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IMPROVING A TECHNIQUE FOR PRODUCING A POLYCOMPONENT SEMI-FINISHED PRODUCT WITH HIGH DEGREE OF READINESS FOR 3-D PRINTING OF FUNCTIONAL FOOD

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The object of this study is the process of producing polycomponent semi-finished products of a high degree of readiness using a model structure of functional equipment, in particular, based on apple, Jerusalem artichoke, table beet, and sea buckthorn.

A feature of the improved technique is the implementation of preliminary heat treatment with hot steam of raw materials: apple – 1.0...2.0 min, Jerusalem artichoke – 3...6 min, and table beet – 6...12 min, respectively. Sea buckthorn was not processed, only technological rinsing was used. Grinding of raw materials was carried out on a double grinding machine (apple, Jerusalem artichoke, and table beet – 0.2...0.5 10^{-3} m, and sea buckthorn – 0.5...1 mm). The combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powder) was implemented using a model structure of functional equipment.

The boiling process in a rotary-film evaporator was carried out at a temperature of 55 °C for 65 seconds to a dry matter content of 25 %. Drying of the cooked multicomponent mass was carried out in a single-drum cylindrical IR dryer at a temperature of 50 °C to a final moisture content of 3...6 % and fractional grinding (0.3...0.6 mm).

The rheological properties of the paste-like multicomponent semi-finished product were determined by the change in dynamic viscosity for composition 2, which is 485 Pa·s, and in the control sample of applesauce, this indicator is 50 Pa·s. When boiling in a rotary-film evaporator at a temperature of 55 °C to a content of 30 % of dry substances, there is an increase in the strength of dynamic viscosity by 3.2 times (600 Pa·s), and in the control (apple paste) this indicator is 178 Pa·s with a dry matter content of 25 %.

Keywords: preliminary heat treatment, polycomponent semi-finished product, functional nutrition, mobile complexes, pastes/fractional powder, model structure, high degree of readiness

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1. Introduction

Rational nutrition is an integral component of the formation of strong immunity and resistance to today's challenges (environmental, chronic, acquired, etc.) in consumer

cooperatives and requires the use of appropriate high-quality approaches from “farm to table” [1]. Changes in living conditions shape consumers' standards for consumption of high-quality products in their daily diet, and the demand for natural products with a physiologically functional purpose,

the minimization of synthetic ingredients and the production of products using modern technologies also increases. The use of modern production technologies allows the use of resource-saving approaches to the high-quality production of functional products of natural origin. For the high-quality implementation of modern production needs, there is a need to improve traditional methods aimed at intensification of the hardware and technological component, including through the use of polycomponent semi-finished products with a high degree of readiness for obtaining functional products [2].

Modern production technologies enable the production of functional products without being tied to the traditional bases of production complexes (processing and food enterprises, hotel and restaurant complexes) [3]. Therefore, their use is relevant, even in mobile complexes under the conditions of using 3-D printing technologies and multi-component natural semi-finished products with a high degree of readiness. Food 3D printing technologies are seen as a potential solution for the production of customized food products, such as military food and food for astronauts. The basis of the food ink material can be various ingredients with predicted rheological properties (pastes/powders), which will make it possible to obtain functional products actually in the field, of high quality and natural composition [4]. Implementation of the proposed innovative engineering and technological solutions will strengthen the world's resistance to numerous crisis situations (military conflicts, natural disasters, and pandemics, etc.) under the conditions of intensification of production approaches to provide the population with food products. Improvement of the methods of rational production of high-quality food under the conditions of combining heat and mass exchange equipment of different performance and especially under extreme conditions (under field conditions, in bomb shelters, during evacuation) is of primary importance. In turn, 3-D printing makes it possible to create products directly at the point of consumption, which significantly reduces dependence on supply chains and guarantees the provision of basic needs of the population in crisis situations. Improvement of technologies for the production of semi-finished products based on natural components contributes to the improvement of the quality of nutrition of military personnel, medics, volunteers, and other people who are under extreme conditions. The use of multi-component semi-finished products with a high degree of readiness will make it possible to provide functional nutrition, which will contribute to the preservation of health, maintenance of physical endurance and quick recovery after exertion. The obtained scientific and practical data also have social significance in ensuring sustainable access to high-quality food for people under extreme conditions, which is especially relevant in the context of military operations and natural disasters. The economic expediency of the introduction of improved technologies is the reduction of storage and transportation costs under the conditions of the implementation of engineering and technological solutions aimed at combining devices of different productivity to expand the production cycle directly at the collection sites. The modern development of new technologies in the processing and food domains is aimed at stimulating the introduction of innovative approaches to open new markets with high-quality functional products without being tied to the classic technological cycle.

2. Literature review and problem statement

Work [5] discusses strategies for the development of functional healthy nutrition under the conditions of consumer adaptation to the variety of colors of the product under the conditions of visual appeal. Paper [6] analyzes the expediency of using plant raw materials in the recipes of various food products to improve their functional properties and provide original rheological and organoleptic characteristics, replacing synthetic components. Special attention is paid to the use of berries as a promising raw material for the creation of functional products that have significant economic potential to support human health. However, further research should be directed to the development of resource-saving hardware and technological solutions for comprehensive support of agro-industrial enterprises, in particular in the context of the production of polycomponent semi-finished products with a high degree of readiness for 3-D printing technology.

