This study explores processes behind comprehensive processing of plant raw materials using pumpkin, apple, and Jerusalem artichoke as examples, for implementing thermal pre-treatment, concentration, and IR-drying on heat and mass exchange equipment with a body-integrated heater. The task addressed is to manage comprehensive processing of plant raw materials by using improved heat and mass exchange equipment.

The designed technological line was experimentally and practically tested for processing 100 kg of functional matrix (30% pumpkin, 20% apple, and 50% Jerusalem artichoke) using rational modes of thermal pre-treatment, rotary film concentration, and IR-drying. The line enabled the production of concentrated semi-finished products with a content of 28...45% dry matter, powdered semi-finished products with a final moisture content of 3...6%, dried fractions (10...14%) and secondary dried fractions (7...10%).

A digital twin recreated the production cycle for obtaining 37.87 kg of concentrate with 45% dry matter and 18.13 kg of powdered semi-finished product at a final moisture content of 6%. The pre-heating apparatus, the rotary film apparatus, and the IR dryer differ by the integration of a film resistive electric heater of the radiant type into the housing and mixing devices, reducing the specific metal capacity by 14.91%, 28.33%, and 30.97%, respectively. The total energy consumption of the main heat and mass exchange equipment was reduced by 7.23%.

The difference of the line is the comprehensive processing of primary and secondary raw materials using resource-saving heat and mass exchange equipment and a physically oriented digital twin. Practical testing of the designed line confirms the possibility of producing concentrated, dried, and powdered semi-finished products with a high degree of readiness

Keywords: pumpkin, apple, Jerusalem artichoke, pre-processing, concentrated semi-finished product, rotary film concentration, powdered semi-finished product, digital modeling, digital twin

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DESIGN AND DIGITAL SIMULATION OF A RESOURCE-EFFICIENT TECHNOLOGICAL LINE FOR COMPREHENSIVE PROCESSING OF PLANT RAW MATERIALS

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1. Introduction

The integration of the European Green Deal is aimed at implementing resource-saving processing of plant raw materials in the context of a complex interaction of rational regimes of thermolabile raw materials and resource-saving production cycle. Special attention is paid to the comprehensive processing of plant raw materials with minimization

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of secondary raw materials (waste after rubbing, etc.). The implementation of comprehensive resource-saving processing of plant raw materials contributes to the reduction of resource consumption and creates the possibility of using secondary raw materials in the production cycle [1]. This necessitates the search for engineering solutions aimed at improving not only individual technological operations but also the formation of a complex production cycle for the production of concentrated, dried, and powdered semi-finished products with a high degree of readiness. One of the practical directions for increasing the efficiency of processing and food production is the intensification of engineering and technological approaches aimed at reducing resource and energy costs [2]. One of the practical limitations to increasing resource efficiency is the use of basic heat supply systems with intermediate heat carriers, which leads to an increase in the level of metal consumption of the equipment, thermal inertia, and other undesirable factors for the high-quality processing of thermolabile raw materials. One of the promising solutions is the direct integration of film resistive electric heaters of the radiant type into the working circuits of heat and mass exchange equipment, thereby directly rejecting intermediate high-temperature heat carriers. The practical effectiveness of integrating an electric heater into the heat exchange surfaces of the apparatus, in particular for the thermal pre-treatment of plant raw materials, is explained in [3].

The implementation of a comprehensive technological line could make it possible to interconnect material flows, temperature rational regimes of thermolabile raw materials, duration of technological operations, and parameters of operation of heat and mass exchange equipment. It is advisable to combine experimental and practical testing with digital modeling of the production cycle simulated by a physically oriented digital twin to obtain a single information environment of processing technology and control of changes in parameters during the technological cycle. Therefore, designing a technological line for comprehensive processing of plant raw materials using heat and mass exchange equipment with a body-integrated heater and simulating the production cycle are urgent scientific and practical tasks. The practical implementation of the results will contribute to the comprehensive use of raw materials, expanding the range of semi-finished products of a high degree of readiness within a resource-saving production cycle.

2. Literature review and problem statement

The European pathway of resource-saving processing of plant raw materials is based on modern processing approaches while fully using all components and involving secondary raw materials for the further comprehensive production of functional food products. A systematization of existing approaches aimed at processing certain types of secondary raw materials obtained during the processing of fruit and vegetable raw materials into functional multi-component products was carried out in work [4]. The feasibility of organizing the sequential use of secondary waste during the production cycle was confirmed; however, certain limitations arise due to the complexity of integrating individual technological operations in a single cycle, which is associated with insufficient economic feasibility. A similar area of research is investigated in [5] by presenting the technological potential of secondary food waste as a source of functional ingredients/components. However, there is a clearly-stated fact of the dependence of the further use of the obtained semi-finished products on the initial technological properties of the raw materials, pre-processing conditions, and the features of the production cycle. Thus, it is noted in [6] that the fruit processing industry is characterized by significant volumes of secondary waste received – 8% of the total volume of food waste. This emphasizes the relevance of finding innovative ways to implement complex resource-saving processing of fruit waste. However, the study notes that most attention is paid to the extraction of individual valuable components from the variety of secondary raw materials, which prevents the possibility of designing a single hardware and technological processing line that could simultaneously process secondary waste. Therefore, the unresolved issue is the ability to devise a comprehensive technological cycle aimed at processing plant raw materials while minimizing secondary waste within a single production cycle with the receipt of a wide range of semi-finished products of a high degree of readiness. From practical and theoretical perspectives, one of the ways to partially solve this issue is to rationalize the complex combination of the operation of pre-heat treatment, rubbing, concentration, and drying with a clear material balance for each cycle.

The feasibility of combining pre-heat treatment in the production of functional pasty semi-finished products is considered in [7]. The technological solutions described enable the production of multi-component fruit and berry semi-finished products, the raw materials for which undergo pre-heat treatment. However, the described approach is aimed at the process of obtaining pasty semi-finished products and does not cover further IR drying or processing of secondary raw materials. The obtained practical resource efficiency of the designed comprehensive production cycle for the full processing of plant raw materials significantly depends on the methods of implementing heat and mass transfer operations, which is associated with the thermolabile properties of raw materials, both primary and secondary waste. One of the examples of assessing the life cycle of concentrated apricot puree production from start to finish is given in [8]. The research used the publicly available Agribalyse database with OpenLCA software (France) and the ReCiPe impact assessment method. The main factors of impact on the environment are the cultivation of apricots with subsequent transportation and boiling with obtaining the result of the scenario regarding the level of use of photovoltaic energy, which slightly reduces the potential for global warming. In particular, work [9] provides data on the analysis of electrification of thermal processes of processing and food industries to determine the potential for the transition from fuel and steam systems to direct electric heat supply. However, the authors note the need for full-fledged studies on processes associated with phase transformations and changes in the structure of the experimental raw materials, in which energy heat supply has an optimal effect from the structure of heat and mass exchange equipment. In turn, the practical application of infrared heat supply is increasingly considered as one of the main directions of intensification of heat and mass exchange processes. For example, in [10], studies are reported to determine the advantages of IR heating in terms of heat transfer speed, control quality, and potential reduction in energy consumption compared to traditional heat transfer methods. This highlights the feasibility of applying engineering approaches to optimize the design of emitters, ensuring their rational integration into various technological apparatuses.

Thus, in [11], the practical efficiency of IR drying under conditions of optimal wavelength, selected for certain properties of the raw material undergoing drying, as well as the practical feasibility of combining IR radiation with convective heat transfer is confirmed. However, the study does not propose a single universal structural approach to the construction of a local radiative heat exchange surface without the use of an intermediate heat carrier, which is partly due to the complexity of upgrading the basic equipment in a single research cycle. In [12], experimental studies of a continuous IR dryer are described by obtaining the dependence of the drying duration, the values of specific energy consumption, and thermal efficiency on the radiation power, its temperature operating range, and air speed. The use of mathematical modeling and machine learning proposed during the testing contributed to the optimization of rational operating parameters; however, the structural resource efficiency of the heat and mass exchange circuit (heating system) and its metal consumption were not evaluated. This highlights the feasibility of studying the aforementioned factors in the processing of plant raw materials. Therefore, most available practical and experimental research is focused on the study of IR processing under conditions of mode optimization without taking into account the structural component of the operation of heat and mass exchange equipment. The possibility of local integration of an electric radiant heater into the contours of heat exchange surfaces of various geometries and the basis of mixing devices of devices for the complete elimination of the intermediate heat carrier, steam jackets, and technical networks needs to be evaluated.

A similar problem is characteristic of the concentration of liquid thermolabile food systems, as confirmed by the results of studies on an industrial falling-film evaporator for fruit concentrates [13]. The results indicate a significant impact of the thermal resistance of the contaminated heat exchange surface during the production cycle on the productivity and energy efficiency of the overall cycle. This, in turn, with insufficient circulation of raw materials or prolonged operation of the heat and mass exchange equipment, leads to a sharp decrease in the intensity of evaporation. Therefore, from practical and theoretical perspectives, the need to reduce auxiliary high-temperature heat transfer links and ensure a clearly regulated heat flow directly to the film layer of the experimental mass is confirmed.

