sun drying were 2.65 times (versus 3.08 times). There was also a smaller decrease in phosphorus and mono- and disaccharides. Dried semi-finished products had a uniform appearance, light yellow color, and natural taste and aroma properties. An improved mechanism for managing the competitiveness of agricultural enterprises combines technical, economic, and organizational aspects for entering the European market and expanding exports

Keywords: solar dryer, mobility, agricultural raw materials, hemispherical collectors, thermal accumulator, autonomous fans, competitiveness, export potential

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1. Introduction

The need to ensure food security, rapid climate change, pandemics, the development of chronic and acquired diseases, military conflicts lead to the population being under extreme conditions. To effectively confront the global challenges of our time, innovative approaches are needed aimed at the development of agriculture. Modern approaches to the development of the agricultural sector involve devising resource-saving combined approaches aimed at increasing the efficiency of processing and production, while simultaneously enabling the preservation of natural resources and improving the quality of products. The concept “From field to fork”, which is a component of the European Green Deal strategy, emphasizes the importance of creating sustainable supply chains that ensure the production of healthy, high-quality products with minimal impact on the environment [1]. Solar dryers as a means of resource-efficient processing of raw materials play an important role in ensuring the competitiveness of the agro-industrial complex as they contribute to reducing energy costs, improving the quality of crop preservation, and expanding the opportunities for exporting local organic products [2]. In this context, the development of vertical-modular mobile structures of solar dryers meets modern challenges in the field of ensuring resource efficiency of farmland, which is achieved by placing mobile equipment directly under the conditions of growing and harvesting plant raw materials. The use of solar energy and the mobility of solar drying will lead to the consolidation of the European green course by farmland, forming modern high-quality approaches to the processing of organic raw materials with natural energy. Thus, it reduces the technological period of raw material processing, reduces transportation and storage costs. The integrated implementation of obtaining dried semi-finished products of a high degree of readiness with a wide range of uses by the processing and production sectors and hotel and restaurant complexes to a certain extent ensures a reduction in the level of capital investments in stationary flow lines for processing raw materials. Scientific research confirms the feasibility of integrating renewable energy sources into the agricultural sector to effectively increase its competitiveness. In work [3], attention is drawn to the high potential of using solar energy in the processing of agricultural products. This is also confirmed by the research of foreign colleagues in the direction of the effectiveness of using mobile solar dryers in preserving product quality and reducing costs [4]. The introduction of innovative engineering and technological solutions aimed at improving the designs of mobile solar dryers for the agricultural sector, taking into account the principles of sustainable development and the concept of “From field to table”, meets the needs of modern European countries. At the same time, the macroeconomic uncertainty of the agricultural business, which is associated with the war unleashed by the Russian Federation on the territory of Ukraine, requires analysis and assessment of risks for the stabilization of agricultural holdings in Ukraine before and after the period of shock and their investment attractiveness, in particular in the context of the introduction of competitive mechanisms [5].

In particular, high-quality natural semi-finished products of high readiness in the formulations of various food products will reduce the need for the use of synthetic ingredients, replacing them with natural components and increasing their nutritional value [6]. In addition, dried semi-finished products of high readiness can be used as an independent product, in particular for people under extreme conditions (doctors, military personnel, etc.). The relevance of research is due to the need to implement innovative solutions, in particular aimed at resource-saving processing of agricultural raw materials in the field, taking into account modern global challenges such as food security, climate change, and economic instability. Integration of the concept “From field to fork” by adapting and implementing mobile solar dryers will contribute to reducing energy costs in the use of natural sources of nutrition, improving crop preservation and production of natural products. This is especially relevant for ensuring sustainable development of the agricultural sector, particularly under extreme conditions that require access to high-quality dried semi-finished products that can replace synthetic ingredients and increase the nutritional value of products.

2. Literature review and problem statement

The development of the “green course” of European countries requires globalization and increasing requirements for sustainable development of the agricultural sector, aimed at increasing competitiveness in the context of the implementation of innovative engineering and technological solutions [7]. One of the promising areas of development of the agricultural sector is the introduction of mobile designs of solar dryers for resource-saving processing of agricultural products into dried semi-finished products of a high degree of readiness for further use by the processing and production sector and people [8]. The relevance of the use of solar dryers in the agricultural sector is associated with the trend of formation of “from field to fork” since this is aimed at ensuring sustainable development and efficient use of resources [9]. In [10], research in the field of materials of future solar collectors, absorbers, and the influence of phase change materials (PCM) in increasing the efficiency of drying is reported. However, in [10], issues related to the configuration of not only the receiving surface of air collectors but also the geometry of the solar dryer for forming the mobility of the device remained unresolved. The reason for this may be objective difficulties associated with a small range of available solar dryers with no mobility and the use of classic solar collectors with focusing mirror elements. One of the options for overcoming the relevant difficulties may be preliminary modeling of the technical process. This is the approach presented in [11], regarding the influence of geometry with different angles of inclination of collectors on the uniformity of drying of raw materials; however, the issue of carrying out structural adaptation to field conditions remained undefined, complicating the formation of mobility. All this allows us to state that it is advisable to conduct research on the search for innovative solutions aimed at maximum absorption of solar energy under conditions of mobility of the device for location in different climatic zones of farmland. In [8], the issue of optimizing the energy efficiency of dryers by using materials with high thermal insulation was studied; however, the determination of the efficiency of integrating heat accumulators to reduce losses at night was left out of consideration. This limitation is due to the technical features of using thermal accumulators in mobile installations, and one of the solutions is to introduce thermal accumulators with stone pebbles in the lower part of the solar dryer. In [12], the influence of solar radiation on the uniformity of drying of raw materials was investigated but the issues related to determining the influence of the design of the opaque frame on the preservation of quality and the feasibility of using additional heat sources remained unresolved. The reason for this may be related to the lack of knowledge of protective technical coatings against ultraviolet in mobile dryers. An option for overcoming the relevant difficulties may be the use of an opaque frame to avoid the effects of ultraviolet rays. In addition, this will prevent direct contact of agricultural raw materials with ultraviolet rays, preserving the natural and organoleptic properties of the raw materials. One of the approaches to using an additional heat source is given in [13] when studying the effectiveness of using IR heaters as a backup heat source for solar dryers on a sunny day. However, the effect of a sharp unplanned change in weather conditions (prolonged cloudiness) was not taken into account when determining the feasibility of using a backup heat source. All this allows us to state that it is advisable to conduct a study aimed at confirming the use of a backup source of thermal energy, the geometry of its location in conditions of ensuring the minimum drying temperature during a sharp change in weather conditions. In work [14], studies were conducted aimed at determining drying shelves with spiral channels for uniform distribution of the heat carrier but without taking into account how the angle of inclination affects the drying rate of various types of agricultural raw materials. This is due to the small number of studies directly under field conditions, emphasizing the feasibility of studies aimed at determining these technical properties. In work [15], the effectiveness of using solar collectors in solar dryers is investigated without determining the impact of the required number of collectors on drying performance. This is partly due to the complexity of integrating a large number of collectors into mobile installations, which requires the implementation of modern solutions to increase the number of collectors and at the same time not be tied to the south side of the location of the apparatus.

