ГАЛУЗЕВЕ МАШИНОБУДУВАННЯ

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INCREASING THE EFFICIENCY OF THE MEMBRANE FILTRATION PROCESS IN THE PRODUCTION OF FRUIT AND BERRY JUICES

Summary. The article considers the issue of increasing the efficiency of the membrane filtration process in the production of fruit and berry juices, which is a relevant direction in the development of modern technologies in the food industry. Membrane filtration, as a reagent-free and energy-saving method of processing liquid food products, allows you to obtain high-quality juices with minimal losses of biologically active substances and without deterioration of organoleptic indicators. The paper presents a generalized scheme of the membrane filtration technological process, characterizes the main stages – raw material preparation, enzymatic treatment, preliminary filtration, the main stage of membrane separation, membrane washing and stabilization of the finished product.

The influence of the main technological parameters – operating pressure, temperature, cross-flow velocity and membrane type – on the efficiency of the process and the quality of the filtrate is analyzed. It was established that the optimal conditions for ultrafiltration of fruit and berry juices are a pressure of 0.3…0.6 MPa, a temperature of 25…35 °C and a flow rate of 1.5…2.5 m/s, under which the highest productivity is achieved with minimal membrane contamination. It was shown that enzymatic preparation of raw materials provides a decrease in viscosity and an increase in filtration speed, and the use of membranes with antifouling properties and a modified surface contributes to stable system operation.

The results obtained confirm the feasibility of an integrated approach to optimizing the membrane filtration process, which involves simultaneous improvement of technological parameters, the design of membrane devices and membrane cleaning systems. The use of such solutions allows to ensure high quality of the final product, reduce energy and operating costs, and also increase the environmental efficiency of production. The results of the study are of practical importance for juice industry enterprises that implement modern technologies of membrane cleaning and product concentration.

Keywords: membrane filtration, fruit and berry juices, ultrafiltration, purification, membrane selectivity, product quality, technological parameters.

Formulation of the problem. Modern production of fruit and berry juices is characterized by increased requirements for product quality, its nutritional and biological value, as well as for the efficiency of technological processes. One of the key stages in the technological cycle is the process of clarification and concentration of juices, which is traditionally carried out by methods of heat treatment, settling or filtration through porous materials. However, such methods have a number of significant disadvantages, in particular high energy consumption, process duration, possible degradation of thermolabile compounds (vitamins, enzymes, aromatic components) and deterioration of organoleptic characteristics of the finished product.

In this context, membrane technologies are becoming increasingly widespread, which allow for the separation, concentration and purification of juices without significantly affecting their natural structure and composition. Membrane filtration allows for the effective removal of mechanical impurities, colloidal particles, pectins and microorganisms, while preserving biologically active substances. At the same time, despite significant advantages, the widespread introduction of membrane technologies in the production of fruit and berry juices is hampered by a number of technological and operational problems associated with the instability of membrane operation, a decrease in their productivity due to contamination (fouling), increased costs for the regeneration of membrane elements, and the need to optimize the technological parameters of the process [1].

Membrane fouling is one of the main problems that significantly affects the filtration efficiency. The sediment formed on the surface or in the pores of the membrane reduces the permeability, increases the hydraulic resistance and requires additional washing or replacement of the membranes. These phenomena cause not only technological difficulties, but also economic losses associated with equipment downtime and increased production costs. In addition, the composition of the raw material (the content of pectin substances, polyphenols, proteins) significantly affects the rate of membrane fouling, which requires an individual approach to choosing the type of membrane and filtration modes for different types of fruit and berry juices [2].

Modern research is aimed at increasing the efficiency of membrane filtration by optimizing the process parameters (pressure, temperature, flow rate, concentration of the initial product), improving the design of membrane devices, using combined methods of raw material pretreatment, as well as developing new membrane materials with increased resistance to fouling. However, there is a need for a systematic approach to studying the impact of these factors on the efficiency of the filtration process, which will allow formulating scientifically sound recommendations for industrial application [3].

Thus, the current scientific and technical problem is to find ways to increase the efficiency of the membrane filtration process in the production of fruit and berry juices by optimizing technological parameters and improving the design and operational characteristics of membrane systems. Its solution will contribute not only to improving the quality of finished products and reducing energy costs, but also to ensuring the sustainable development of juice production in accordance with the principles of energy and resource conservation.