For example, in [14], the combination of membrane distillation with vacuum evaporation of apple juice was proposed as one of the practical solutions aimed at reducing energy consumption, by almost 60%, compared to classical evaporation. At the same time, the proposed improved scheme requires the use of an additional membrane stage and does not provide a solution to the issue of structural metal capacity and thermal inertia of the evaporation equipment directly modernized in this way. Therefore, for the implementation of concentration operations, the search for structural approaches aimed at forming a thin-film flow of thermolabile raw materials during vacuum concentration and local heat supply to reduce the structural mass remains relevant.

The implementation of digital transformations is consistent with the principles of constructing sustainable business models focused on innovative design and rational use of resources [15]. This approach allows for comprehensive optimization of production processes, increasing their transparency, minimizing costs, and ensuring the effective functioning of enterprises in the face of the challenges of the digital economy and fierce competition [16]. In this context, one of the directions for increasing the efficiency of processing and food complexes is the practical digital reproduction of technological processes. It makes it possible to assess their stability and response to sudden changes in various production and technological factors, taking into account modern risks and trends in digital transformations of production [17].

In [18], a multi-level concept of digital models of the above-mentioned industries was devised, aimed at a comprehensive combination of physical models, sensor data, and analytical tools. The work indicates that certain individual digital modeling and data collection tools are widely available, but their practical integration into unified life cycle models of production cycles continues to be insufficient. For example, in [19], the practical use of digital twins for modeling and calendar planning of the production cycle was demonstrated, which allowed the authors to confirm the feasibility of rationalizing approaches to the recipe-oriented representation of the production cycle. However, most attention in the research is on production planning, and not on the relationship between heat and mass exchange modes, material balance, and resource efficiency of the cycle. This is partly due to the limitations of the set of practical studies in a single practical implementation. In particular, the practical application of a digital twin in the sterilization of vegetable broth is given in [20]. Such actions made it possible to show the possibility of reducing steam consumption by 62% and startup time by 63% when simulating different strategies for the operation of heat and mass exchange equipment in the production process. In the course of the study, the authors identified one of the further areas of practical research, aimed at integrating digital models with streaming sensor data, control/management systems in the context of predictive analytics of the thermal process. Thus, the practical feasibility of using digital twins is confirmed not only for the visualization of production cycles but also for a comprehensive combination of technological and energy indicators of the technological process.

The systematic review of digital twins of industries given in [21] emphasizes the need to combine different levels of data collection, physical or mathematical models, simulation, and application according to technological needs. One of the main unresolved issues is the linking of data, models, and technological processes in a single complex for further scaling and standardization of existing digital solutions. For example, in [22], the study on the prospects of integrating digital twins with artificial intelligence (AI) and the Internet of Things (IoT) for optimizing production processes continues. However, attention is drawn to the insufficient level of data standardization and the limited number of implementations of production cycles.

Our review of related literature reveals that the results of studies partially confirm the effectiveness of the integrated use of secondary plant raw materials under the conditions of local electrification of IR heat supply with thin-film concentration and drying and practical support of digital twins. However, available papers did not fully make it possible to implement an integrated approach to combining in one technological line the processing of the main raw material and secondary waste, thermal pre-treatment, film concentration, and IR drying. When using equipment with a locally integrated radiant electric heater and simultaneous digital modeling of material, regime, and energy parameters of the production cycle. This emphasizes the need for the design

and experimental and practical testing of a comprehensive technological line for the processing of plant raw materials and secondary waste. This highlights the need for the practical development of a physics-based digital twin, with the simultaneous quantitative determination of the material balance, specific metal consumption, and thermal and energy consumption of the main heat and mass transfer equipment, compared with the corresponding indicators of the baseline equipment.

The above allows us to argue about the feasibility of conducting research on the development and experimental and practical testing of a technological scheme for the comprehensive processing of plant raw materials and secondary waste under rational regimes. It is also expedient to build a physically oriented digital twin of the production complex cycle with subsequent assessment of the design and technical properties and economic efficiency of the technological line.

3. The aim and objectives of the study

The purpose of our research is to design a technological line for comprehensive resource-saving processing of plant raw materials into semi-finished products of high readiness with modeling of the production cycle based on a digital twin and an overall assessment of the resource-saving of heat and mass exchange equipment. This will make it possible to implement comprehensive processing of plant raw materials and secondary raw materials in the production of concentrated, dried, and powdered semi-finished products in a resource-saving cycle.

To achieve the goal, the following tasks were set:

– to devise a technological scheme for comprehensive processing of plant raw materials using the example of pumpkin, apple, and Jerusalem artichoke with further determination of technological operations and operating parameters for obtaining concentrated, dried, and powdered semi-finished products;

– to build a digital twin of the designed technological line for modeling the relationships between the operating structure and technological parameters of basic heat and mass exchange equipment during its operation;

– to determine the resource efficiency of basic heat and mass exchange equipment of the designed technological line with integrated FREhRT by comparing the main engineering and technological indicators and assess the economic effect of its implementation.

4. The study materials and methods

The object of our study is the processes of comprehensive processing of plant raw materials on the example of pumpkin, apple, and Jerusalem artichoke when implementing thermal pre-treatment, concentration, and IR-drying on heat and mass exchange equipment with a body-integrated heater.

The principal hypothesis assumes that the implementation of technological operations of processing plant raw materials in the designed technological line could contribute to reducing the metal intensity and energy consumption of the production cycle by integrating FREhRT into the housing of basic heat and mass exchange equipment. The practical implementation of the designed line would contribute to compliance with rational modes of thermal pre-treatment, rotary film concentration, and IR-drying of heat-labile raw materials.

The assumptions were adopted to use the constant thermophysical properties of heat-labile raw materials during the testing studies on heat and mass exchange processes. The accepted simplifications included not taking into account local heat losses, transient modes of basic heat and mass exchange equipment, and the probable spatial non-uniformity of the temperature field.

To model the interaction of technological parameters of basic heat and mass exchange equipment, a digital twin (DT) was used to enable control over the course of technological operations and compliance with the specified parameters of the production cycle. In order to digitally reproduce the operation of the designed technological line, a digital twin was built, the structure of which includes the production cycle of comprehensive processing of raw materials.

Experimental and practical studies were carried out at the State Biotechnological University (Kharkiv, Ukraine). For experimental and practical testing of the technological line, ripe raw materials collected in the territories of the front-line Kharkiv oblast were used, specifically pumpkin, apple, and Jerusalem artichoke, with further determination of the regime parameters as well as determining the material balance of the components of the technological cycle and the yield of concentrated, dried, and powdered semi-finished products.

The structure of DT includes technological operations with their duration, material flows, recipe composition of the blended matrix, temperature regimes, dry matter content, final moisture content of concentrated and dried semi-finished products, as well as calculated indicators of heat and mass exchange equipment. The basic scenario of digital reproduction provides for experimental and practical testing of the production cycle. Namely, the processing of 100 kg of functional blended matrix with a recipe ratio of: 30% pumpkin, 20% apple, and 50% Jerusalem artichoke with an initial dry matter content (DM) of 17.04%. The modeling of the production cycle was carried out during the implementation of the main technological stages (thermal pre-treatment, rotary film concentration, and IR drying) with control over the material balance of technological processing in compliance with rational modes in the established operating ranges. The indicators of structural and technological efficiency were determined through comparison of the indicators of the basic heat and mass exchange equipment and the improved one. During the research, the practical and calculated change was determined: specific metal capacity, heating heat of the devices, total, specific heat, and energy costs for production cycles. The economic assessment was carried out by comparing the data when changing the estimated cost of metal structures and current energy costs for the production cycle with further scaling of the indicators for the annual production cycle. The estimated cost assessment of the production cycle was carried out using the cost approach, taking into account the cost of the resource components in the production cycle being implemented [23]. The conversion of the estimated cost indicators into US dollars was carried out in accordance with the official exchange rate by NBU as of September 04, 2026 – 44.7273 UAH/USD.

5. Results of designing, digital modeling, and assessing resource efficiency of the technological line

5. 1. Construction of a technological scheme for the comprehensive processing of plant raw materials

During experimental and practical research, a technological scheme for the comprehensive processing of plant

raw materials was devised using the example of pumpkin, apple, and Jerusalem artichoke with the determination of the sequence of technological operations and operating parameters (Fig. 1). After acceptance, plant raw materials are sent for inspection and washing. Pumpkin preparation includes removal of the fruit stalk, seed chamber with subsequent separation of seeds, apple – removal of the fruit stalk, seed chamber and, if there are damaged parts of the fruit. For Jerusalem artichoke, non-technological surface parts are removed after washing the raw materials. The cleaned and suitable for the technological cycle vegetable raw materials are crushed before the implementation of thermal pre-treatment, taking into account the natural structural and mechanical properties.