The issue of efficiency of heat accumulation in solar dryers to ensure stable operation was studied in [16] but the issues related to the possibility of creating a conditional "thermos" of the device, especially at night, in addition to the use of a heat accumulator were not considered. The lack of research in this area may be due to insufficient attention to heat preservation in mobile dryers. However, as an option, various additional heat-accumulating covers can be used for additional heat storage at night and in cloudy weather, requiring field research in this area as well. In [17], research was conducted to determine the impact of the use of fans on the regulation of the heat carrier speed, but in most cases, this is implemented through non-autonomous power supply. At the same time, the introduction of autonomous power supply of fans is one of the modern engineering approaches that can be implemented under conditions of using Peltier elements. In [18], the technology of processing agricultural raw materials to obtain semi-finished products with a high degree of readiness was considered but without studying the possibility of integrating such technologies into mobile solar dryers. This is partly due to the limited number of comprehensive studies on the combined use of mobile dryers for processing directly in field conditions. Therefore, it is relevant to develop a mobile solar dryer design capable of producing high-quality dried semi-finished products with a high degree of readiness to simplify the trend "from field to fork". In particular, in [19], the designs of mobile dryers for different types of agricultural raw materials were studied, but the issue of the efficiency of the devices in different geographical latitudes was not considered. This is partly due to insufficient adaptation to variable conditions of solar radiation, although one of the technical solutions to this is to provide adjustable collectors with a certain slope for maximum solar energy absorption. The development of mobile vertical modular solar dryers may have not only technical but also economic and managerial significance for the food security of European countries [8]. In turn, the formation of mobile modular equipment for the agricultural sector requires the implementation of IT innovative approaches to form sustainable business models in the single European energy market. Ways to improve the mobile design of a vertical modular solar dryer are expedient due to the integration of the principles of sustainable development and the concept of "from field to fork", which corresponds to the European green course. The use of radiation energy ensures environmentally friendly processing of organic raw materials, and the implementation of modern IT solutions [20], such as the Internet of Things and intelligent networks, contributes to automation, reducing energy consumption and increasing the efficiency of the agricultural sector, ensuring its competitiveness in the international market. This simultaneously confirms the relevance of research in this area, contributing to increasing the competitiveness of the agricultural sector of countries, ensuring its sustainable development and integration into international markets [21]. In addition, this will make it possible to create an effective food chain "from field to fork" in the formation of dried semi-finished products of a wide range of uses – from processing and production, hotel and restaurant complexes to consumer cooperatives [22]. One of the promising areas of processing plant raw materials is the improvement of resource-saving thermal equipment for obtaining concentrated organic semi-finished products of a high degree of readiness (pastes, powders, etc.) [23]. To artificially increase the physiologically functional properties of natural semi-finished products of a high degree of readiness, blending of various raw materials is implemented, thereby providing original organoleptic and organoleptic properties [24]. Natural dried semi-finished products of a high degree of readiness obtained under field conditions, in fact, in places where raw materials grow, are a natural box of functional ingredients and are widely used in various food formulations. Widespread use is observed in meat products due to the replacement of a portion of bread with natural blended dried mixtures and giving the product juiciness [25–27]. The introduction of mobile solar dryer designs is a promising direction for the development of the agricultural sector and will contribute to resource-saving and environmentally friendly processing of agricultural raw materials in accordance with the concept of "from field to fork" and the European "green course". However, the issues of optimizing the geometric parameters of air collectors without tying them to the sunny side, adapting the designs to different climatic conditions, and effective heat accumulation remain unresolved. The use of backup energy sources to maintain the rational operation of the solar dryer during cloudy days/nights and sudden changes in weather conditions, regulating the heat carrier speed, and integrating modern IT solutions for remote process control. In turn, the development and adaptation of a mechanism for managing the competitiveness of agricultural enterprises will make it possible to optimize processing processes, strengthen positions in international markets, and ensure the environmental sustainability of production. This will contribute to increasing the efficiency of the agricultural sector and ensuring stable operation of dryers under different conditions, forming a competitive food chain. Preliminary assumptions are the feasibility of introducing mobile vertical-modular solar dryers for processing agricultural raw materials into the agricultural sector, which will make it possible to obtain high-quality dried semi-finished products with a high degree of readiness. This will further increase competitiveness and contribute to expanding export potential.

3. The aim and objectives of the study

The purpose of our research is to improve the mobile structure of a vertical-modular solar dryer for the agricultural sector, taking into account the principles of sustainable development and the concept of "from field to fork". This will make it possible to use radiation energy within the framework of the green course of European integration for high-quality processing of local raw organic base into dried vegetable semi-finished products of a high degree of readiness.

To achieve the goal, the following tasks were set:

– to adapt the hardware and technological solutions in a model sample of a mobile vertical-modular solar dryer for drying vegetable raw materials in the context of "from field to fork";

– to determine the efficiency of using an improved mobile vertical-modular solar dryer.