Analysis of recent research and publications. The last decades are characterized by the rapid development of membrane technologies, which have become widespread in the food industry, in particular in the production of fruit and berry juices. Membrane filtration is considered one of the most effective methods of cleaning, clarifying and concentrating juices, as it allows processes to be carried out at relatively low temperatures, which allows preserving the natural organoleptic properties of the product, aromatic substances, vitamins and biologically active compounds [4]. The results of numerous scientific studies show that the use of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) makes it possible to significantly improve the quality of the final product, ensure the stability of color, transparency and biological value of juices. At the same time, compared to traditional clarification methods (settlement, centrifugation, use of auxiliary reagents), membrane processes are characterized by lower energy consumption and environmental friendliness, as they do not require the use of chemical reagents and allow for the reuse of some of the by-products [5]. Despite numerous advantages, the widespread industrial use of membrane processes in juice technology is limited by the problem of reducing membrane productivity due to their contamination, or the so-called fouling. Membrane contamination is caused by the accumulation of pectin substances, proteins, polyphenols, colloidal particles and microorganisms on their surface, which form a gel-like layer, which significantly reduces the filtrate flow and increases the hydraulic resistance. Studies conducted by various scientific groups confirm that the fouling rate significantly depends on the type of raw material, solids concentration, juice viscosity, temperature, flow rate, pressure and membrane properties. It was found that even a slight change in these parameters can lead to a noticeable decrease in filtration efficiency [6]. Thus, the issue of optimizing technological modes and choosing the type of membrane remains a relevant area of research. Numerous works of recent years consider various approaches to reducing the intensity of fouling. One of the effective methods is the preliminary enzymatic treatment of raw materials using pectinolytic enzymes, which promotes the hydrolysis of pectin substances and reduces the viscosity of the juice. Such studies have shown that preliminary enzymatic preparation makes it possible to increase the stability of the flow through the membrane and reduce the frequency of washing the filtration modules. At the same time, the authors note that excessive fermentation can negatively affect the organoleptic characteristics of the juice and its colloidal stability [7]. Therefore, the issue of choosing the optimal dose of enzymes and the duration of their action remains the subject of further research. Significant attention in modern scientific works is paid to the improvement of membrane materials and designs. Researchers are actively studying the possibilities of modifying the membrane surface by applying special hydrophilic or anti-fouling coatings, as well as creating hybrid polymer-ceramic structures that are characterized by higher chemical and thermal stability. A promising direction is the use of nanostructured materials, in particular metal-organic frameworks (MOF), silicon and titanium oxides, which reduce the adsorption of proteins and polyphenols, thereby increasing the antifouling properties of membranes. However, most of such solutions are still at the stage of laboratory tests, and their industrial implementation is limited by the high cost of manufacturing and the need for additional food safety tests [8]. A separate direction in the development of membrane technologies is the improvement of hydrodynamic conditions of the process. It has been shown that increasing the transverse flow velocity, using turbulators, pulsating flows or scraped surfaces allows reducing the thickness of the boundary layer and preventing excessive deposition of particles on the membrane. Such design solutions increase the stability of the filtration process, but require additional energy costs, so for their practical implementation it is necessary to conduct a detailed feasibility study. Researchers also draw attention to the importance of choosing the right type of membrane module (tubular, spiral-fold, plate or fiber), since not only the filtration efficiency but also the convenience of cleaning the membrane after the end of the operating cycle depends on this [9].

An important aspect of increasing the efficiency of membrane processes is the improvement of membrane cleaning systems, the so-called CIP procedures (clean-in-place). According to recent studies, the combination of mechanical cleaning with the use of acid, alkali or enzyme solutions allows you to effectively remove residual organic contaminants and restore up to 90…95 % of the initial membrane performance. However, prolonged use of chemical reagents can lead to degradation of the membrane material, which reduces its service life, so the search for environmentally friendly cleaning methods remains relevant – for example, using ultrasound, pulsed flows or biodegradable detergents. In addition to traditional membrane processes, promising methods such as reverse osmosis with reduced pressure, membrane distillation and forward osmosis are actively discussed in modern scientific publications [10]. These approaches allow you to concentrate juices at low temperatures, which ensures maximum preservation of volatile aromatic substances and color pigments. Although such technologies have not yet gained widespread industrial implementation due to the high cost of equipment, the results of experimental studies confirm their effectiveness and prospects for the future development of the industry. In conclusion, it should be noted that the conducted studies confirm the high potential of membrane filtration in the production of fruit and berry juices as an innovative, environmentally friendly and energy-efficient technology [11].