Pumpkin was crushed to a particle size of 10...15 mm, apple – 8...12 mm, and Jerusalem artichoke – 5...8 mm. To soften the structure of plant raw materials before rubbing, thermal pre-treatment is provided by the line in the thermal pre-treatment apparatus with direct integration of FREhRT into the heat exchange surface of the working chamber and the contour of the moving device. Thermal pre-treatment in gentle temperature ranges: pumpkin and Jerusalem artichoke were treated at a temperature of 50...55°C for 240...300 min^{-1}, and apple in the range of 45...50°C for 180...240 min^{-1}. After thermal pre-treatment, the plant mass is sent to a two-stage rubbing, contributing to preliminary rubbing, and softening of the structure at the first stage and final rubbing at the second stage to achieve homogeneity of the puree mass. The diameter of the holes of the wiping sieves was selected taking into account the structural and mechanical properties of the raw material. For grinding pumpkin, sieves with a hole diameter in the range of 0.5...0.6 mm were used, for apples – 0.3...0.5 mm, and for Jerusalem artichoke – 0.2...0.4 mm. After two-stage grinding, a homogeneous puree-like flow and a solid secondary fraction are obtained, suitable for technological processing into semi-finished products of a high degree of readiness.

From each scrubbing machine, puree flows are fed to blending in accordance with previously adopted recipe ratios of functional matrices based on pumpkin:apple:artichoke (50:30:20; 30:50:20; and 30:20:50) to form a multifunctional blended mass. The resulting homogeneous mass is fed by a gear pump to a vertical rotary film apparatus with local heat supply by a film heater. Vacuum concentration at a mass flow rate of the blended puree mass is implemented at an absolute pressure in the range of 12...15 kPa and a working medium temperature within 63...68°C. The rotor rotation frequency is 180...200 min^{-1}. A modernized mixer with an additional working circuit is fixed to the rotor by hinges, which is heated to stabilize the temperature difference of the film flow with a layer thickness of 0.25...0.50 mm after cutting. Concentration in the rotary-film apparatus was carried out in accordance with technological needs to rational levels of dry matter (DM) content to expand the spectrum of practical use of concentrated semi-finished products of a high degree of readiness in the formulations of special-purpose food products. A pasty blend-

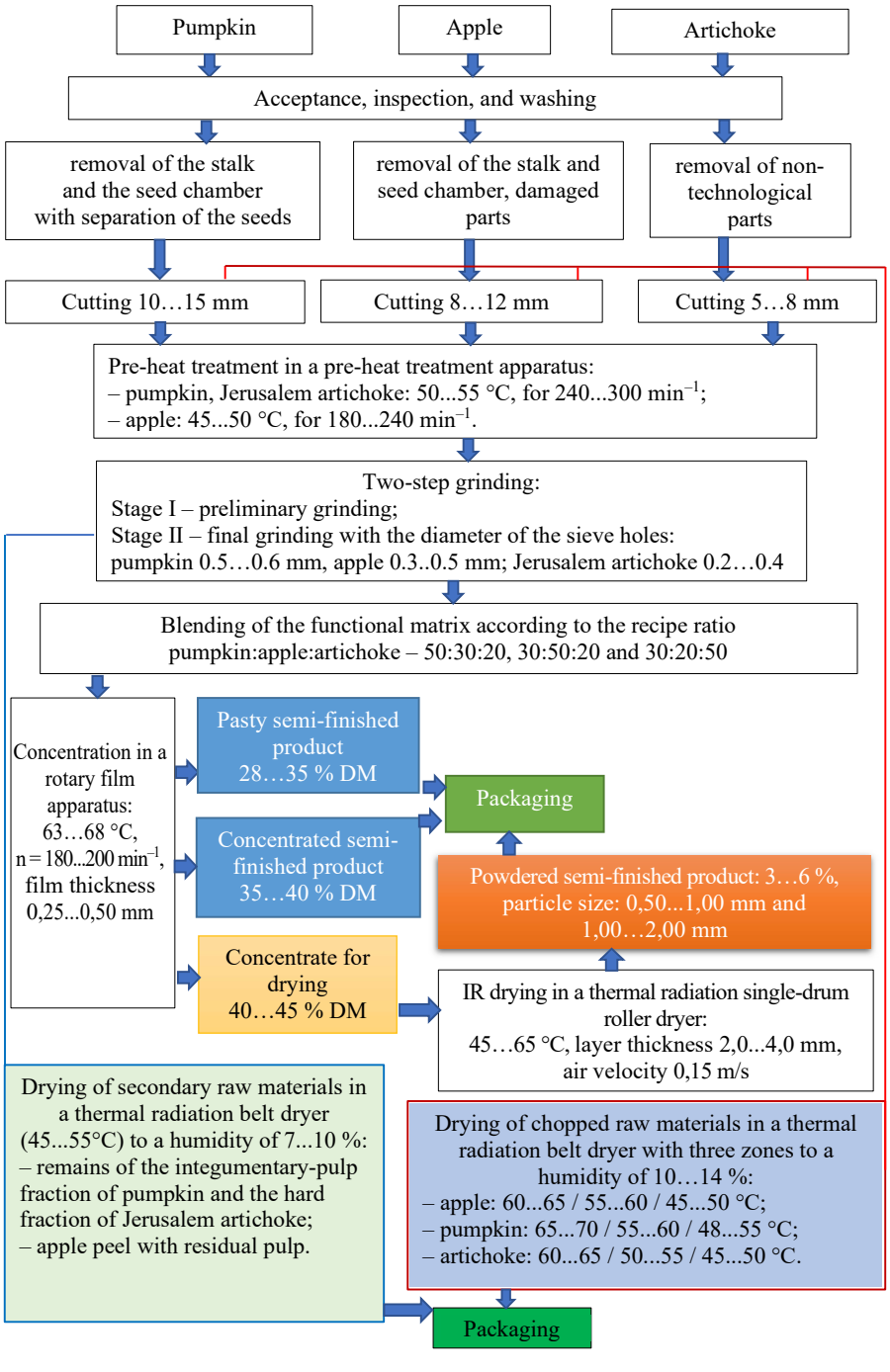


Fig. 1. Technological scheme of comprehensive processing of plant raw materials

ed semi-finished product with a content of 28...35% DM was obtained, a concentrated semi-finished product with a content of 35...40% DM was obtained with subsequent packaging in a sealed container. The concentrate with a content of 40...45% DM was sent for further IR drying in a thermal radiation single-drum roller dryer to obtain powder fractions. IR drying was carried out at a temperature of 45...65°C with a layer thickness of the pre-concentrated mass within 2...4 mm and an air flow velocity in the working chamber of 0.15 m/s. After IR drying, the layer from the working surface is cut with knives and fed to a grinding mechanism to obtain powdery fractions with a size of 0.50...1.00 mm and 1.00...2.00 mm with a final humidity of 3...6% with subsequent packaging.

To obtain dried semi-finished products, the designed technological line provides for the formation of a separate technological flow for processing plant raw materials without going through the technological stages of thermal pre-treatment, grinding, and concentration. After inspection and washing, apples are cut into 4...12 mm thick slices, Jerusalem artichoke – 4...8 mm, and pumpkin – 4...8 mm. After cutting, the raw materials were dried in a thermoradiation belt dryer with adjustable temperature zones. For apples, the temperature regimes selected for the first zone were 60...65°C, for the second – 55...60°C, and for the third zone – 45...50°C, pumpkin was processed at the temperature of the first zone – 65...70°C, for the second – 55...60°C, and for the third – 48...55°C. For Jerusalem artichoke, the temperature was 60...65°C in the first zone, 50...55°C in the second and 45...50°C for the third. The final humidity of the dried fractions after the technological cycle was 10...14% with subsequent packaging in light-tight sealed containers. The technological line provides for the processing of secondary raw materials separated after grinding: for pumpkin – the remains of the skin-pulp fraction, for apples – the peel with the remaining pulp after removing the unsuitable parts, for Jerusalem artichoke – the remains of the solid fraction after grinding. IR drying of the secondary fraction of plant raw materials is carried out in a thermal radiation belt dryer at a temperature of 45...55°C to the final humidity of the resulting semi-finished product within 7...10% with subsequent packaging. The practical implementation of the designed technological line makes it possible to form interconnected technological flows for the production of concentrated semi-finished products with a regulated content of dry substances, dried, and powdered semi-finished products using secondary raw materials in the technological cycle. According to the material balance per 100 kg of prepared raw materials, the yield of pasty semi-finished products is in the range of 33.71...79.29 kg. Concentrated semi-finished products before IR drying – 26.22...55.50 kg and 13.11...25.81 kg of dried fractions and 12.16...23.62 kg of powdered semi-finished products. For further experimental and practical testing of the technological line, a functional matrix with a recipe ratio of 30% pumpkin, 20% apples, and 50% Jerusalem artichoke with an initial dry substance content of 17.04% was selected.

5. 2. Construction of a physically-oriented model of a digital twin for the designed technological line for comprehensive processing of plant raw materials

Preliminarily obtained experimental and practical data allowed us to recreate the designed technological line for comprehensive processing of plant raw materials into semi-finished products of a high degree of readiness in the form of a physically-oriented model of a digital twin, implemented in the Node-RED environment (Great Britain). The digital model reproduces the technological route of processing plant raw materials taking into account changes in the operating parameters of basic heat and mass exchange equipment during the production cycle. The generalized structure of the constructed physically-oriented model of a digital twin for a comprehensive technological line is shown in Fig. 2.