Work [7] analyzed consumer preferences for balanced food products based on vegetable raw materials, which made it possible to create a general picture of the population's preferences. However, the issue of effective methods of blending raw materials, which not only increase the health-promoting properties, but also the competitiveness of products, requires further study. Improved methods of blending plant raw materials, in particular, taking into account the functional properties of the ingredients and their organoleptic characteristics, are promising for the production of multicomponent semi-finished products, which will ensure the naturalness of products and avoid the use of synthetic additives [8].

The use of our own raw material resource base will allow us to support the agro-industrial sector of the countries, the processing industry directly in the places of cultivation due to the implementation of functional hardware and technological solutions. Also the production domain, namely the mobility of the production cycle when using multi-component semi-finished products of a high degree of readiness under the conditions of the latest production technologies. The use of mobile complexes with 3-D printing technologies of functional products will provide support for consumer cooperatives and one of the components of food security of countries, which will contribute to the expansion of the range of products with immunomodulating effects. Thus, work [9] provides an analysis of the consumption of natural food products within the daily diet for the formation of the needs of consumer cooperatives. However, the issue of providing ways to determine and approbation-practical research of the multicomponent composition of compositions not only in the recipes of individual products, but also under the conditions of the formation of multicomponent semi-finished products of a high degree of readiness, remains unsolved. This is explained by the need to carry out large-scale complex studies taking into account physical-chemical and rheological properties, their changes during equipment and technological processing and the production cycle, which is quite difficult to implement. One of the simplest ways to produce functional products is the implementation of modern trends in the field of improving equipment and technological methods, including for the production of vegetable polycomponent semi-finished products with a high degree of readiness. They can simultaneously act as ready-to-eat products, natural fillers for the recipes of various products to increase the nutritional value and minimize the synthetic component.

Also, they can be a successful basis when using modern 3-D printing technologies, obtaining products even in mobile complexes, which is relevant in countries that are in military conflicts and after various man-made situations.

The use of the country's own resource capacities for the production of functional polycomponent semi-finished products of a high degree of readiness with predicted structural and organoleptic properties is optimal in terms of supporting the country's agro-industrial sector [10]. However, there is a need to implement various methods of improving technological and hardware solutions to ensure resource-saving processing of plant raw materials into functional semi-finished products with the possibility of further use in modern technological approaches, and therefore requires approbation studies. For example, in [11], one of the solutions for the technological implementation of the method of production of multicomponent fruit and vegetable paste based on apple, viburnum, rowan, pumpkin, and beet is given. The recipe ratio is selected according to the physiological properties and the obtained rheological and organoleptic properties. The question related to the effect on the rheological behavior of the quality of the implementation of heat and mass exchange treatment, which is explained by the study of only the technological component, remained undefined. When obtaining polycomponent semi-finished products based on thermolabile raw materials, there is a need to provide a homogeneous powdery mass for further basic heat and mass exchange operations of concentration and drying [12]. Therefore, there remains a need to conduct comprehensive research aimed at simultaneous forecasting and research of hardware and technological solutions to ensure optimization of the production cycle.

In [13], research is reported on the study of the technological cycle from processing to the production of food products with physiologically functional properties. However, issues related to the level of scientific and technical progress, the possibility of using modern technologies and the availability of one's own raw material base remain neglected. Special attention should be paid to the initial physiological properties of raw materials, the level of resource efficiency of the equipment and technological components, and the quality of the obtained products during the production of functional polycomponent semi-finished products of a high degree of readiness. As an example, work [14] presents a heat-mass transfer model of boiling in a film evaporator for the purpose of analyzing changes in the properties of raw materials heated in certain temperature ranges. However, the actual effectiveness of the technological process of cooking, depending on the method of heat supply and the uniformity of the temperature range, as a shaping factor of the quality of raw material preservation, was neglected. In order to minimize the influence of the temperature range in evaporating devices, in most cases, the method of heat supply is replaced, and the designs of mixing devices are additionally intensified. The functionality of the equipment and technology cycle for the production of polycomponent semi-finished products with a high degree of readiness is possible under the conditions of a complex equipment combination of the process of concentration and drying. The implementation of this approach in practice will make it possible to obtain semi-finished products of a high degree of readiness directly in mobile complexes located in agro-industrial sectors and to produce products for the country's production facilities, including for field mobile complexes. Confirming the relevance

of scientific and practical research aimed at improving the technological method and hardware implementation for the production of products with predicted properties.

Research data on the rheological properties of children's vegetable purees in the temperature range from 5 °C to 65 °C in a wide range of shear rates (5...200 s⁻¹) are given in [15]. However, the expediency of further drying the pasty concentrate immediately after cooking to form an extension of the functional properties of semi-finished products of a high degree of readiness remains overlooked. This is due to the probable lack of equipment to implement the drying process during the approbation studies. However, this is an artificial limitation that emphasizes the expediency of further practical research in the direction of the production of polycomponent semi-finished products with a high degree of readiness, including for further use in 3-D printing technology.