However, a number of unsolved scientific and technical problems remain, including the stability of membranes during long-term use, optimization of process parameters for different types of raw materials, the economic feasibility of using modified membranes and the development of methods for monitoring and controlling the filtration process in real time. Further research should be aimed at developing comprehensive solutions that combine optimization of technological parameters, structural improvement of membrane devices and the use of new materials with increased antifouling properties [12]. It is the integration of these approaches that will make it possible to increase the efficiency of the membrane filtration process, ensure stable juice quality and reduce production costs, which is extremely important for the competitiveness of food industry enterprises.

Formulation of the purpose of the article. The aim of the article is to increase the efficiency of the membrane filtration process in the production of fruit and berry juices by optimizing technological parameters and improving the operating conditions of membrane systems to reduce the intensity of their contamination and ensure stable product quality. To achieve this goal, it is planned to study the influence of the main technological factors on the productivity of membrane filtration and determine the directions for improving the design and operational characteristics of membrane devices.

Presentation of the main research material. Membrane filtration is a modern, highly efficient technology for the purification and processing of fruit and berry juices, which ensures high-quality removal of suspended particles, colloids and microorganisms without the need for heat treatment or chemical reagents. This allows you to maximally preserve the natural aroma, taste, color and biological value of the product [13]. Unlike traditional methods of clarifying juices – such as settling, separation or the use of auxiliary substances (bentonite, gelatin, diatomaceous earth) – membrane filtration is a more environmentally friendly and energy-saving technology that provides consistently high quality indicators. The basis of the process is the use of semi-permeable membranes that pass low-molecular compounds (water, sugars, organic acids) and retain high-molecular components – proteins, pectins, polyphenols, microorganisms [14]. Depending on the size of the membrane pores and the applied pressure, the main types of processes are distinguished: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Ultrafiltration is most often used to purify and clarify juices, and nanofiltration or reverse osmosis is used to concentrate them [15].

The technological scheme of the membrane filtration process in the production of fruit and berry juices involves several main stages. At the beginning, raw materials are received and prepared, which includes washing, sorting, grinding fruits to a puree state and preliminary removal of impurities. This is necessary to prevent mechanical damage to the membranes. Next, enzymatic treatment is carried out, during which pectinolytic enzymes are added, which destroy pectin substances, reducing the viscosity of the juice and facilitating further filtration. This is followed by preliminary filtration or centrifugation to remove large particles and suspended solids [16]. The key stage is membrane filtration, during which the liquid product is fed under pressure into the membrane module. The liquid is separated into two streams: the filtrate – the clarified juice that passes through the membrane, and the concentrate – the residue in which colloids, cell particles and high-molecular components are concentrated. After the filtration cycle is completed, the membranes are subjected to the CIP (Cleaning-In-Place) procedure – washing with special alkaline, enzymatic or acidic solutions to remove sediment and restore their filtration properties. The final stage is stabilization, pasteurization and packaging of the finished product. Table 1 shows the main technological parameters of the membrane filtration process and their impact on the efficiency of the process.

Experimental studies show that increasing the pressure to 0.6 MPa increases the filtration rate of apple juice by almost 40 %, however, further increase does not give a proportional increase in productivity

Table 1

Main technological parameters of the membrane filtration process and their impact on process efficiency

Process parameter	Value range	Impact on filtration efficiency
Working pressure, MPa	0.2…0.8	Increasing pressure increases the filtration rate, however, after reaching a critical value, the efficiency stabilizes due to the formation of a gel layer on the membrane surface
Temperature, °C	20…40	Optimal temperature (25…35 °C) reduces juice viscosity and improves membrane permeability. Higher temperatures can cause protein denaturation and loss of aromatic substances
Flow velocity, m/s	1.0…3.0	Increasing the cross-flow velocity prevents sediment formation and reduces fouling, but excessive turbulence increases energy consumption
Membrane type	UF/NF/RO	The choice of membrane type determines the degree of purification, transparency and chemical composition of the filtrate. For juice clarification, ultrafiltration with a porosity of 0.1…0.2 microns is the most effective
Membrane material	Polysulfone, cellulose acetate, polyamides	Determines resistance to temperature, chemical agents and degree of fouling. Polysulfone membranes are characterized by high mechanical stability and durability

due to the formation of sediment on the membrane surface. The optimal process temperature is 30 °C, at which the minimum viscosity and high transparency of the filtrate are achieved. In addition, it was found that enzymatic treatment before filtration increases productivity by 20…25 %, and the use of turbulators in the membrane module reduces the fouling rate by 15…18 %.