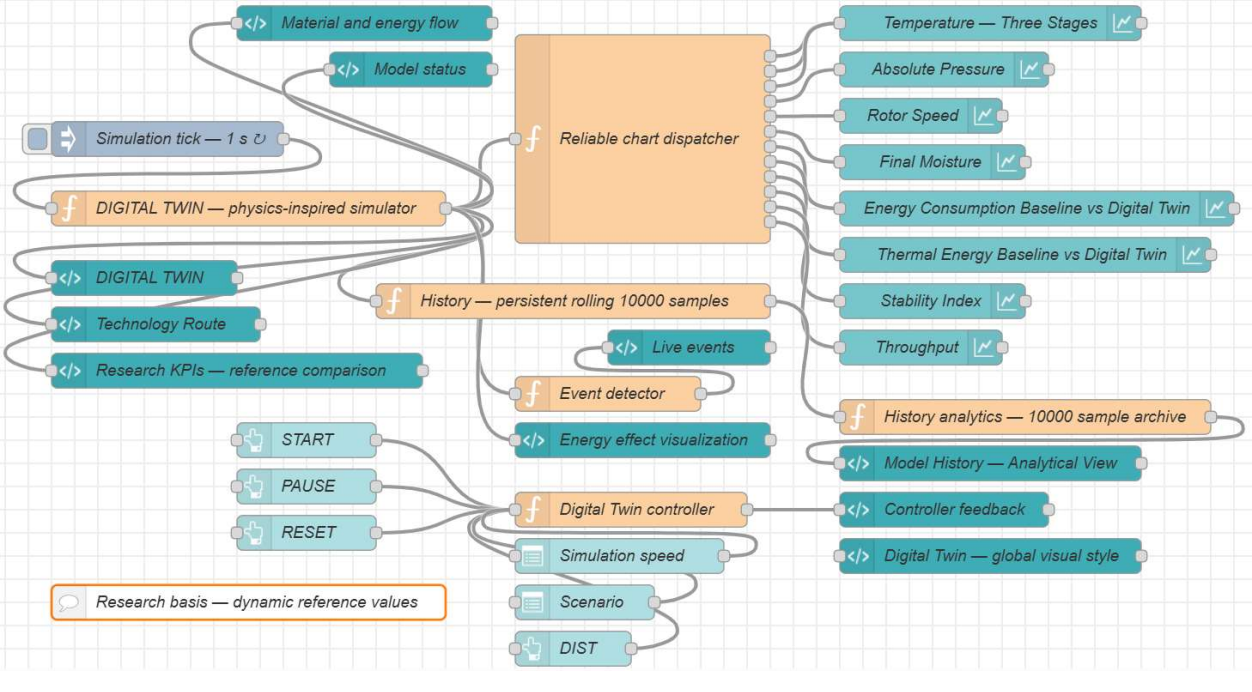


Fig. 2. Software structure of a physically-oriented model of a digital twin for a comprehensive technological line in the Node-RED environment

The above digital twin reflects the experimental and practical testing of a functional blended plant matrix based on 30% pumpkin, 20% apple, and 50% Jerusalem artichoke and at an initial content of 17.04% DM. At a testing calculated productivity of the technological line of 100 kg/h, the digital model provides a reproduction of the passage of raw materials of thermal pre-treatment and blended homogeneous mass through the main heat and mass exchange processes: rotary film concentration and roller IR drying. According to the material balance, when processing 100 kg of the experimental functional blended matrix after rotary film concentration to a content of 45% DM, the yield of the concentrated semi-finished product is 37.87 kg. And with further IR drying to a final moisture content of 6%, the yield of the powdered fractional semi-finished product is 18.13 kg. Based on the technological and design parameters, a digital twin was built, which provides end-to-end reproduction of the material flow of plant raw materials in accordance with the technological cycle of comprehensive processing. The resulting structural implementation of the digital twin combines in a single information environment the technological parameters of auxiliary and main heat and mass exchange operations, material and energy indicators, taking into account the time-controlled parameters and the state of the production cycle. The structural scheme of the digital twin provides for the use of the Controller feedback block for feedback within the digital environment and simulation of the reproduction of the system's reaction to various changes in controlled technological parameters. For the variable reproduction of the technological process of comprehensive processing of plant raw materials, three operating scenarios are provided: Normal Mode, Energy-Saving Mode, and High Load. The scenarios provide research on changes in technological parameters depending on the operating modes of the designed line. The interface of the digital twin with a display of the current state of the technological line is shown in Fig. 3.



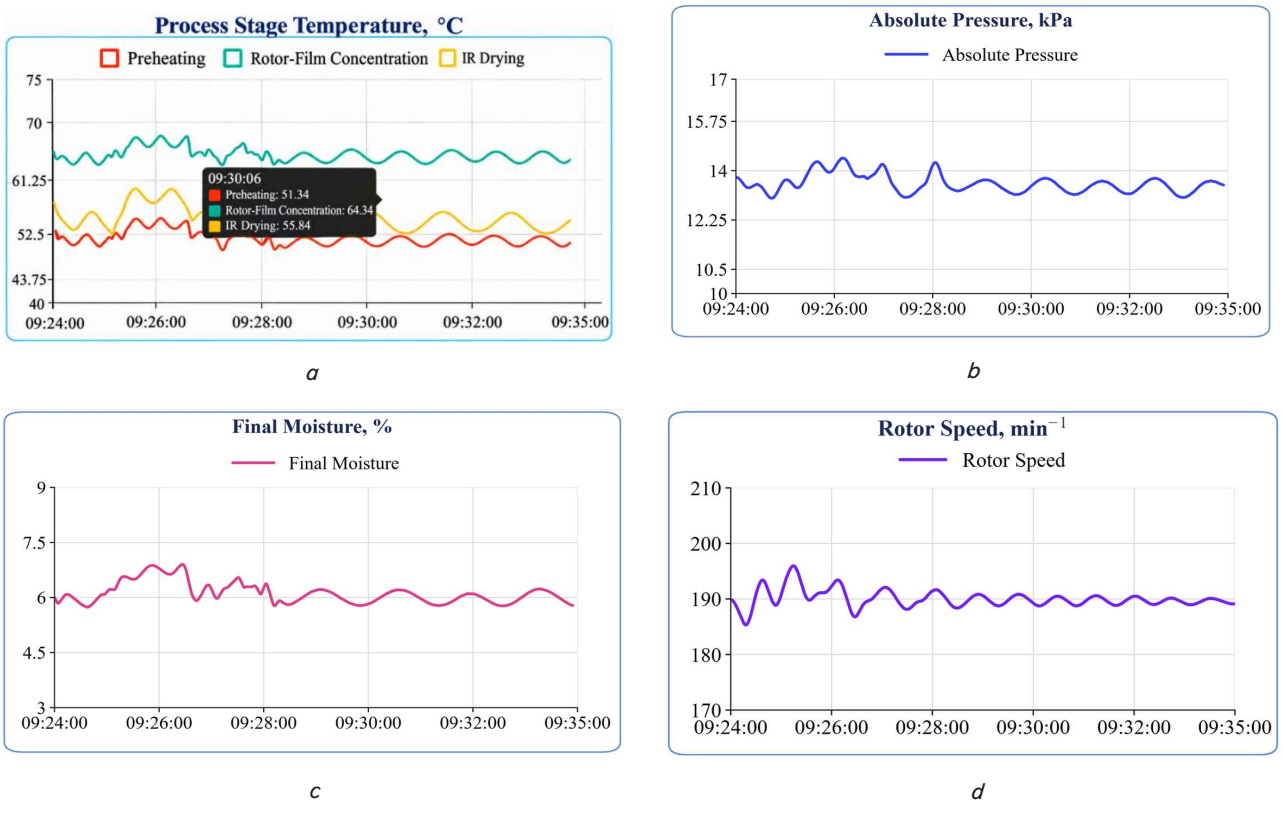
Fig. 3. Model representation of the technological route for processing a functional plant matrix and the yield of a powdered semi-finished product

The interface values of the technological route of processing the functional plant matrix are the current model testing parameters of the technological cycle with a dynamic change within the pre-established rational operating ranges relative to the reference values of the Normal Mode scenario. According to the Normal Mode scenario, the pre-established parameters of the formed digital model correspond to the rational modes of comprehensive processing of the experimental functional plant matrix. For the preliminary stage of heat treatment of plant raw materials, the operating processing temperature was adopted at 52.5°C, which corresponds to the proposed temperature range within 50...55°C of the thermal treatment of pumpkin and Jerusalem artichoke. For the rotor-film concentration of the blended mass, the model temperature value corresponded to 65°C (absolute pressure 13.5 kPa) and the rotor rotation frequency was 190 min^{-1}. The adopted technological parameters are within the rational ranges of processing thermolabile raw materials: temperature – 63...68°C, absolute pressure – 12...15 kPa, and rotor rotation frequency 180...200 min^{-1}. For the final stage of obtaining a powdered semi-finished product with a final humidity of 6% in a roller IR dryer, the working surface temperature was maintained at 55°C with a rational technological range of 45...65°C.

Reproducing the technological cycle with a digital twin makes it possible to track changes in the amount of blended mass during the sequential passage of the main heat and mass transfer operations. Production time series of temperatures for thermal pre-treatment, rotary film concentration with a rotor rotation frequency (absolute pressure) and roller IR drying, and the final humidity of the powdered semi-finished product are shown in Fig. 4.