4. The study materials and methods

The object of our study is the radiation drying of the agricultural sector's local resource raw material base using the example of Jerusalem artichoke (Kyivskyi white variety) and apples (Williams variety) in an improved mobile design of a vertical modular solar dryer.

The hypothesis of the study assumes effectiveness of the proposed hardware and technological solutions, which are based on:

– ensuring the mobility of the device, the feasibility of mounting 4 hemispherical convex air collectors on the sides of the mobile platform;

– designing a cylindrical working chamber of the solar dryer based on the body in the form of a tubular light-absorbing coil;

– the feasibility of using heat accumulators, a fabric cover;

– ensuring the autonomy of fans and installing a central base with a backup IR emitter.

A characteristic feature of the device is the use of hemispherical air collectors, a heat-insulated working space of the working chamber, a heat-insulating cover. Autonomy of fans under the conditions of using Peltier elements, an internal heat accumulator, and an internal backup infrared heater, which leads to increased resource efficiency of the device under field conditions. Testing of the proposed mobile design of a vertical-modular solar dryer was carried out during the summer-autumn decade of 2024 in the territory of the frontline Kharkiv Oblast (the experiments would begin at 12.00). The choice of months such as July, August, September is explained by seasonal changes in the intensity of solar radiation and air temperature, which significantly affect the efficiency of solar drying. For maximum testing of the solar dryer at the start, a clear sunny day was chosen, under the conditions of the meteorological service forecast that the next day would be sunny. During solar drying, in addition to obtaining kinematic data, the average daily temperature and relative humidity of the air were determined during the specified decades of 2024. In turn, in 2025, it is planned to continue field research for full testing of the proposed hardware and technological solutions in the coverage of research data in further publications. The repeatability of the research was implemented in 5-fold repeatability with a relative error of no more than 3 % when processing experimental and practical data during drying of plant raw materials.

The angle of inclination of the air collector to the horizon varied from 20° to 45° to expand the spectrum of use of the device in different geographical latitudes. The average value of energy illumination on a sunny day was within 300...650 W/m^2. The processing of experimental and practical data was implemented at the scientific and educational center "Innovative resource-saving technologies for processing organic products", the State Biotechnological University (Kharkiv, Ukraine).

For testing the mobile vertical-modular solar dryer, raw materials with high physiologically functional ingredients (inulin-containing ingredients, vitamin C, pectin, and other useful components) for the daily diet were selected. To conduct research on the experimental design of a mobile vertical modular dryer, the raw material previously underwent basic preparatory technological operations (washing, inspection, sorting/calibration, cleaning (removal of the stalk and surface layer). Any plant raw material requires high-quality processing after harvesting, and solar drying makes it possible to maximally preserve the initial properties of the raw material and save on electricity. The initial humidity of the experimental raw material was as follows: Jerusalem artichoke – 77.8 %, apple – 88.0 %. The raw material was cut as follows: Jerusalem artichoke (rectangle thickness 4, 6, 8 mm) and apple – into circles 4, 8, 12 mm with subsequent loading onto mesh pallets into the working environment of the solar dryer. Reducing the thickness of the cut leads to crumbling and breaking of the samples, and increasing it, accordingly, increases the drying duration. The total mass of the working environment loading of the model solar dryer design is 6.0 kg (control of the change in the weight of the device was implemented using strain gauges) with hourly measurement.

To determine the kinetics of the experimental raw materials, the improved design has built-in thermocouples, humidity sensors, an anemometer, strain gauges, and video cameras located along the geometric contour of the device. Data on technological parameters are received by the control unit with a built-in wireless Wi-Fi module for remote processing and control of the drying process. Drying kinetics curves were constructed using experimental points using a recorder.

Obtaining technological parameters in real time under conditions of remote data transmission make it possible to study the features of the implementation of solar drying and test the improved device placed under field conditions without direct physical contact with it. Determination of the chemical composition [28] and organoleptic indicators [29] in experimental samples of plant raw materials was carried out using classical methods. To compare the effectiveness of solar drying in comparison with the classical technology of drying plant raw materials, a comparison of the main chemical and organoleptic indicators before and after drying was carried out. At the same time, during convective drying, a temperature regime within 55 °C was used, which corresponded to the actual drying conditions under the field conditions of the solar dryer.

The temperature of the heat carrier (heated air) entering the working environment of the solar dryer is 20....50 °C in the daytime, and 30...20 °C in the evening), the speed of the heat carrier is 0.05...2.0 m/s (measurement was carried out with an anemometer). The average moisture content of the external air environment during the experimental period was 12.8 g/kg (during the experimental period, the moisture content was within 9.5...13.5 g/kg of dry air). The duration of solar drying of raw materials without preliminary treatment (blanching or aging in sugar syrup) was from 30.5 to 50.0 hours. The assumptions of the study include the need to prevent direct contact of ultraviolet rays with the raw material under study, for the possible loss and storage of nutrients in organic raw materials. This factor is also being investigated in parallel with a similar solar dryer, but with a light-transmitting surface (housing).