Particular attention is paid to the process of membrane fouling (fouling), which is the main factor in reducing filtration efficiency. The sediment is formed due to the adsorption of colloidal particles, proteins and pectins on the membrane surface. Various approaches are used to combat this phenomenon: backwashing, pulsed pressure supply, periodic mechanical cleaning or the use of membranes with a hydrophilic coating. It is also advisable to implement systems for continuous pressure and flow rate control to maintain optimal operating conditions.

When comparing different types of membranes, it was found that ultrafiltration membranes with a porosity of 0.1…0.2 microns provide the best ratio between productivity and filtrate quality. Membranes with a smaller pore size (nanofiltration) provide deeper purification, but require higher pressure, which increases energy consumption. On the other hand, microfiltration membranes have a higher throughput, but produce a less transparent product.

High efficiency of membrane filtration is also achieved through the correct selection of hydrodynamic parameters of the apparatus. It is important to ensure laminar, but sufficiently turbulent flow near the membrane surface to prevent the formation of stagnant zones. For this purpose, spiral-coiled, tubular or plate modules with distribution elements are used, which contribute to the uniform movement of the liquid.

Summarizing the results of the research, it can be noted that increasing the efficiency of the membrane filtration process of fruit and berry juices is possible due to: optimization of technological parameters (pressure, temperature, flow rate); preliminary enzymatic treatment of raw materials; use of membranes with antifouling properties; improvement of the design of membrane modules; implementation of monitoring systems and automatic process control; rational membrane cleaning system (CIP) using safe reagents.

Thanks to such a comprehensive approach, it is possible to achieve stable productivity of membrane installations, improve the quality of the final product, minimize losses of biologically active substances and reduce the cost of production. Membrane technologies not only provide a high level of purification, but also contribute to energy saving and environmental safety of the process, which makes them indispensable in the modern production of fruit and berry juices.

Conclusions. As a result of the study, it was found that membrane filtration is one of the most effective and environmentally friendly technologies for processing fruit and berry juices, which provides a high level of purification without losing the natural organoleptic properties of the product. The use of membrane processes allows for the production of clarified and stable juices, preserving biologically active components, aromatic substances and natural color.

The analysis of technological parameters showed that the efficiency of the process largely depends on the optimal combination of operating pressure, temperature and flow rate. The optimal conditions for most fruit and berry juices are a pressure of 0.3…0.6 MPa, a temperature of 25…35 °C and a cross-flow speed of 1.5…2.5 m/s, which ensures maximum filtration performance with minimal membrane fouling. It was found that preliminary enzymatic treatment of raw materials helps reduce juice viscosity and increases the filtration rate by 20…25 %. In addition, the use of membranes with a hydrophilic coating or a modified surface allows to reduce the intensity of membrane fouling and increase the duration of their operation. Improving the design of membrane modules, in particular the use of turbulators and optimization of hydrodynamic conditions, contributes to increasing the stability of the process and uniformity of flow distribution. An important aspect is the implementation of effective membrane cleaning systems (CIP) using alkaline and enzyme solutions, which ensure the full restoration of their filtration properties without damaging the material. This allows reducing operating costs and extending the service life of the equipment.

In general, the improvement of the membrane filtration process in the production of fruit and berry juices should be based on an integrated approach that combines the optimization of technological parameters, rational selection of the type and material of the membrane, effective preparation of raw materials and the implementation of automated control systems. Such an approach will ensure stable quality of the final product, increase production efficiency, reduce energy consumption and contribute to the environmental safety of the technological process. Thus, the results of the study confirm that the use of membrane technologies in the production of fruit and berry juices is a promising direction of development of the food industry, which meets modern requirements for energy efficiency, environmental friendliness and quality of food products.