When testing the intake of 100.00 kg of the experimental functional plant matrix to the rotary film concentration with an initial content of 17.04% DM, the yield of the concentrate with a content of 45% DM was 37.87 kg; therefore, the amount of evaporated water was 62.13 kg. The technological implementation of drying the pre-concentrated semi-finished product in the IR field to a final humidity of 6% makes it possible to obtain 18.13 kg of powdered semi-finished product, with technological removal of 19.74 kg of water. The values of material flows obtained in the digital model correspond to the previously adopted material balance of the technological line for comprehensive processing of plant raw materials in accordance with the interconnected control parameters of its functioning. Time reproduction of the production technological cycle of processing of plant raw materials contributes to the simultaneous tracking of possible changes in the temperature of the thermal pre-treatment, the temperature (absolute pressure) during rotary film concentration, and the rotor rotation frequency. Based on the selected rational operating parameters, the digital model produced energy, thermal, and economic performance indicators (KPIs) for the production cycle when processing 100 kg of the functional matrix 30:20:50 (Fig. 5).

Setting the Normal Mode scenario in the digital model allows the model values of the main technological parameters to be formed within the specified rational ranges of heat and mass exchange processing, thereby providing a visual reproduction of the stable mode of operation of the technological line. At the same time, the digital model provides for the registration of short-term deviations in pre-selected controlled parameters from the set technological limits, contributing to the further return of the digital system to the specified operating technological mode. For the quantitative assessment of the technological line for the comprehensive processing of plant raw materials, the digital twin additionally displays the productivity, energy indicators, and the current physical state of basic technological heat and mass exchange operations.



a *b*

c *d*

Fig. 4. Time series obtained in the digital twin: temperatures at the technological stages of heat and mass transfer processing, absolute pressure, final humidity, and rotor speed: *a* — Process Stage Temperature, °C; *b* — Absolute Pressure, kPa; *c* — Final Moisture, %; *d* — Rotor Speed, min^{-1}

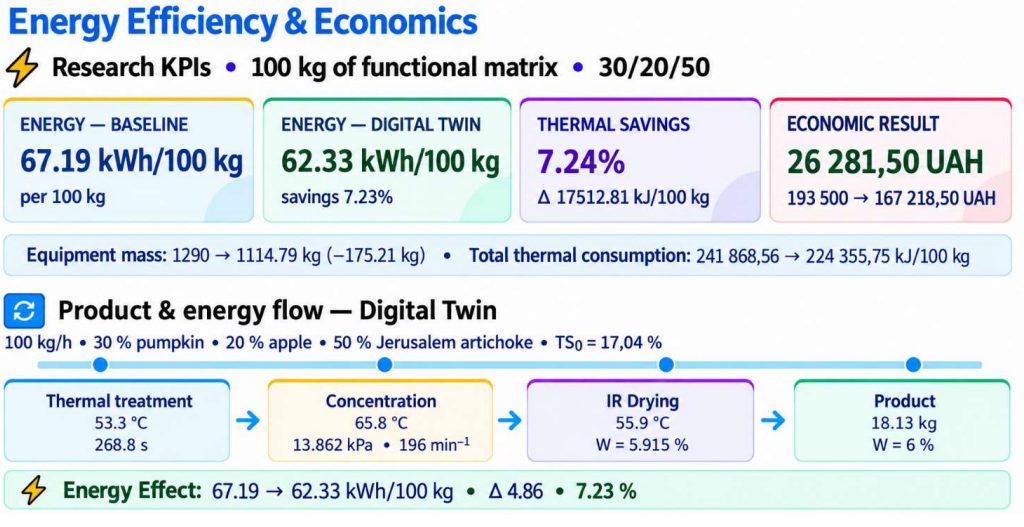
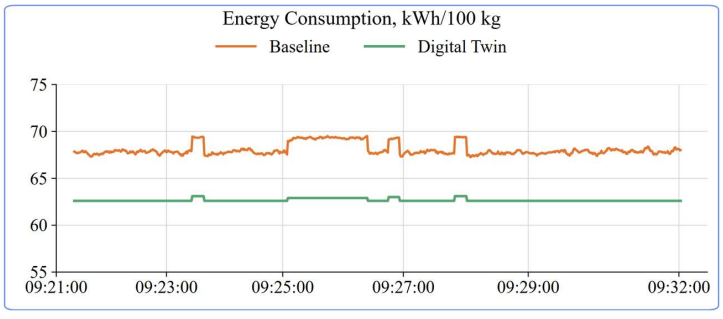
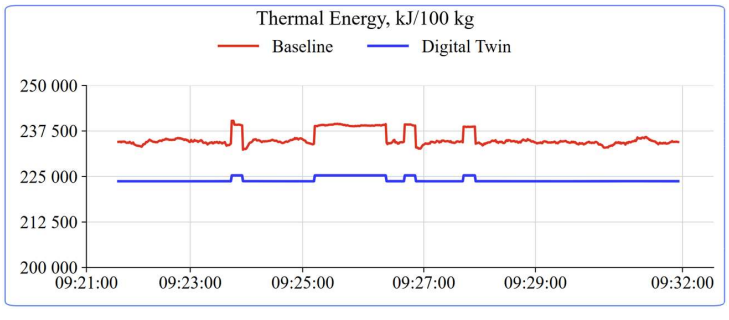


Fig. 5. Current energy, thermal, and economic indicators of the digital model for 100 kg of functional matrix 30:20:50

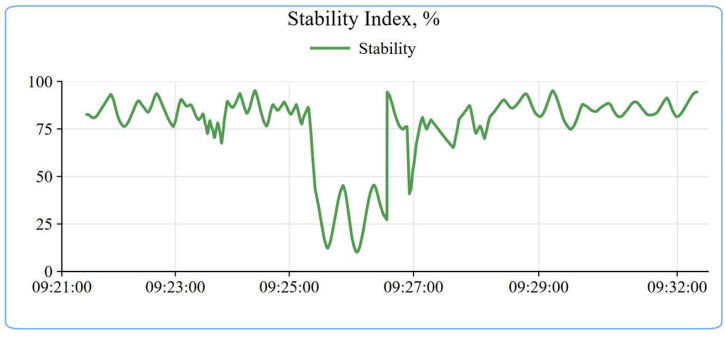
At a calculated productivity of the technological line of 100 kg/h, the reference total energy consumption of basic heat and mass exchange equipment of the basic variant is 67.19 kWh/100 kg of experimental functional plant matrix. While for the improved device with integrated FREhRT in the heat exchange surface and the working circuit of the moving device, 62.33 kWh/100 kg. At the same time, the calculated reduction in energy consumption is 4.86 kWh/100 kg, or 7.23%, and the total heat consumption is reduced from 241868.56 kJ/100 kg to 224355.75 kJ/100 kg of the experimental matrix, which corresponds to a decrease of 7.24%. These calculated values are used in the digital twin as control reference values when comparing with the current model energy parameters of the production cycle. The current model values of energy indicators change over time in accordance with changes in the state of the controlled technological parameters and the selected technological cycle. Therefore, the obtained instantaneous model values of energy consumption and energy effect may differ slightly from the accepted reference values, which in turn contributes to the use of calculated values as control points. The obtained current model values contribute to the reflection of the dynamics of the energy state of the technological line, in particular, the reflection of material, technological, and energy KPIs for the constructed digital twin, shown in Fig. 6.



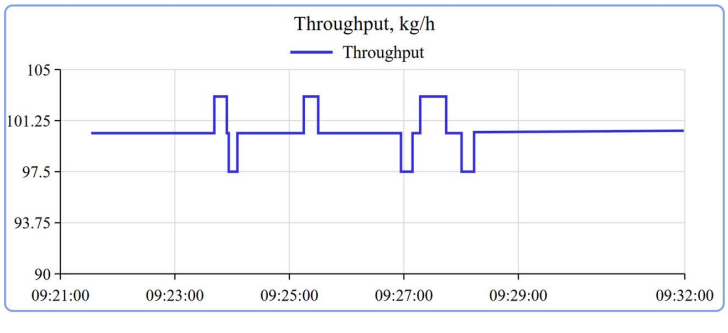
a



b



c



d



e

Fig. 6. Dynamics of model energy consumption, heat consumption, stability index, and productivity obtained from the digital twin of the technological line: *a* – Energy Consumption, kWh/100 kg; *b* – Thermal Energy, kJ/100 kg; *c* – Stability Index, %; *d* – Throughput, kg/h; *e* – Energy effect / Digital Twin

For practical assessment of the reaction of the digital twin to probable changes in the conditions of the production cycle, a model reproduction of a controlled disturbance was carried out using the example of one of the technological parameters. After artificial introduction of a disturbance to one of the technological parameters, a predicted deviation in the controlled parameter from the set operating value occurs with a subsequent change in the current state of the technological operation. After the end of the influence of the artificially simulated disturbance, the technological parameter returned to the set operating range of the production cycle and, therefore, was accompanied by the restoration of the standard state of the working production cycle. An illustrative example of the reaction of the digital model to a controlled artificial disturbance and the subsequent restoration of the production cycle mode is shown in Fig. 7.

The resulting structure of the digital twin also provides registration of changes in various states of the technological process and accumulation of production time series of the main operating parameters. During the functioning of the digital model, the current values of temperature (absolute pressure), rotor speed, final moisture content of plant masses, production productivity, and energy indicators are recorded, facilitating further comparison of the established technological limits with the actual model values of operating parameters under the condition of simultaneous detection of the moments of occurrence of any technological deviations.