Modern 3-D printing technology is characterized by its popularity due to the production of food products without being tied to a production base in the presence of a 3-D printer and food material for high-quality printing with special matrices [16]. Thus, work [17] reports the results of 3D printing of food products using wheat flour, lyophilized mango powder, olive oil, and water. Thus, when adding 2 % of the total weight of olive oil, the best print quality was obtained at a flour:water:olive oil ratio of 55:2.75:30. The optimum compression pressure, needle speed, needle diameter, and internal fill factor to provide the best print quality were 600 kPa, 6 mm/s, 0.58 mm, and 50 %, respectively. Food samples produced using these optimal parameters demonstrated numerous advantages, including a well-organized package structure, a distinct internal texture profile, and less overall deformation. The main requirement for food material in 3D printing is the use of semi-finished products not only with predicted rheological properties but also with high functional natural properties and their maximum preservation during production. The analysis of modern literary research allowed us to form possible ways of improving the method of production of a multicomponent semi-finished product of a high degree of readiness with a high content of physiologically functional ingredients. In particular, issues related to the use of optimal gentle regime parameters for storing thermolabile properties of plant raw materials under the conditions of gentle heat and mass transfer processing need approbation determination. It is necessary to find ways to ensure combined hardware design for the production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders), as well as to determine the rheological properties of the multi-component semi-finished product for further selection of the 3D printer matrix for printing functional products, including in mobile complexes. It is advisable to carry out experimental and practical research to ensure the production of polycomponent semi-finished products of a high degree of readiness, which, in turn, will allow expanding the range of competitive natural semi-finished products of a wide range of uses.

The improvement of the method of production of polycomponent semi-finished products of a high degree of readiness is aimed at the formation of resource-efficient approaches in the following main directions:

- the use of optimal gentle technological regimes taking into account the heat-labile properties of plant raw materials under the conditions of using one's own raw material resource base, in particular the country of development.

– implementation of innovative hardware and technological solutions aimed at forming functional properties by combining certain heat and mass exchange devices into a single system. This will make it possible to minimize auxiliary technological operations and equipment, and therefore will lead to improvement of technical and economic indicators;

– adaptation of the equipment and technological properties of the production cycle to today's conditions for the production of multi-component semi-finished products of a high degree of readiness with further use in 3-D printing technologies of food products.

3. The aim and objectives of the study

The purpose of our study is to improve the method of production of a multi-component semi-finished product with a high degree of readiness for use in 3-D printing technology for obtaining functional nutrition. This will ensure the receipt of functional products, including on mobile complexes through 3-D printing (in field conditions, bomb shelters, and other safe places). Thus, it will be possible to provide the population, including those under extreme conditions (military personnel, doctors, volunteers, first responders) with functional products for fast consumption with a high content of natural ingredients.

To achieve the goal, the following tasks were set:

– to form a technological scheme with operating parameters for the production of a multi-component semi-finished product of a high degree of readiness under the conditions of using a model structure of functional equipment;

– to develop an experimental model of functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders);

– to determine the rheological properties of a paste-like multicomponent semi-finished product for the further adaptation of the technology of obtaining functional semi-finished products under the conditions of 3-D printing.

4. The study materials and methods

The object of the research is the process of production of polycomponent semi-finished products of a high degree of readiness using a model structure of functional equipment, in particular, based on apple, Jerusalem artichoke, table beet, and sea buckthorn.

The research hypothesis assumes the possibility of producing semi-finished products of a high degree of readiness based on plant raw materials with a high content of functional ingredients due to the use of an improved production method with resource-saving modes and the use of functional equipment. This will contribute to providing the population, in particular under extreme conditions, with functional products containing a high content of natural ingredients and meeting the requirements of quick consumption and high nutritional value.

The main assumptions are the use of plant raw materials for the production of polycomponent semi-finished products to reduce the cost price and increase the availability of functional products, especially under crisis conditions. Optimization of rheological properties of multicomponent semi-finished products for technological features of heat

and mass exchange equipment with the possibility of using products in the process of 3-D printing. The use of the obtained polycomponent semi-finished products with a high degree of readiness, in particular, in 3-D printing technology, will make it possible to quickly and efficiently provide food to people under extreme conditions (military, medical personnel, volunteers), increasing their endurance and productivity.

Adaptation of resource-saving engineering and technological solutions aimed at improving the method of production of multi-component semi-finished product with a high degree of readiness and its further use in 3-D printing technologies were implemented at the State Biotechnology University (Kharkiv, Ukraine). The work was carried out within the framework of the state budget topic of the project of young scientists of Ukraine with the support from the Ministry of Education and Science of Ukraine.

For research, plant raw materials collected under the conditions of their ripeness at the agricultural enterprises of the Kharkiv oblast near the front were used, namely: apple (variety "Antonivka"), Jerusalem artichoke (variety "Lviv"), beetroot (variety "Tsyndra"), and sea buckthorn (variety "Botanichna") The content of the main functional ingredients (chemical composition) for the further production of polycomponent semi-finished products with predicted rheological properties was determined according to classical methodology [18–20] and is given in Table 1.