5. Improving the design of a mobile vertical-modular solar dryer for sustainable drying of plant raw materials in the context of the concept "from field to fork"

5. 1. Adaptation of hardware and technological solutions in a model of a mobile vertical-modular solar dryer for drying plant raw materials in the context of the concept "from field to fork"

When improving a mobile vertical-modular solar dryer for drying plant raw materials in the "from field to fork" trend, the hardware and technological solutions formed are aimed at:

– forming the mobility of the device by placing it on a mobile platform. This will allow the device to be placed directly under field conditions for processing organic raw materials in places of cultivation into semi-finished products of a high degree of readiness. The resulting dried semi-finished products can act as independent products and at the same time as organic natural ingredients in the recipes of various food products. Forming the actual European trend "from field to fork";

– mounting on the sides of the mobile platform 4 hemispherical convex air collectors. This makes it possible to neglect the needs of location (movement) of the solar dryer with 1 collector relative to the location of the solar energy source or to use additional focusing elements. The possibility of adjustable lowering of the air collectors contributes to maximum absorption of solar energy;

– design of the working chamber of the solar dryer in the form of a cylinder with a body in the form of a tubular light-absorbing coil. This allows for maximum absorption of solar energy during a sunny day and prevents direct contact of ultraviolet rays with plant raw materials;

– use of heat accumulators and a fabric cover. This will allow for the accumulation of thermal energy coming from the air collectors in the working chamber of the solar dryer to preserve heat in the device at night and changing weather conditions. For additional heat storage at night and prolonged cloudy weather, the device is equipped with a liquid-free protective fabric cover;

– autonomy of fans and the central base with a backup IR emitter. The autonomy of the exhaust fans is ensured by the location of Peltier elements in the heat-accumulating zone. And the central location of the backup IR emitter will make it possible to maintain the minimum drying temperature in prolonged cloudy weather conditions.

A model of a mobile vertical-modular solar dryer (Fig. 1) to expand the competitive range of use in the agricultural sector is located on a mobile platform 1 with a mount for vehicles 2. The side walls of the platform 1 have hemispherical convex air collectors 3 (1.0 m long), which are lowered after the platform is installed at the place of drying agricultural raw materials and have an adjustable angle of inclination to the horizon (20...45°). This provides an expansion of the range of use of the solar dryer in different geographical latitudes under conditions of maximum perception of solar energy. In addition, the use of 4 air collectors makes it possible to not waste time turning the corrector to the south side (the side of maximum solar radiation) and to abandon additional inconvenient mirror focusing devices under field conditions. Thus, independent concentration of solar energy by the solar dryer collectors is ensured.

The working chamber of the solar dryer 4 for the formation of the most uniform perception of solar energy has a cylindrical shape, the height of which is equal to its diameter. On the movable platform 1, a working cylinder is mounted in the form of a tubular light-absorbing coil 5 (black) with an air environment, which acts as a thermos for the internal environment of the device. It is proposed to have a light-tight contour of the working cylinder to prevent direct ultraviolet rays from hitting the plant raw materials. At night or during prolonged cloudiness/rain, a liquid-free protective fabric cover 6 is mounted in the upper part for additional thermal insulation of the solar dryer body, which is lowered as needed. Structurally, the working cylinder has the ability to open 1/2 of the cylinder due to hinges 7 for loading and unloading raw materials, and to prevent depressurization of the air environment of the coil, there are rubber ring seals at the joints.

The lower base of the working cylinder is additionally thermally insulated to a height of 150 mm for the location of thermal accumulators 8 and covered for technical protection with a mesh casing 9. On the outer surface of the casing 9, exhaust autonomous fans 10 with a spiral guide are installed to ensure an adjustable heat carrier speed (0.05...2.0 m/s) for intensive movement of the air medium along a spiral trajectory. The exhaust fans are powered by Peltier elements 11 built into the thermally insulated lower base of the working cylinder, which convert the internal heat of the medium into a low-voltage supply voltage (4 W is generated at 30 °C). The lower base of the working cylinder is additionally connected by a flexible line to air collectors 3, thus the heated heat carrier preheats 100 mm of the thermal accumulator layer (stone pebbles 50...80 mm in size).

Pre-cut raw materials are loaded into perforated inclined spiral pallets 12, mounted on the central inner rack 13, externally wrapped with a film-like resistive electric heater of the radiant type 14 (FlEHRr [30]). FlEHRr is an IR radiator installed on the outer surface of the rack and acts as a backup heat source (600 W) to maintain the minimum activity of the device. For example, when changing weather conditions (unplanned by weather forecasts: rain, prolonged cloudiness, a sharp decrease in temperature at night in the spring and autumn decades of the year, etc.). Or other factors that make it impossible to use solar energy (failure of collectors, etc.). The inclination of perforated inclined spiral trays 12 made of food material at an angle of 10° makes it possible to form a technical channel for spiral movement of the heat carrier (hot air). From the lower part (inlet of the heated heat carrier) to the upper part of the tube dryer (outlet of the saturated moisture-containing heat carrier) through the pipe 15. Technological parameters such as temperature, humidity, rotation speed of autonomous fans are controlled by the control unit 16, which is connected to a wireless Wi-Fi module for remote control of the drying process.

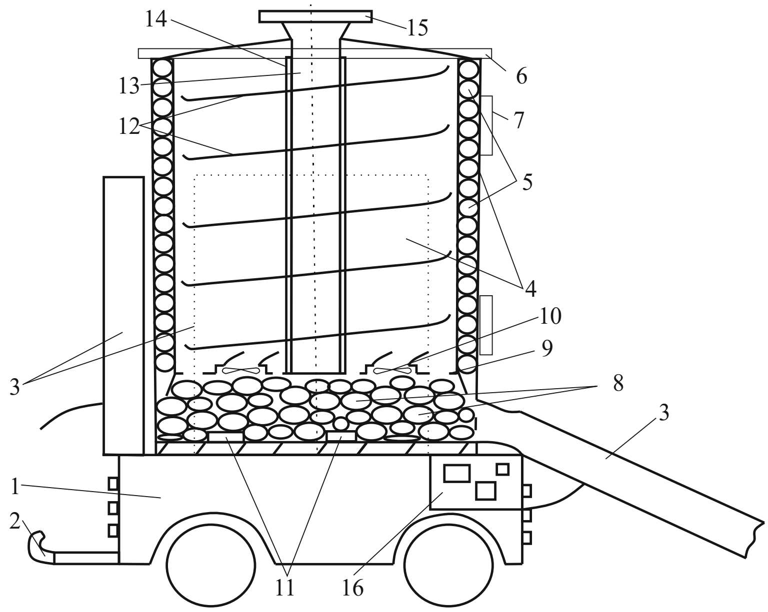

Fig. 1. Schematic diagram of a model of a mobile vertical modular solar dryer: 1 — movable platform; 2 — attachment to a vehicle; 3 — hemispherical convex air collectors; 4 — working chamber of the solar dryer; 5 — tubular light-absorbing coil; 6 — liquid-non-absorbing protective fabric cover; 7 — hinges; 8 — thermal accumulator; 9 — protective mesh casing; 10 — exhaust autonomous fans; 11 — Peltier elements; 12 — perforated inclined spiral trays; 13 — central internal rack; 14 — film-like resistive electric heater of the radiant type; 15 — branch pipe; 16 — control unit