The constructed physically-oriented model of the digital twin of the technological line of comprehensive processing of plant raw materials implements the interconnected reproduction of the material flow, operating and energy parameters of the production cycle. For the experimental functional plant matrix based on 30% pumpkin, 20% apple, and 50% Jerusalem artichoke and a productivity of 100 kg/h, the digital model reproduces the production of 45% DM of concentrated semi-finished product – 37.87 kg. As well as 18.13 kg of powdered semi-finished product with a final moisture content of 6%. The operating parameters of the main heat and mass exchange operations are controlled and implemented within practical limits of rational ranges, and the use of reference indicators makes it possible to visualize the reduction in the estimated energy consumption of basic heat and mass exchange equipment of the experimental functional matrix.

5. 3. Practical assessment of the structural, thermal, and economic efficiency of the designed technological line

For a comprehensive comparison of the basic and improved standard heat and mass exchange equipment with integrated FREhRT in the heat exchange surface and the contour of the moving device, a calculation of structural and technological indicators was carried out when processing 100 kg of functional matrix at the following ratio: 30% pumpkin, 20% apple, and 50% Jerusalem artichoke, and the initial dry matter content of 17.04% (Table 1). During the study, for the pre-heat treatment devices, the heat consumption of the functional blended experimental mass of matrices was determined differentially according to the recipe composition of the components. The practical calculation was carried out for a test sample containing 30 kg of pumpkin, 20 kg of apple, and 50 kg of Jerusalem artichoke, and the upper limits of the temperature ranges of heat treatment (55, 50, and 55°C, according to the data in Fig. 1).

Modernization of the basic equipment by integrating FREhRT into the heat exchange surface and the contour of the moving device improves the structural, thermal, and energy performance. Thus, the specific metal content of the pre-heat treatment apparatus decreased by 14.91%, the rotary film apparatus by 28.33%, and the roller IR dryer by 30.97%. The heating heat of the pre-heat treatment apparatus decreased by 86.29%, the rotary film apparatus by 52.82%, and the roller IR dryer by 32.83%. The total heat consumption when using the improved pre-heat treatment apparatus decreased by 41.47%, the rotary film apparatus by 0.69%, and the roller IR dryer by 9.74%. Energy consumption when using the improved pre-heating apparatus decreased by 41.46%, which is 2.79 kW·h, the rotary film apparatus by 0.69% or 0.29 kW·h, the roller IR dryer by 9.74% or 1.78 kW·h.

Thus, the total energy consumption of basic heat and mass exchange equipment per 100 kg of the experimental batch decreased by 7.23% or 4.86 kW·h, the total heat consumption by 7.24% or 17512.81 kJ. Reducing the metal content of the equipment and energy consumption of the improved equipment when using it ensures a reduction in capital and current costs, which are the basic components for assessing the economic effect [24].

Status, Events & Results

◉ Digital Twin Events

Time	Level	Stage	Stability Index, %
09:30:32	NORMAL	Rotor-Film Concentration	80.8%
09:29:36	NORMAL	Preheating	77%
09:28:36	NORMAL	Roller IR Drying	87.59%
09:28:15	NORMAL	Rotor-Film Concentration	79.09%
09:28:10	CRITICAL	Rotor-Film Concentration	65.55%
09:28:01	DISTURBANCE	Rotor-Film Concentration	68.54%
09:27:59	NORMAL	Rotor-Film Concentration	77.33%
09:27:42	NORMAL	Rotor-Film Concentration	77.57%
09:27:30	CRITICAL	Rotor-Film Concentration	68.24%
09:27:29	CRITICAL	Preheating	69.14%
09:27:16	NORMAL	Preheating	76.92%
09:27:09	NORMAL	Preheating	80.83%

Fig. 7. Digital twin model event log with recording of the state of technological stages, stability index, and controlled disturbances

Table 1

Comparative calculations of structural, thermal, and energy performance of basic heat and mass exchange equipment of the technological line when processing 100 kg of functional matrix

Main heat and mass exchange equipment	Indicator	Basic heat and mass exchanger	Improved device with integrated FREhRT in the heat exchange surface and the contour of the moving device	Estimated difference in main engineering and technological indicators
Pre-heat treatment apparatus	Specific metal content, kg/m²	$m_b = 380 / 0.98 = 387.76$	$m_i = 485 / 1.47 = 329.93$	$K_m = (387.76 - 329.93) / 387.76 \times 100 = 14.91\%$
	Heat of heating the device, kJ	$Q_{b.} = 200 \times 0.48 \times (55 - 20) + 138 \times 0.48 \times (145 - 20) = 11{,}640.00$	$Q_{i.} = 95 \times 0.48 \times (55 - 20) = 1{,}596.00$	$K_{Qapp} = (11{,}640 - 1{,}596) / 11{,}640 \times 100 = 86.29\%$
	Heat of heating of experimental blend, kJ	$Q_{prod} = 30 \times 3.7 \times (55 - 20) + 20 \times 3.7 (50 - 20) + 50 \times 3.7 \cdot (55 - 20) = 12{,}580.00$	$Q_{prod} = 30 \times 3.7 \times (55 - 20) + 20 \times 3.7 (50 - 20) + 50 \times 3.7(55 - 20) = 12{,}580.00$	for the experimental blend 30% pumpkin, 20% apples and 50% Jerusalem artichoke – test weight 100 kg
	Total heat consumption, kJ	$Q_{tot} = 11{,}640.00 + 12{,}580.00 = 24{,}220.00$	$Q_{tot} = 1{,}596.00 + 12{,}580.00 = 14{,}176.00$	$K_{Qtot} = (24{,}220.00 - 14{,}176.00) / 24{,}220.00 \times 100 = 41.47\%$
	Specific heat consumption, kJ/kg of test mass	$q_b = 24{,}220.00 / 100 = 242.20$	$q_i = 14{,}176.00 / 100 = 141.76$	$K_q = (242.20 - 141.76) / 242.20 \times 100 = 41.46\%$
	Energy consumption, kWh/100 kg of initial mass	$E_b = 24{,}220.00 / 3{,}600 = 6.73$	$E_i = 14{,}176.00 / 3{,}600 = 3.94$	$K_E = (6.73 - 3.94) / 6.73 \times 100 = 41.46\%$; $\Delta E = 6.73 - 3.94 = 2.79$ kWh
Rotary film machine	Specific metal content, kg/m²	$m_b = 60 / 0.75 = 80.00$	$m_i = 43 / 0.75 = 57.33$	$K_m = (80.00 - 57.33) / 80.00 \times 100 = 28.33\%$
	Concentrate yield at 45% DM, kg	$m_{45\%} = 100 \times 17.04 / 45 = 37.87$	$m_{45\%} = 37.87$	$\Delta m_{45\%} = 0.00$ kg
	Amount of evaporated water, kg	$m_{evap} = 100 - 37.87 = 62.13$	$m_{evap} = 62.13$	$\Delta m_{evap} = 0.00$ kg
	Heat of heating and evaporation of the product, kJ	$Q_{prod} = 100 \times 3.7 \times (65 - 55) + 2{,}350 \times 62.13 = 149{,}713.33$	$Q_{prod} = 149{,}713.33$	$\Delta Q_{prod} = 0.00$ kJ
	Heat of heating the device, kJ	$Q_b = 38 \times 0.48 \times (65 - 25) + 22 \times 0.48 \times (143 - 25) = 1975.68$	$Q_i = 38 \times 0.48 \times (65 - 25) + 5 \times 0.9 \times (70 - 25) = 932.10$	$K_{Qapp.} = (1{,}975.68 - 932.1) / 1{,}975.68 \times \times 100 = 52.82\%$
	Total heat consumption, kJ	$Q_{tot} = 149{,}713.33 + 1{,}975.68 = 151{,}689.01$	$Q_{tot} = 149{,}713.33 + 932.10 = 150{,}645.43$	$K_{Qtot} = (151{,}689.0 - 150{,}645.43) / 151{,}689.01 \times 100 = 0.69\%$
	Specific heat consumption, kJ/kg of initial mass	$q_b = 151{,}689.01 / 100 = 1516.89$	$q_i = 150{,}645.43 / 100 = 1{,}506.45$	$K_q = (1{,}516.89 - 1{,}506.45) / 1{,}516.89 \times 100 = 0.69\%$
	Energy consumption, kWh/100 kg of initial mass	$E_b = 151{,}689.01 / 3{,}600 = 42.14$	$E_i = 150{,}645.43 / 3{,}600 = 41.85$	$K_E = (42.14 - 41.85) / 42.14 \times 100 = 0.69\%$; $\Delta E = 42.14 - 41.85 = 0.29$ kWh
Roller IR dryer to $W = 6\%$	Specific metal content, kg/m²	$m_b = 850 / 1.12 = 758.93$	$m_i = 586.79 / 1.12 = 523.92$	$K_m = (758.93 - 523.92) / 758.93 \cdot 100 = 30.97\%$
	Heat of heating the structure, kJ	$Q_b = 763.12 \times 0.48 \times (65 - 25) + 86.88 \times 0.48 \times (143 - 25) = 19{,}572.88$	$Q_i = 498.46 \times 0.48 \times (65 - 25) + 88.33 \times 0.9 \times (70 - 25) = 13{,}147.65$	$K_{Qapp} = (19{,}572.88 - 13{,}147.65) / 19{,}572.88 \times 100 = 32.83\%$
	Concentrate at the inlet, kg	$m_{45\%} = 37.87$	$m_{45\%} = 37.87$	$\Delta m = 0.00$ kg
	Yield of powdered semi-finished product, kg	$m_{steam} = 17.04 / 0.94 = 18.13$	$m_{steam} = 18.13$	$\Delta m_{steam} = 0.00$ kg
	Amount of water removed, kg	$m_{evap} = 37.8667 - 18.13 = 19.74$	$m_{evap} = 19.74$	$\Delta m_{evap} = 0.00$ kg
	Heat of vaporization of water, kJ	$Q_{prod} = 2350 \times 19.739 = 46386.67$	$Q_{prod} = 46{,}386.67$	$\Delta Q_{prod} = 0.00$ kJ
	Total heat consumption, kJ	$Q_{tot.b} = 46{,}386.67 + 19{,}572.88 = 65{,}959.55$	$Q_{tot.i} = 46{,}386.67 + 13147.65 = 59{,}534.32$	$K_{Qtot} = (65{,}959.55 - 59{,}534.32) / 65{,}959.55 \times 100 = 9.74\%$
	Specific heat consumption per 1 kg of powder, kJ/kg	$q_b = 65{,}959.55 / 18.13 = 3{,}638.14$	$q_i = 59{,}534.32 / 18.13 = 3{,}283.75$	$K_q = (3{,}638.14 - 3{,}283.75) / 3{,}638.14 \times 100 = 9.74\%$
	Energy consumption, kWh/100 kg of initial mass	$Eb_b = 65{,}959.55 / 3{,}600 = 18.32$	$E_i = 59{,}534.32 / 3{,}600 = 16.54$	$K_E = (18.32 - 16.54) / 18.32 \times 100 = 9.74\%$; $\Delta E = 18.32 - 16.54 = 1.78$ kWh
Total energy consumption of the main heat and mass exchange equipment, kWh/100 kg of experimental batch		$E_{\Sigma.b} = 6.73 + 42.14 + 18.32 = 67.19$	$E_{\Sigma.i} = 3.94 + 41.85 + 16.54 = 62.33$	$\Delta E_\Sigma = 67.19 - 62.33 = 4.86$ kWh/100 kg; $\Delta E_\Sigma = (4.86 / 67.19) \times 100 = 7.23\%$
Total heat consumption, kJ/100 kg of experimental batch		$Q_{\Sigma b} = 24{,}220.00 + 151{,}689.01 + 65{,}959.55 = 241{,}868.56$	$Q_{\Sigma i} = 14{,}176.00 + 150{,}645.43 + 59{,}534.32 = 224{,}355.75$	$\Delta Q_\Sigma = 241{,}868.56 - 224{,}355.75 = 17512.81$ kJ; $\Delta Q_\Sigma = 17{,}512.81 / 241{,}868.56$ kJ $= 7.24\%$