Table 1
Chemical composition of plant raw materials for conducting approbation studies for the further production of polycomponent semi-finished products (per 100 g of raw materials)

Physiologically functional ingredients	Initial raw materials (100 g)			
	Apple	Jerusalem artichoke	Red beetroot	Sea buckthorn
Vitamin A, µg	0.28	2.3	0.11	10.9
Vitamin B ₁ , mg	0.27	0.79	0.31	0.25
Vitamin B ₂ , mg	0.02	0.10	0.22	0.04
Vitamin B ₉ , mcg	1.9	16.1	11.6	9.3
Vitamin PP, mg	0.9	1.83	0.53	0.19
Vitamin C, mg	10.3	6.3	13.4	49.8
Phosphorus, mg	10.8	78.6	15.1	–
Calcium, mg	16.4	15.4	10.6	20.8
Potassium, mg	268.0	42.3	26.3	173.8
Mono- and disaccharides, mg	8.6	3.1	4.4	1.0
Dietary fibers, g	1.75	4.3	1.7	1.6
Organic acids, g	0.81	0.10	0.11	0.08
β-carotene	–	10.8	8.1	3.8

The hardware and technological processing was carried out at the laboratory and practical facilities of the State Technical University. The initial stage of plant raw material processing is classical operations aimed at inspection, washing (for sea buckthorn, rinsing). Further preliminary grinding (5...10 mm) depending on the type of raw material for high-quality technological operations of preliminary heat treatment (blanching, aging, etc.). For testing, the recipe ratio of the experimental 3 compositions (Table 2) per 100 g is proposed of ready pureed mass, which will undergo further heat and mass exchange treatment by

boiling and drying. Apple was used as the main structure-forming component of the kept puree-like multicomponent mass, therefore apple puree was used to control changes in the further functional properties of the compositions.

Table 2

Recipe ratio of approbation puree-like polycomponent semi-finished product

Recipe and component composition, %	Composition		
	1	2	3
Apple	30	35	45
Artichoke	20	25	35
Table beet	25	30	15
Sea buckthorn	25	10	5
Control (applesauce)	100	100	100

The production technique of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders) was realized at the pre-simulated model structure of functional equipment at DBTU. Puree-like compositions (Table 2) underwent technological processing according to the proposed scheme, followed by detailed rheological data of composition 2, as an average test sample according to the recipe ratio. At the same time, other compositions differed to some extent in rheological and organoleptic properties, which is explained by changes in the recipe ratio of components. The studies were repeated in 5-fold repeatability with a relative error of no more than 3% in accordance with traditional methods for processing experimental and practical data.

5. Results of efficient engineering and technological solutions in the improved production technique of polycomponent semi-finished products

5.1. Technological scheme for the production of a multi-component semi-finished product with a high degree of readiness based using a model structure of functional equipment

A feature of the improved technique (Fig. 1) is the selection of the duration of preliminary heat treatment to implement the preparation of raw materials in a rational operating cycle with minimum durations of intermediate technological stages to preserve the initial properties. Thus, preliminary heat treatment was implemented in a universal multifunctional device [21]. The following were treated with hot steam: apple (1.0...2.0 min), Jerusalem artichoke (3...6 min), and table beet (6...12 min). After preliminary heat treatment, the raw material underwent the stage of wiping on a double wiping machine with an initial particle size of 0.2...0.5 10⁻³ m and 0.5...1 mm for sea buckthorn.