The proposed structure of a solar dryer based on innovative design and technological solutions is aimed at rational drying of agricultural raw materials in the trend "from field to fork" by directly processing organic raw materials into dried semi-finished products of a high degree of readiness. The absorbed solar energy by air collectors and the outer surface of a cylindrical chamber with a light-tight frame provides optimal heating intensity and prevents contact of raw materials with ultraviolet rays. Inclined spiral designs of drying shelves provide vortex movement of heated air to intensify the solar drying process. For heat accumulation in the device, the following are provided: a tubular light-absorbing coil, which acts as a frame of the working chamber; a thermal accumulator in the lower part of the chamber (stone pebbles 50...80 mm in size). A liquid-non-absorbing protective fabric cover, for use at night, prolonged cloudy weather, and adverse weather conditions.

The trend "from farm to fork" requires the implementation of a mechanism for managing the competitiveness of agricultural enterprises (Fig. 2) based on innovative hardware and technological solutions that combine technical, economic, and organizational aspects for competitiveness in the European market.

The technical component is based on the adaptation of resource-saving equipment designs – mobility provides the ability to adapt to different climatic conditions and production scales under the conditions of a universal tool for the agricultural sector. The integration of digital technologies (the use of remote monitoring of the process makes it possible to control the process remotely) and the use of solar surfaces leads to a reduction in energy costs while preserving the environment, creating energy efficiency. Financial sustainability is the key to economic advantage aimed at reducing the cost of production (ensuring the mobility of the solar dryer will make it possible to reduce resource costs while preserving agricultural raw materials during drying). In particular, the development of financial support mechanisms in the form of cheap loans and grants contributes to the rapid introduction of innovative technologies among farmers. The formation of added value for dried raw materials obtained in the solar dryer will make it possible to obtain dried semi-finished products of a high degree of readiness and offer premium goods for export.

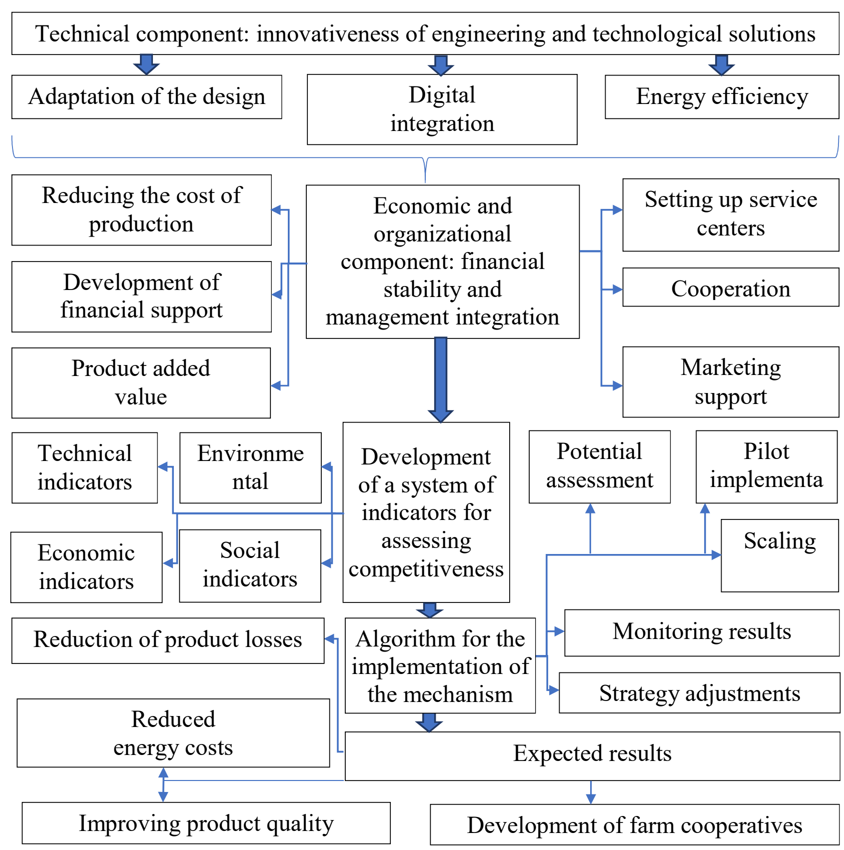

Fig. 2. An improved mechanism for managing the competitiveness of agricultural enterprises based on innovative hardware and technological solutions that combine technical, economic, and organizational aspects for competitiveness in the European market

Organizational component: management integration is based on the creation of mobile service centers aimed at supporting the agricultural sector through training, advanced training, and technical support for the effective use of innovative engineering and technological solutions. The formation of a cooperation model will make it possible to form cooperation between small and medium-sized enterprises to reduce the costs of purchasing and servicing solar dryers. The creation of marketing support will ensure the development and adaptation to today's conditions of a promotion strategy, focusing on the concept of "from field to fork", ensuring transparency and consumer trust, which is important for the development of the organic product brand.

The development of a system of competitiveness assessment indicators should include technical indicators aimed at assessing energy efficiency, productivity of solar dryers and the level of resource saving in the production of eco-semi-finished products. Economic indicators will make it possible to analyze the cost, added value, and profitability of an agricultural enterprise. Environmental indicators are aimed at determining the reduction of the carbon footprint and determining the efficiency of using renewable energy sources. Social indicators will provide a definition of the impact on the level of employment, the creation of agricultural cooperatives and the improvement of the well-being of farming communities.