The change in capital costs of the improved main heat and mass exchange equipment occurs due to a change in the mass of metal structures. The calculation was performed using the cost of stainless steel C_{met} = 150.00 UAH/kg, namely:

– pre-heat treatment apparatus: the total mass of the improved structure increased from 380.00 kg to 485.00 kg due to the integration of additional elements, which led to an increase in the cost of metal by 27.6% or UAH 15,750.00 (USD 352.13) (from UAH 57,000.00 (USD 1,274.39) to UAH 72,750.00 (USD 1,626.52);

– rotary film apparatus: the total mass of the improved structure decreased from 60.00 kg to 43.00 kg, which led to a decrease in the cost of metal by 28.33%, or UAH 2,550.00 (USD 57.01), from UAH 9,000.00 (USD 201.22) to UAH 6,450.00 (USD 144.21);

– roller IR dryer: the total mass of the improved structure decreased from 850.00 kg to 586.79 kg, which led to a decrease in the cost of metal by 30.97% or UAH 39,481.50 (USD 882.72), from UAH 127,500.00 (USD 2,850.61) to UAH 88,018.50 (USD 1,967.89).

The total cost of the complex of improved basic heat and mass exchange equipment decreased by UAH 26,281.50 or 13.59% (from UAH 193,500.00 (USD 4,326.22) to UAH 167,218.50 (USD 3,738.59)). Integration of FREhRT into the heat exchange surface and the contour of the moving device in the improved equipment ensures a reduction in energy consumption, which contributes to a decrease in the current costs of the enterprise. The calculation of energy consumption savings was performed when processing 100 kg of functional matrix, in particular, the estimated production cycle with parallel operation of the equipment is 60.0 min/100 kg. The duration of individual technological operations: thermal pre-treatment – 4.0...5.0 min; rotary film concentration – 60.0 min; roller IR drying to W = 6% – 15.1...26.4 min, duration of one batch during sequential operation of the equipment – 79.1...91.4 min.

During the comparative economic assessment, the average estimated cost of electricity including VAT was adopted for the processing of 100 kg of functional pre-sand mass. For consumers of the 2nd class, in accordance with the conditions of energy supply of the testing complex at the State Biotechnological University at the level of C = 9.00 UAH/kWh as of 2026. The adopted value contributed to the comparison of operating energy costs of basic and improved equipment during further calculation of savings from reducing energy costs of the production cycle:

– pre-heat treatment apparatus: when using an improved apparatus, the reduction in heat consumption is 41.47% or 10044.00 kJ/100 kg, reduction in energy consumption – 2.79 kWh/100 kg, cost savings per batch – 25.11 UAH/batch;

– rotary film apparatus: when using an improved apparatus, the reduction in heat consumption is 0.69% or 1043.58 kJ/100 kg, reduction in energy consumption – 0.29 kWh/100 kg, cost savings per batch – 2.61 UAH/batch;

– roller IR dryer: when using an improved device, the reduction in heat consumption is 9.74% or 6425.23 kJ/100 kg, the reduction in energy consumption is 1.78 kWh/100 kg, the cost savings per batch are 16.02 UAH/batch.

Thus, the total savings in current energy costs when processing one functional matrix weighing 100 kg in the improved equipment is: 4.86 kWh/100 kg 9.00 UAH / kWh = 43.74 UAH/batch. To assess the economic effect of the introduction of the equipment, the calculated indicators were scaled to the annual production cycle. Based on the duration of the work shift of 8 hours and 247 working days in 2026, the estimated production cycle is 60.0 minutes when processing 100 kg of functional matrix. While at full load of the line, the maximum number of processed batches is 8 batches per shift, or 1976 batches per year. A visual representation of the economic effect of implementing improved equipment (Fig. 8) reflects one-time savings in capital costs, changes in accumulated savings in current costs, and the total economic effect depending on the number of batches processed (in the range from 1 to 1976).

The total economic effect is formed as the sum of one-time savings in capital costs (UAH 26281.50) and accumulated savings in current costs, which increases linearly with an increase in the number of processed batches (by UAH 43.74 for every 100 kg of functional matrix). In the case of full loading of the equipment during the annual production cycle (1976 batches), the total economic effect of UAH 112711.74 indicates the economic efficiency of implementing the improved technological line.

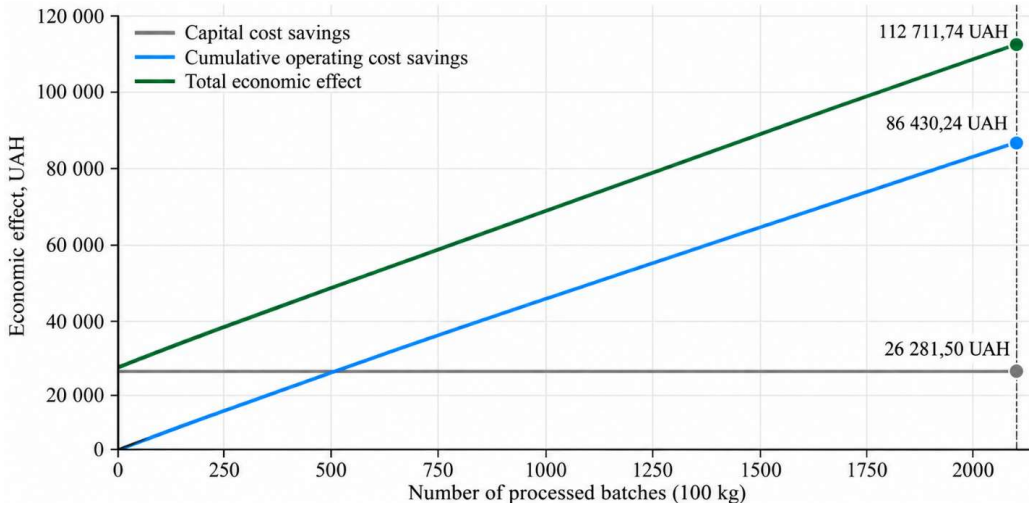


Fig. 8. Economic effect of implementing improved equipment over an annual production cycle