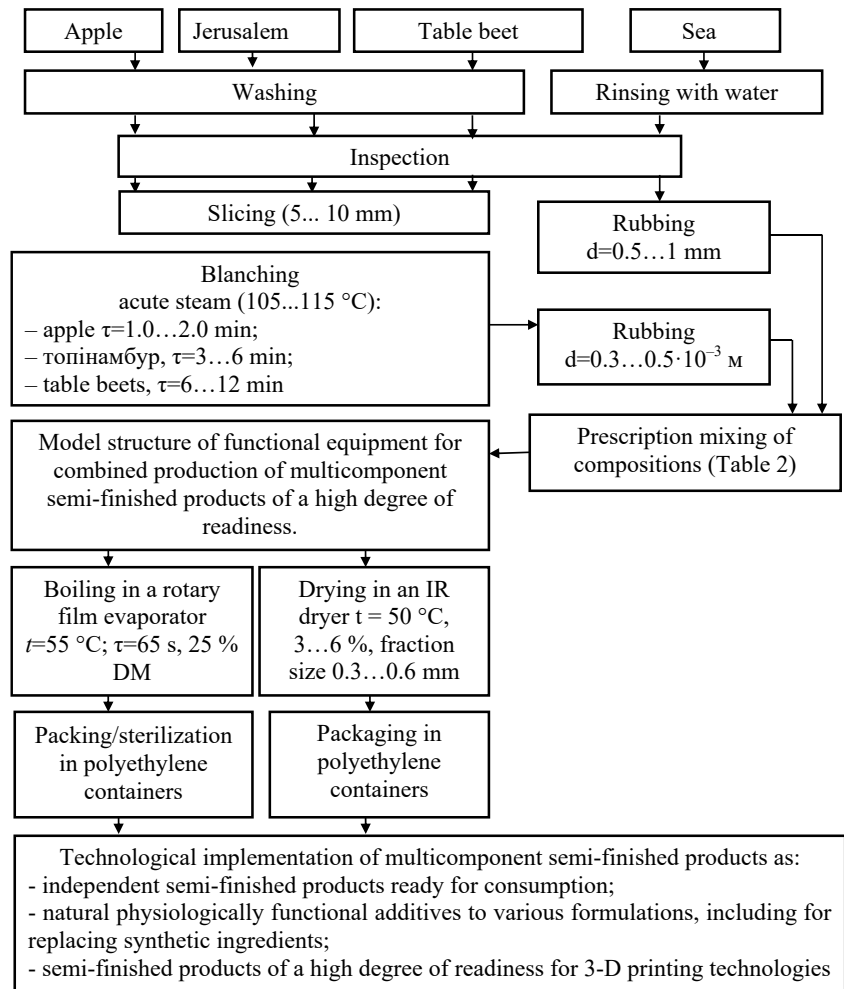


Fig. 1. Technological diagram of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders) obtained under the conditions of using a model structure of functional equipment

Engineering solutions during the design of a model structure of the functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders) allow the installation of wiping machines on the assembly platform. At the same time, the rubbed mass comes from the wiping machines to the mixing container, where the stage of single-row mixing of puree-like masses into a puree-like multicomponent mass is realized.

The test mass in accordance with the recipe ratio of the compositions of the puree-like polycomponent semi-finished product is submitted for further technological processing to the model structure of functional equipment for the combined production of multi-component semi-finished products of a high degree of readiness. Low-temperature cooking is carried out in a rotary-film evaporator at a temperature of 55 °C, for 65 seconds, and when the content of dry substances in the cooked mass is reached – 25%. The cooked mass passes through the technological nozzle to the packaging-sterilizing mechanism for further storage of the paste-like puree-like semi-finished product of a high degree of readiness in a light-proof polyethylene container with use, in accordance with further technological needs.

The structural implementation of the rotary-film evaporator makes it possible to implement the process of drying

the cooked polycomponent mass in a single-drum cylindrical IR dryer at a temperature of 50 °C. The dried raw material is characterized by a final moisture content of 3...6 %, and with the help of a powder grinding mechanism with cutting knives, it receives the necessary fractionation within the range of 0.3...0.6 mm. After drying, the fractional powdered semi-finished product of a high degree of readiness in a light-proof polyethylene container for use in further technological needs.

Polycomponent semi-finished products of high degree of readiness (pastes/fractional powders) in accordance with technological needs after packing in polyethylene containers can be used as main ingredients. Including in the production of functional food products using modern 3-D printing technologies, in accordance with the predicted rheological properties, moisture content and consistency. food products.

5. 2. Experimental model of functional equipment for the combined production of polycomponent semi-finished products with a high degree of readiness

The engineering-technological solution is aimed at the formation of a combined hardware-technological implementation of the production processes of multicomponent semi-finished products of a high degree of readiness (pastes/fractional powders) under the conditions of a combination of continuous heat and mass exchange processes in devices of different productivity without the use of storage tanks. The proposed structural and technological solutions made it possible to design a model structure of functional heat and mass exchange equipment (Fig. 2) for use at processing (in the places of targeted cultivation of raw materials) and production facilities with the possibility of additional installation at the technical site of the wiping machine. The functionality of the heat and mass exchange equipment is realized through a combined structural combination of the concentration process to obtain a pasty semi-finished product with the simultaneous possibility of drying a certain volume of concentrated mass to a dried powdery fraction.

Heating of the heat-insulated working surfaces of the functional heat-mass exchange equipment in the form of the working surface of the rotary-film evaporator (4) and the single-drum roller dryer (11) and the heated surfaces (9 and 13) is carried out by a film-like resistive electric heater of radiating type (FIREhRT) [22].

The operation of the functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness involves the arrival of vegetable raw materials to the double rubbing machine 1. After rubbing, the puree-like raw material enters the mixing container (2), where the preparation of the polycomponent puree-like mass takes place in accordance with the previously selected ratio of the component composition of the ingredients and subject to compliance with technological parameters.

The hollow shaft of the spindle (5) acts as a transport pipeline of the multicomponent pureed mass to the distribution disk (9), which implements film formation with subsequent cooking in the working chamber of the rotary-film evaporator at a temperature of 55 °C. To intensify the cooking process, the outer surface of the spindle shaft (5) has an additional heated housing (9), providing additional heating of the mashed mass before it enters the distribution disk (9). Along the inner walls of the evaporator, the film-like puree-like mass is moved by blades (6) by cutting the layer. The design of the cutting blade provides a reflective

surface with additional heating (black blades do not have an additional heating surface). The steam component during boiling enters the separating compartment (10) with subsequent cooling.