A separate important component of the mechanism is the implementation algorithm, which involves assessing the potential in the context of a preliminary analysis of the needs of agricultural enterprises in reducing losses of agricultural raw materials, products, and improving competitiveness. An important role is also played by pilot implementation in testing a mobile solar dryer in production regions to assess efficiency and adaptation to the needs of the agricultural holding. This will make it possible to scale up engineering and technological solutions embodied in a mobile design to expand the use of modern solutions through support by state programs and cooperation with farmers. After pilot adaptation and scaling, it is necessary to continue monitoring the results to assess the results of the implementation in terms of economic, environmental, and social impact. This will make it possible to adjust the strategy by updating management approaches based on the collected data to improve efficiency under the conditions of rapid changes today.

The expected result of adhering to the adapted mechanism will be a reduction in product losses under conditions of remote process control and a reduction in energy costs through the use of solar energy. It is also expected to increase the quality of products compared to existing assortments in the domestic and foreign markets, contributing to increased export opportunities. In addition, the development of farmer cooperatives will lead to increased economic sustainability of rural communities through the joint use of innovative solutions. The implementation of the proposed mechanism by the agricultural sector will provide an opportunity for the effective implementation of innovative solutions in the agro-industrial sector of countries, supporting food security in the context of sustainable development, competitive advantages, and globalization and a changing climate. The integration of innovative hardware and technological solutions, in particular in the form of mobile solar dryers with remote monitoring, will contribute to resource saving and preservation of product quality. The system of performance assessment indicators proposed in the mechanism based on economic, environmental, and social aspects is scientifically substantiated in the trend "from field to fork". The practical implementation of a competitive mechanism involves the creation of service centers, farmer cooperatives, financial support, and pilot testing, which will increase the resource efficiency of the technical and technological process, improve the quality of dried semi-finished products, and expand the country's export potential.

5. 2. Experimental and practical testing of the effectiveness of engineering and technological solutions under the conditions of using a model sample of a mobile vertical-modular solar dryer

Studies on the drying kinetics of the experimental raw materials were carried out under experimental field conditions when loading the vertical-modular sector of the device with 6.0 kg (Fig. 3).

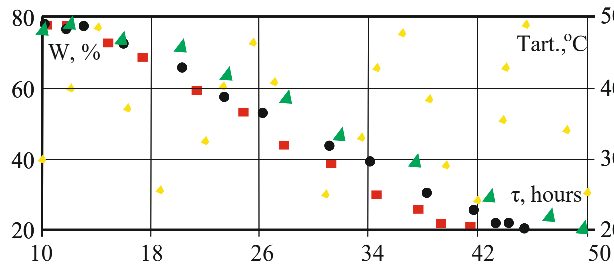

Fig. 3. Kinetics of Jerusalem artichoke drying: ■ – rectangle 4 mm thick (drying date 07/15/2024); ● – rectangle 6 mm thick (drying date 08/15/2024); ▲ – rectangle 8 mm thick (drying date 09/15/2024); ◆ – temperature of the experimental raw material

The drying time of Jerusalem artichoke with a rectangle thickness of 8 mm is 50 h when dried in mid-July; for a 6 mm rectangle, the duration of sun drying was 43.5 h (for August), and for a 4 mm rectangle, respectively 38.6 h for September. The temperature of the experimental raw material varied from 22 °C to 50 °C, respectively.

The drying time of an apple previously cut into circles with a thickness of 4 mm is 30.5 h (drying in July, Fig. 4); for 8 mm, the duration of sun drying was 34.8 h (for August), and for 12 mm, respectively 37 h for September. The temperature of the experimental raw material varied from 23 °C to 48 °C, respectively. The amount of moisture that needs to be removed in the sun drying process when loading 1 module of the apparatus with 6.0 kg of raw material is: for Jerusalem artichoke (77.8 %) – 3.5 kg; apple (87.0 %) – 4.2 kg, respectively.

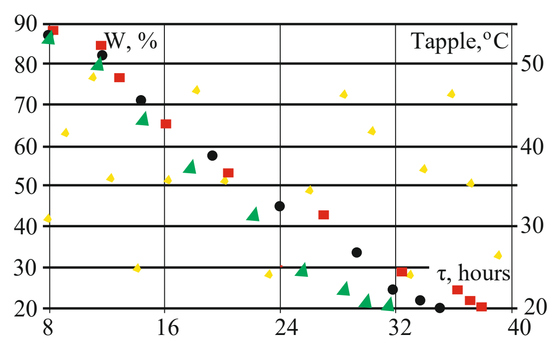

Fig. 4. Kinetics of apple (circles) drying: ▲ – 4 mm thick (drying date 07/20/2024); ● – 8 mm thick (drying date 08/20/2024); ■ – 12 mm thick (drying date 09/20/2024); ◆ – temperature of the experimental raw material

Data were obtained on changes in the content of the main chemical ingredients of the experimental raw materials before and after sun drying in comparison with the experimental raw materials during convective drying at a temperature of 55 °C (Table 1). Also, data were obtained on the organoleptic indicators of dried experimental semi-finished products of high degree of readiness, obtained in an improved apparatus and during convective drying (Table 2).