6. Discussion of results based on designing, digital modeling, and assessment of resource efficiency of the technological line

The concept of the designed line is aimed at the experimental and practical implementation of complex thermal pre-treatment, two-stage grinding, blending to a homogeneous functional matrix, rotary film concentration, and IR drying with simultaneous drying of chopped and secondary plant raw materials (Fig. 1). The proposed engineering approach complements the practical results highlighted in [4–6] regarding the justified and rational use of secondary raw materials; however, the complexity of the combined integration of individual operations into a single technological cycle is noted. The practical implementation of the designed line makes it possible to partially solve the problem through the complex formation of clearly distributed material flows of functional matrices with a certain output of semi-finished products of a high degree of readiness for each technological sub-direction. A rational determination of heat and mass transfer treatment modes for the production of pasty semi-finished products (28...35% DM), concentrated semi-finished product with a content of 45% DM intended for further drying, and powdered semi-finished products at a final humidity of 3...6%. In addition, the line provides for parallel production of dried fractions (final humidity 10...14%) and dried fractions from secondary raw materials (final humidity 7...10%). With basic practical processing of 100 kg of plant raw materials into a blended functional matrix (30% pumpkin, 20% apple, and 50% Jerusalem artichoke), 37.87 kg of concentrated semi-finished product (45% DM) is obtained. And 18.13 kg of powdered semi-finished product with a final humidity of 6%. This confirms the practical feasibility of combining technological approaches aimed at the integrated use of raw materials and, therefore, is a characteristic difference from studies [4–6] aimed at the processing of a certain type of secondary raw materials.

The proposed design approach to the formation of resource efficiency of the designed line is confirmed by the comparative data in Table 1, which is explained by the integration of FREhRT into the heat exchange surfaces and contours of the moving devices. This contributes to a decrease in the specific metal capacity of the main heat and mass exchange devices: the pre-heat treatment device by 14.91%, the rotary film device by 28.33%, and the roller IR dryer by 30.97%. At the same time, the heat of heating the devices is reduced by 86.29%, 52.82%, and 32.83%, respectively. This is explained by the elimination of intermediate heating systems in the basic designs during their improvement and develops the provisions [8–12] regarding the efficiency of direct electric IR heat supply with their simultaneous addition by a design and technological assessment of prospects. In [13], the negative impact of additional thermal resistances of the basic heat exchange surfaces on the productivity and resource efficiency of the evaporation production cycle is noted, while in [14] the reduction of energy consumption is achieved by introducing additional membrane preparation. Along with this, the designed line is characterized by the use of basic heat and mass exchange equipment with an electric heat supply system integrated into the housing and mixing devices without any additional operational design and technological stages. This ensures a reduction in the specific metal capacity of the rotary film apparatus by 28.33% when forming a low-temperature concentration regime for thermolabile raw materials (63...68°C) and a rotor rotation frequency of 180...200 min^{-1}.

The constructed physically oriented DT provides the reproduction of the material flow, operating parameters, and energy indicators of the comprehensive production cycle (Fig. 2–4), while in the previous study [19] it is focused on the calendar planning of production. The resulting model allowed us to link the material balance with the temperature, absolute pressure, rotor speed, final humidity of the functional matrices, as well as the energy and structural and technological parameters of the heat and mass exchange equipment. This approach corresponds to the promising direction given in [18, 21] regarding the integration of physical models of production cycles with selected technological modes into a single digital technological process. Reproduction of the DT of a number of main technological indicators in the energy, thermal, and technological KPIs (Fig. 5, 6) and forecasting of probable reactions to controlled disturbances (Fig. 7). This contributes to the practical assessment of the current state of the designed technological line and the stability of production modes to possible predicted and abnormal changes in certain mode parameters of the production cycle. A similar solution was considered in [20] when using DT to optimize the thermal process by reducing steam consumption. The difference of our results is the integrated approach of DT to reproduce not individual heat and mass exchange operations but a sequential production cycle using thermal pre-treatment, rotary film concentration, and IR drying. The reduction of total energy consumption by 7.23% and heat consumption by 7.24% was taken as a quantitative basis for further assessment of the resource efficiency of the digital scenario.

The practical structural and technological effect of the implementation of the designed line is confirmed by the economic component in the sector of reducing the estimated cost of metal structures of advanced heat and mass exchange equipment – UAH 26,281.50. At the same time, the savings in current energy costs are UAH 43.74 per 100 kg of functional matrix. With the assumed annual load of 1976 batches, the total estimated effect during the first year could equal UAH 112,711.74 (Fig. 8). Our approach makes it possible to partially resolve the issue indicated in work [4] regarding the insufficient economic feasibility of integrating certain resource-saving approaches into a single production cycle. Our results confirm the possibility of forming a comprehensive approach to the implementation of a technological line for the processing of plant raw materials and secondary waste. With the simultaneous use of advanced basic heat and mass exchange equipment for pre-heat treatment, concentration and drying with an integrated electrical heat supply system, and digital reproduction of material and operating production parameters.

Among the limitations of our comprehensive study, one should note the practical testing of the experimental line on three types of plant raw materials and the use of a digital scenario for the 30:20:50 functional matrix. Comparison of design and technological indicators and economic evaluation were performed for a previously adopted production cycle productivity of 100 kg/h. The disadvantage of the study is the lack of long-term industrial verification of the physically oriented digital twin at changes in the productivity of the designed line. The practical elimination of this drawback requires the accumulation of operational data on the production cycle for clarification of model dependences of predicted and actual parameters of the regime. Further experimental

and practical studies could aim at expanding the industrial verification of DT at variable capacities of the production cycle and expanding the type of plant raw materials being processed.

7. Conclusions

1. A technological scheme for the comprehensive processing of plant raw materials has been developed as a result of experimental and practical tests using the example of pumpkin, apple, and Jerusalem artichoke for the production of concentrated, dried, and powdered semi-finished products with a high degree of readiness. The technological line provides a set of technological operations for the resource-saving implementation of thermal pre-treatments, two-stage grinding, blending, rotary-film concentration, and IR-drying with simultaneous processing of secondary raw materials into a dried fraction. Rotary-film concentration ensures the production of blended semi-finished products at a range of 28...45% DM. At the same time, the possibility of IR-drying of the pre-concentrated mass to powdered semi-finished products with a final humidity of 3...6%, drying of chopped raw materials to 10...14% final humidity, and secondary fractions to a final humidity of 7...10%. According to the material balance, from 100 kg of prepared thermolabile raw materials, the yield of pasty semi-finished products is within 33.71 kg...79.29 kg, concentrated semi-finished products with 45% DM before IR drying – 26.22 kg...55.50 kg. Dried fractions are within 13.11 kg...25.81 kg and powdered semi-finished products from 12.16 kg to 23.62 kg.

2. A physically oriented digital twin of the designed technological line was built to reproduce the complex interaction between material flows, regime, and structural-technological parameters of basic thermal equipment. The basic scenario simulated the technological process of processing 100 kg of functional plant matrix at an initial content of 17.04% DM while reproducing the main heat and mass transfer operations: thermal pre-treatment, rotary film concentration, and IR drying. The transition of the material flow from 100 kg of the initial matrix to a concentrated semi-finished product with a content of 45% DM in the volume of 37.87 kg and 18.13 kg of a powdered semi-finished product with a final humidity of 6% was described. The duration of the thermal pre-treatment was determined by digital reproduction within 4.0 min...5.0 min, rotary film concentration was 60 min, and IR drying was 15.1 min...26.4 min. The total duration of sequential passage of one experimental batch of plant raw materials is 79.1...91.4 min.

3. Based on the results of our calculations, it was found that the estimated cost of metal structures of the set of improved basic heat and mass exchange equipment is reduced by 13.59% or UAH 26281.50. At the same time, the savings in current energy costs when processing 100 kg of functional matrix is UAH 43.74. Under the condition of full loading of the technological line during the annual production cycle (1976 batches in 247 working days), the total economic effect of the implementation of the improved technological line is UAH 112711.74. Our results indicate that the integration of FREhRT into the heat exchange surface and the contour of the moving device ensures increased resource efficiency of the basic heat and mass exchange equipment of the technological line. In particular, the specific metal content of the improved devices has been reduced: the pre-heating device by 14.91%, the rotary film device by 28.33%, and the roller IR dryer by 30.97%. In addition, the heat of heating the specified structures by 86.29%, 52.82%, and 32.83%, respectively. At the same time, the total energy consumption of basic heat and mass exchange equipment is reduced by 7.23%, and the total heat consumption by 7.24%.

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 and 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 declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript under the full control of the authors.

Artificial intelligence was not used to create, process or interpret scientific data, draw conclusions, or other elements of scientific results.

Tool used: ChatGPT (OpenAI GPT-5, version 2025).

The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

Author contributions

Andrii Zahorulko: Conceptualization, Project administration; **Tetiana Savchenko**: Software; **Iryna Voronenko**: Visualization, Investigation; **Mariana Sashnova**: Investigation, Data Curation; **Klymenko Nataliia**: Methodology; **Oleksandr Voronenko**: Investigation; **Artem Onyshchenko**: Visualization; **Alla Solomon**: Formal analysis; **Galuzina Liudmyla**: Formal analysis; **Ruslan Zakharchenko**: Data Curation.

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