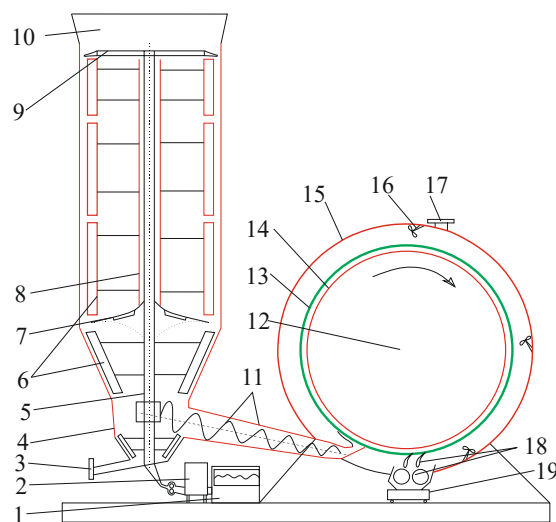


Fig. 2. Scheme of the model structure of functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness (paste/powder):
 1 – double wiping machine; 2 – container-mixer; 3 – outlet pipe for the boiled semi-finished product; 4 – heat-insulated housing of the rotary-film apparatus; 5 – hollow spindle shaft; 6 – a cutting blade and a reflective surface with additional heating (black blades do not have an additional heating surface); 7 – reflective surface with Peltier elements; 8 – additional body of the hollow shaft of the spindle, which is heated; 9 – distribution disk; 10 – separating department; 11 – charging screw; 12 – single-drum roller IR dryer; 13 – grooved drum; 14 – inner surface that is heated; 15 – heat-insulated surface (casing) that is heated; 16 – autonomous fan; 17 – air outlet pipe; 18 – powder grinding mechanism with cutting knives; 19 – storage capacity

Structurally, the rotary-film apparatus has a lower compartment, which is separated from the main working area by a reflective surface with Peltier elements (7). In the lower part, the further movement of the cooked pureed mass continues, with a partial discharge through the technical pipe (3). The content of dry substances in the cooked mass is 25 %, which allows the simultaneous use of the finished pasty semi-finished product in the technology of 3-D printing of food products as the main platform of future products. This is rational for further drying under the conditions of application to the corrugated surface of the working drum of a roller dryer.

In addition, in the lower part, a partial ingress of the cooked mass into the injection screw (11) with a heat-insulated casing that is heated is ensured. The auger (11) implements the injection of the cooked mass to the working area of the single-drum roller IR dryer (12), ensuring uniform application of the cooked mass to the corrugated drum (13).

The roller dryer (12) has an inner surface (14) that is heated and a heat-insulated surface (sheath) that is heated (15), and the drying process is realized at a temperature of 50 °C. For the convective movement of the air environ-

ment in the internal environment of the dryer 12, there are autonomous fans (16, in the amount of 3 pcs.). The low-voltage supply voltage in the range of 3...6 W comes from the Peltier elements located on the reflective surface (7). The air from the working chamber of the dryer is discharged to the environment using nozzle 17. The dried raw material with a final moisture content of 3...6 % is given the necessary fractionation (0.3...0.6 mm) with the help of a grinding mechanism with cutting knives, which is optimal for matrices in 3-D printing of food products.

During the research of the improved technique, the content of physiologically functional ingredients of multicomponent compositions for a pasty semi-finished product was determined (Table 3) in comparison with the control – traditional apple paste.

Table 3
Content of physiologically functional ingredients of multicomponent paste-like semi-finished products obtained in the model structure of functional equipment (per 100 g of product)

Substance	Measurement unit	Control, apple paste	Composition 1	Composition 2	Composition 3
Dry matter content	%	25±1.15	25±1.15	25±1.15	25±1.15
Food fibers		1.73±0.02	5.31±0.03	6.12±0.06	6.81±0.12
Organic acids are listed as malic acid	mcg per 100 g	0.49±0.01	0.75±0.05	0.82±0.05	0.96±0.05
Vitamin A		5.05±0.01	6.38±0.02	8.8±0.02	10.2±0.02
Vitamin B ₁		0.042±0.01	0.074±0.01	0.011±0.01	0.015±0.02
Vitamin B ₂		0.042±0.01	0.0082±0.001	0.0013±0.001	0.0164±0.001
Vitamin C		23.1±0.85	38.8±1.25	35.2±1.25	31.6±1.25
Potassium		532.8±2.0	482.8±2.0	468.9±2.0	448.0±2.0
Calcium		30.5±1.15	31.5±1.15	32.1±1.15	31.2±1.15

The resulting polycaposition compositions of paste-like semi-finished products obtained under the conditions of an improved technique with a final content of dry substances within 25 % are characterized by an increase in dietary fibers and organic acids, including the main vitamin group (Table 3). The increase in the content of physiologically functional ingredients indicates the expediency of practical testing of the proposed hardware and technological solutions for the creation of functional products.