Table 1

The content of components of the chemical composition of samples obtained in an improved model structure and during convective drying (temperature 55 °C)

Indicator	Advanced solar dryer	Convective dryer	Advanced solar dryer	Convective dryer
	Jerusalem artichoke		Apple:	
	(initial content/ final content)			
Dry matter, %	77.8±1.00/20.0±1.00	77.8±1.00/20.0±1.00	87.0±1.00/20.0±1.00	87.0±1.00/20.0±1.15
Vitamin C, mg/%	6.1±1.25/2.8±1.25	6.1±1.25/1.9±1.25	9.3±1.25/4.1±1.25	9.3±1.25/3.6±1.25
Dietary fiber, gr.	4.5±0.02/1.96±0.02	4.5±0.02/1.35±0.02	1.8±0.02/0.8±0.02	1.8±0.02/0.46±0.02
β-carotene	11.4±0.01/4.3±0.01	11.4±0.01/3.7±0.01	–	–
Phosphorus, mg	76.9±0.05/15.2±0.05	76.9±0.05/12.6±0.05	11.2±0.05/4.8±0.05	11.2±0.05/4.1±0.05
Mono – and disaccharides, mg	3.3±0.02/1.15±0.02	3.3±0.02/1.03±0.02	9.2±0.02/3.8±0.02	9.2±0.02/3.15±0.02

Table 2

Organoleptic indicators of experimental samples obtained in an improved model structure and during convective drying (temperature 55 °C)

Organoleptic indicators	Samples at:	
	drying in an experimental model apparatus	convective drying
Appearance	Homogeneous fractional dried mass	Homogeneous fractional dried mass with partial darkening of certain areas of raw materials
Taste and smell	Pleasant harmonious taste and smell of Jerusalem artichoke/apple	Taste and smell of Jerusalem artichoke/apple
Color	light yellow uniform color	dark yellow color of a non-uniform nature

It was found that during sun drying, vitamin C in Jerusalem artichoke decreases by 2.17 times, and during convective drying by 3.21 times, respectively. For apples, during sun drying, it decreases by 2.26 times and 2.58 times, respectively, during convective drying. Dietary fiber in Jerusalem artichoke decreases by 2.29 times during sun drying, and by 3.33 times during convective drying. Dietary fiber in apple raw materials decreases by 2.25 times during sun drying, and by 3.91 times during convective drying, respectively. β-carotene in Jerusalem artichoke decreases by 2.65 times during sun drying, and by 3.08 times during convective drying. In terms of the percentage of reduction in phosphorus and mono- and disaccharides, the experimental samples also have an advantage when dried in an improved sun dryer. The experimental semi-finished products obtained in a sun dryer have a uniform appearance, light yellow color, and pleasant taste and aromatic properties, confirming the effectiveness of using a sun dryer.

6. Discussion of results regarding the effectiveness of the proposed hardware and technological solutions for improving the mobile solar dryer

The implemented hardware and technological solutions are aimed at increasing the competitive properties of the mobile design of a vertical modular solar dryer for the agricultural sector, taking into account the principles of sustainable development and the concept "from field to fork". Unlike foreign analogs [9], a feature of our improved design is the absorbed solar energy by hemispherical convex air collectors mounted on a mobile moving platform. This, in turn, allows the device to be used under different climatic field conditions without being tied to the location of the solar energy source. In addition, the circular geometry of the solar dryer chamber does not require the use of various mirror surfaces to focus solar energy. The transparency of the working environment due to the tubular light-absorbing coil prevents direct ultraviolet rays from falling on the plant raw materials, and the air gap acts as a "thermos", storing thermal energy in the device [9]. The presence of a thermally insulated cylinder with a thermal accumulator and a fabric cover in the lower part of the device creates a conditional thermos device, increasing the resource-saving of its use at night and in prolonged overcast conditions [15]. In addition, existing solar dryers do not have the ability to operate autonomously, such as fans, and in most cases require the use of a solar panel or additional power supply [16]. Unlike an improved mobile solar dryer, in which the autonomous power supply of the fans is provided by Peltier elements.

The improved design of the mobile vertical-modular solar dryer (Fig. 1) combines innovative solutions that ensure effective drying of agricultural raw materials in resource-saving conditions. The structure includes adjustable (tilt angle from 20° to 45°) hemispherical convex air collectors (item 3) for maximum absorption of solar energy under different geographical conditions. A thermally insulated cylinder with a thermal accumulator (item 8, stone pebbles 50...80 mm in size) for heat preservation and heat accumulation, as well as a backup infrared heater (item 14) for stable operation under adverse weather conditions. In addition, the device has a protective leather casing (item 6) to create a "thermos" effect at night and during long periods of cloudiness. Perforated inclined spiral pallets (item 12) enable uniform moisture removal, and the opaque frame (item 5) protects the raw materials from the harmful effects of ultraviolet light. The design of the solar dryer makes it possible not only to process organic raw materials into semi-finished products of a high degree of readiness but also increase resource efficiency due to the autonomous power supply of fans (item 10) from Peltier elements (item 11). Due to the mobile platform, placement under field conditions is ensured, contributing to the sustainable development of the agricultural sector.

An improved mechanism for managing the competitiveness of agricultural enterprises based on innovative hardware and technological solutions (Fig. 2) allows for the integration of innovative hardware and technological solutions in the form of mobile solar dryers with remote monitoring of resource efficiency and preservation of product quality. The proposed mechanism system combines the main competitive advantages: economic, environmental, and social aspects, and is scientifically based in the trend "from farm to fork".

The results of our study show the dependence of the duration of solar drying on the shape of the slice (rectangular/round), the thickness of the raw material (4, 6, 8, and 12 mm), and the speed of the heat carrier (0.05…2.0 m/s). The justification for choosing the slice thickness of 4, 6, 8, and 12 mm is due to the need to assess the influence of the thickness of the raw material on the duration of the drying process and ensure uniform dehydration of the product. Since the thickness of the raw material is one of the determining factors of drying, to ensure the correctness of the results, each series of experiments was carried out taking into account the same conditions: a fixed slice thickness for each individual experiment, the same dryer loading mode, and conducting tests under stable climatic conditions of the corresponding month. An important factor in the efficiency of the process is the seasonality of the year, which led to the choice of the summer–autumn decades of 2024 (July, August, and September) for conducting experiments. All studies began at 12:00, which ensured stable test conditions. To ensure the typicality of the study, the drying duration was compared for different months with different cutting thicknesses in different periods (July, August, September) with the same initial content of the test raw material. This approach made it possible to obtain a series of pile studies aimed at forming generalized conclusions and correctly assessing the influence of meteorological conditions on the drying process. To minimize the errors of comparative analysis in a series of field studies, experiments were carried out with the same thickness of the raw material in different months and in 3 experimental solar dryers, which made it possible to more accurately assess the influence of external factors on the drying process. Dependence of drying duration on the thickness of the test raw material (Fig. 3 – Jerusalem artichoke, Fig. 4 – apple). The duration of solar drying of Jerusalem artichoke with a thickness of 4 mm in July was 38.6 h, 6 mm in August – 43.5 h, and 8 mm in September – 50.0 h. Similarly for apples: 30.5 h (4 mm, July), 34.8 h (8 mm, August), and 37.0 h (12 mm, September). These data indicate a regular increase in the duration of drying with increasing thickness of the raw material. During drying, the temperature of the raw material varied in the range of 22…50 °C for Jerusalem artichoke and 23…48 °C for apples, which confirms the stability of the process and compliance with technological parameters. Moisture evaporation when loading 6.0 kg of raw material was 3.5 kg for Jerusalem artichoke (77.8 % humidity) and 4.2 kg for apples (87.0 % humidity). The drying process brought the samples to a residual moisture content of 20.0 %, which ensures the quality of preservation of dried products (Table 1). The results obtained confirm the effectiveness of the experimental design of the solar dryer and its ability to provide stable drying parameters under different experimental conditions. At the same time, taking into account various influencing factors, it is advisable to conduct additional studies to clarify the dependence of the drying process parameters on climatic changes and design features of the dryer.