5.3. Study of the rheological parameters of the multicomponent pasty semi-finished product when using the functional equipment model structure

A classic practice in the production of multicomponent semi-finished products with predicted structural properties is the determination of the rheological properties of natural plant ingredients in compositions taking into account the recipe ratio, especially for the implementation of 3-D printing technology of food products. The nature of the structure of the polycaposition pasty semi-finished product with the determination of the dependence of the dynamic viscosity on the shear rate is shown in Fig. 3 (the control was apple paste, the structural properties are given for composition 2, according to the recipe in Table 2). The choice of control as apple paste is explained by its structure-forming properties, a wide range of use in production technological schemes as a recipe ingredient (in the production of marshmallows, etc.). Apple raw materials are grown in significant volumes and

are available for the production of multicomponent semi-finished products with predicted rheological properties under the conditions of comparison of changes in the dynamic viscosity of the obtained compositions.

Recipe composition 2 is characterized by the strength index of the rheological structure at the level of 485 Pa·s, while in the control this indicator is 50 Pa·s (apple puree). When boiling in a rotary-film evaporator at a temperature of 55 °C up to a content of 30 % DM leads to an increase in the strength index in fact by 3.2 times (600 Pa·s), while in the control (apple paste with a content of DM of 25 %, this indicator is 178 Pa·s). Our data confirm the possibility of obtaining the predicted structural properties in the multicomponent paste-like product, taking into account the recipe ratio. In addition, the high dynamic viscosity indicators allow the drying process of the paste-like product by applying it to the grooved working surface of the drum, which rotates, without possible peeling of the applied layer during drying. In turn, the high index of dynamic viscosity allows the use of a multi-component paste-like semi-finished product with a high degree of readiness as the main raw material platform during the implementation of the technology of 3-D printing of food functional products on rice (wafer) paper. In turn, the use of this type of paper in 3-D printing technology is due to its lack of taste, and therefore it is the basis for printing various products. At the same time, the high dynamic viscosity of the multicomponent paste-like semi-finished product prevents possible changes in the geometry of the printed form of the product and delamination, which is the main requirement when printing with food printers.

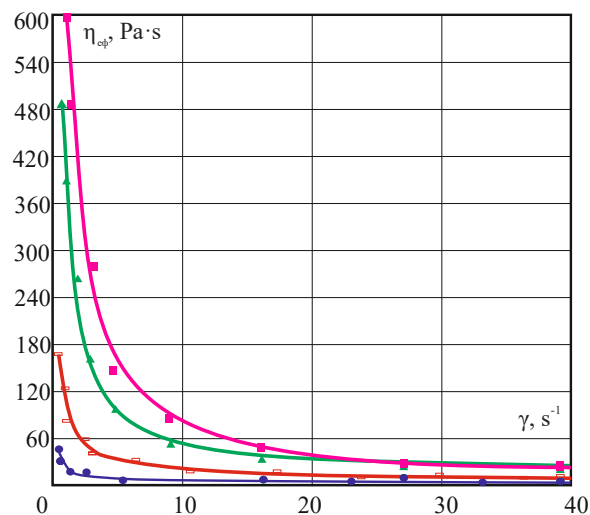


Fig. 3. Visualization of the rheological behavior of multicomponent composition 2 investigated at room temperature $t=22\text{ }^{\circ}\text{C}$: ● – control (apple puree 10 % of dry substances); □ – control (apple paste 25 % of dry substances); blend B: ▲ – 25 % of dry substances; ■ – 30 % of dry substances

6. Discussion of results related to the improved production technique of polycomponent semi-finished products with a high degree of readiness

When testing the improved technique for producing a multicomponent semi-finished product with a high degree of readiness, a vegetable raw material base based on apple, Jerusalem artichoke, table beet, and sea buckthorn with a high content of functional and physiological ingredients was taken according to the recipe ratio (Table 2). A feature of the improved technology is the implementation of preliminary heat treatment with hot steam: apple (1.0...2.0 min), Jerusalem artichoke (3...6 min), and red beet (6...12 min), which is presented in the technological scheme (Fig. 1). Rubbing of raw materials on a double rubbing machine (apple, Jerusalem artichoke, and table beet – $0.2...0.5 \cdot 10^{-3}$ m, and sea buckthorn – 0.5...1 mm). The combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powder) was implemented using a model structure of functional equipment (Fig. 2). Boiling in a rotary-film evaporator at a temperature of 55 °C for 65 seconds to a dry matter content of 25 %. Drying of the boiled polycomponent mass in a single-drum cylindrical IR dryer at a temperature of 50 °C to a final moisture content of 3...6 % and fractional grinding (0.3...0.6 mm).

The rheological properties of the pasty polycomponent semi-finished product were determined (Fig. 3). The dynamic viscosity of composition 2 is 485 Pa·s, and in the control this indicator is 50 Pa·s (apple puree). When boiled in a rotary-film evaporator at a temperature of 55 °C to a content of 30 % DM, the strength index increases by 3.2 times (600 Pa·s). Then, as in the control of apple paste with a DM content of 25 %, this indicator is 178 Pa·s.

The relevance of experimental and practical research is confirmed by the approbation of the improved technique under the conditions of using a model structure of functional equipment (Fig. 2) in a laboratory complex for the production of multicomponent semi-finished products of a high degree of readiness. The obtained semi-finished products can be used in the future as independent products, fillers for recipes of various food products and in modern technologies of 3-D printing of functional products in mobile complexes. A wide range of use of multi-component semi-finished products in practice will make it possible to increase and expand the competitive range of “functional natural products” of food, including by replacing synthetic and basic raw materials with a low content of physiological ingredients with a multi-component composition, to ensure a complete diet, including military and medical personnel.