Sun drying compared to convective drying allows for more efficient preservation of the main chemical indicators: the content of vitamin C in Jerusalem artichoke decreases by 2.17 times, and with convective drying by 3.21 times, respectively. For apples with sun drying – by 2.26 times and 2.58 times, respectively, with convective drying (Table 1). Dietary fiber of Jerusalem artichoke during sun drying decreases by 2.29 times, and 3.33 times with convective drying. Dietary fiber of apple raw materials during sun drying decreases by 2.25 times and with convective drying – by 3.91 times, respectively. β-carotene in Jerusalem artichoke during sun drying decreases by 2.65 times and 3.08 times with convective drying. In terms of the percentage of phosphorus and mono- and disaccharides reduction, the experimental samples also have an advantage when dried in an improved solar dryer. The experimental semi-finished products obtained in a solar dryer have a uniform appearance, light yellow color, and pleasant taste and aromatic properties (Table 2).

The improved design of a mobile vertical-modular solar dryer has prospects for use in comparison with traditional drying technologies. Due to the use of hemispherical air collectors, a heat-insulated working space of the working chamber, a heat-insulating cover. Autonomy of fans under conditions of using Peltier elements, an internal heat accumulator and an internal backup infrared heater. This leads to an increase in the resource-saving of the device under field conditions compared to similar devices in foreign studies [6]; the proposed system is more adapted to changing environmental conditions.

A limitation of our study is the choice of stone pebbles as a heat-accumulating material. The use of air collectors with different geometric structures may make it impossible to use the proposed engineering solutions effectively and requires additional research. Structural changes without prior research will likely lead to a decrease in the efficiency of solar drying and require field adaptation to technological needs. With the onset of the summer decade of 2025, field tests will continue to optimize the operation of the solar dryer under different climatic conditions, which will allow the device to be adapted for different types of agricultural raw materials and different climatic zones. In addition, further research may be aimed at improving efficiency by testing additional engineering solutions aimed at increasing energy efficiency [8].

7. Conclusions

1. The adaptation of hardware and technological solutions under field conditions has made it possible to improve the model of a mobile vertical-modular solar dryer for drying plant raw materials in the "from field to fork" context. The movable platform provides mobility, and four adjustable hemispherical air collectors (tilt angle 20–45°) maximize the absorption of solar energy. The cylindrical working chamber with a tubular light-absorbing coil minimizes the impact of ultraviolet radiation, and the fabric cover and thermal accumulator with stone pebbles (50–80 mm) retain heat. For stable operation under difficult conditions, a backup IR heater (600 W) and autonomous fans with Peltier elements are provided. Loading agricultural raw materials onto perforated spiral pallets enables uniform drying and optimal air circulation (0.05–2.0 m/s).

The proposed mechanism for managing the competitiveness of agricultural enterprises based on innovative hardware and technological solutions will contribute to resource saving, improving product quality, and expanding export potential. Integration of mobile solar dryers with remote monitoring will contribute to the efficient use of energy, reducing losses of agricultural raw materials, and sustainable development of the agricultural sector in the face of global challenges.

2. In the study of duration of sun-drying of Jerusalem artichoke, it was found that the drying time depends on the thickness of slices and the month of experiment. Thus, for samples with a thickness of 4 mm in July, drying lasted 50.0 h, for 6 mm in August – 38.6 h, and for 8 mm in September – 43.5 h. At the same time, the temperature range of the experimental raw material during drying varied from 22–50 °C. In the study of duration of sun-drying of apples, it was found that the drying time depends on the thickness of slices and the month of experiment. Thus, for samples with a thickness of 4 mm in July, drying lasted 30.5 h, for 8 mm in August – 34.8 h, and for 12 mm in September – 37.0 h. At the same time, the temperature range of the experimental raw material during drying varied from 23–48 °C. Moisture removal when loading 6.0 kg of raw materials was 3.5 kg for Jerusalem artichoke (77.8 % moisture) and 4.2 kg for apples (87.0 % moisture). It was found that sun drying provides a smaller decrease in the content of vitamin C, dietary fiber, and β-carotene in Jerusalem artichoke and apples compared to convective drying. In particular, the loss of vitamin C in Jerusalem artichoke is 2.17 times (versus 3.21 times with convective drying), and in apples – 2.26 times (versus 2.58 times). Dietary fiber in Jerusalem artichoke is reduced by 2.29 times (versus 3.33 times), and in apples – by 2.25 times (versus 3.91 times). Loss of β-carotene in Jerusalem artichoke during sun drying is 2.65 times (versus 3.08 times). There is also a smaller reduction in phosphorus and mono- and disaccharides. Semi-finished products obtained in the improved solar dryer have a uniform appearance, light yellow color, and preserved taste and aroma properties.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

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

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