The advantages of the improved technique, taking into account the physiologically functional ingredients of its own raw material base, are the use of a rational duration of preliminary heat treatment with minimal intermediate technological stages to preserve the initial properties. Proposed engineering solutions in the form of a model structure of functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders) with low-temperature heat-mass transfer processing and the possibility of placing them on the assembly platform of wiping machines.

The application in production practice of the model structure of functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powder) makes it

possible to obtain a choice in the places of collection of raw materials. In the classical form, the technological process of puree-like mass concentration is implemented in rotary-film devices [23] with various designs of mixing bodies for intensifying the cooking process and with a characteristic top supply of raw materials. At the same time, the drying process can be carried out in roller IR dryers [24]. The difference between the proposed model structure of functional equipment for the combined production of polycomponent semi-finished products of a high degree of readiness (paste/fractional powder) is the combination of the design of the rotary-film apparatus and the cylindrical IR dryer. This became possible due to the change in the structural structure of the lower part of the apparatus for concentration with the simultaneous additional installation of a blade and an injection screw for partial redirection of the concentrated paste for further drying in the dryer. The use of a modular design of functional equipment (Fig. 2) for the combined production of multi-component semi-finished products of a high degree of readiness in an improved production method will allow obtaining a semi-finished product for use in 3-D printing technology in the production of functional nutrition. This will allow supporting the country's own agro-industrial domain during the production of polycomponent semi-finished products of a high degree of readiness under the conditions of the location of the modular structure in the places of collection of raw materials. Among the limitations of research is the need to take into account the thermolabile properties of plant raw materials, including compliance with the proposed regime ranges, since not taking this into account will lead to a decrease in the efficiency of heat treatment and the quality of the obtained semi-finished products with a high degree of readiness. At the same time, only composition 2 (Table 2) can be considered as a drawback of the research during the approbation of the research results, but it is average in terms of recipe composition and rheological properties, and other compositions are similar to the chosen one.

Despite a significant body of research aimed at the production of polycomponent vegetable semi-finished products with the aim of further obtaining functional food products, there is a need for constant improvement to meet the needs of consumer cooperatives. For example, work [25] provides simulation data on heat and mass transfer processing of plant raw materials under simulated modeling conditions, but there is a certain difference between the practical implementation, which is related to the thermolabile properties of raw materials. The difference between the proposed results is the combination of heat and mass exchange processing of plant raw materials under conditions of concentration in a rotary-film apparatus with the possibility of partial drying in a roller dryer. This expands the potential of using the proposed model design, in particular by placing it in places where raw materials are collected. However, high-quality semi-finished plants are widely used even in innovative confectionery production technologies [26], but they require predicted rheological properties in the first place. The introduction of confectionery products into recipes leads to enriched physiologically functional ingredients. Further research can be directed to the practical implementation of 3-D printing of functional products based on polycomponent semi-finished products with a high degree of readiness on the “Decoplotter” printer.

7. Conclusions

1. The peculiarity of the technological scheme is that preliminary grinding (of apples, Jerusalem artichokes, and red beets) was carried out to the size of 5...10 mm. Hot steam treatment for apple lasted 1.0...2.0 min, Jerusalem artichoke – 3...6 min, and table beet – 6...12 min, respectively. Grinding of raw materials was carried out on a double grinding machine, for apple, Jerusalem artichoke and red beet, the particle size was 0.2...0.5 10–3 m, and for sea buckthorn – 0.5...1 mm. The combined production of polycomponent semi-finished products of a high degree of readiness (pastes/powders) was implemented using a model structure of functional equipment. Boiling in a rotary-film evaporator at a temperature of 55 °C for 65 seconds to a dry matter content of 25 %. Drying of the boiled polycomponent mass in a single-drum cylindrical IR dryer at a temperature of 50 °C to a final moisture content of 3...6 % and fractional grinding (0.3...0.6 mm).

2. An experimental prototype of functional equipment was designed for the combined production of polycomponent semi-finished products of a high degree of readiness (pastes/fractional powders) with the possibility of installing a double wiping machine and a mixing tank on the assembly platform. The heat-insulated working surfaces of the rotary-film evaporator and the single-drum roller dryer and other heated surfaces are heated by a film-like resistive electronic heater of the radiating type. The low-voltage supply voltage in the range of 3...6 W for autonomous operation of exhaust fans comes from Peltier elements located on the reflective surface.

3. The rheological properties of the pasty polycomponent semi-finished product were determined using the recipe ratio of 2 compositions, namely, the dynamic viscosity is 485 Pa·s, and in the control this indicator is 50 Pa·s (apple puree). When boiled in a rotary-film evaporator at a temperature of

55 °C to a content of 30 % DM, the strength index increases by 3.2 times (600 Pa·s) while in the control of apple paste with a DM content of 25 %, this indicator is 178 Pa·s.

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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