Bibliography

1. Baklouti S., Ellouze-Ghorbel R., Mokni A., Chaabouni C. Clarification of pomegranate juice by ultrafiltration: study of juice quality and of the fouling mechanism. *Fruits*. 2012. Vol. 67 (3). P. 215–225. https://doi.org/10.1051/fruits/2012010

2. Wibisono Y., Alvianto D., Argo B. D., Hermanto M. B., Witoyo J. E., Bilad M. R. Low-Fouling Plate-and-Frame Ultrafiltration for Juice Clarification: Part 1 – Membrane Preparation and Characterization. *Sustainability*. 2023. Vol. 15(1), 806. https://doi.org/10.3390/su15010806

3. Gulec H. A., Bagci P. O., Bagci U. Clarification of Apple Juice Using Polymeric Ultrafiltration Membranes: a Comparative Evaluation of Membrane Fouling and Juice Quality. *Food and Bioprocess Technology*. 2017. Vol. 10 (5). P. 875–885. https://doi.org/10.1007/s11947-017-1871-x

4. Li Z., Wu C., Huang J., Zhou R., Jin Y. Membrane Fouling Behavior of Forward Osmosis for Fruit Juice Concentration. *Membranes*. 2021. Vol. 11 (8), 611. https://doi.org/10.3390/membranes11080611

5. Deinychenko G., Dmytrevskyi D., Honchar D., Piddubnyi O., Lavreniuk V. Technical review and intellectual property aspects of innovative membrane technologies in juice production. *Прогресивні техніка та технології харчових виробництв ресторанного господарства і торгівлі* : зб. наук. пр. Харків : ДБТУ, 2025. Вип. 1 (37). С. 164–173.

6. Khan F., Ur Rehman W., Younus M., Muhammad A., Ali W., Khan I. Optimal clarification of apple juice using crossflow microfiltration without enzymatic pre-treatment under different operation modes. *NUST Journal of Engineering Sciences*. 2016. Vol. 9 (1). https://doi.org/10.24949/njes.v9i1.178

7. Fahmi M. M. S., Qun W. FO-based integrated system for juice concentration: system design and experimental investigation. *Distilat: Jurnal Teknologi Separasi*. 2024. Vol. 11 (1). https://doi.org/10.33795/distilat.v11i1.6875

8. Deynychenko G., Guzenko V., Dmytrevskyi D., Chervonyi V., Kolisnichenko T., Omelchenko O., Nykyforov R. Study of the new method to intensify the process of extraction of beet pulp. *Eastern-European Journal of Enterprise Technologies*. 2018. Vol. 4(11–94). P. 15–20. https://doi.org/10.15587/1729-4061.2018.140126

9. Bhattacharjee C., Saxena V.K., Dutta S. Fruit juice processing using membrane technology: a review. *Innovative Food Science and Emerging Technologies*. 2017. Vol. 43. P. 136–153. https://doi.org/10.1016/j.ifset.2017.02.009

10. Deynichenko G., Dmytrevskyi D., Guzenko V., Omelchenko O., Perekrest V. Prospects of using equipment for membrane separation of food liquids. *Науковий вісник Таврійського державного агротехнологічного університету: електронне наукове фахове видання* / ТДАТУ ; гол. ред. д-р техн. наук, проф. В. М. Кюрчев. Запоріжжя : ТДАТУ, 2023. Вип. 13, том 2. С. 1–11. https://doi.org/10.31388/2220-8674-2023-2-12

11. Akpinar O. S., Kayiran Ö. Effects of pretreatment and various operating parameters on permeate flux and quality during ultrafiltration of apple juice. *International Journal of Food Science & Technology*. 2012. Vol. 47 (2). P. 315–324. https://doi.org/10.1111/j.1365-2621.2011.02729.x

12. Deynichenko G., Dmytrevskyi D., Honchar D., Chervonyi V., Horielkov D. Review and analysis of membrane juice processing in food industry enterprises. *Праці Таврійського державного агротехнологічного університету : наукове фахове видання* / ТДАТУ ; гол. ред. д-р техн. наук, проф. В. М. Кюрчев. Запоріжжя : ТДАТУ, 2025. Вип. 25, т. 2. С. 148–156. https://doi.org/10.32782/2078-0877-2025-25-2-18

13. Rai R. et al. Potential of nanofiltration for the concentration of bioactive compounds from watermelon juice. *International Journal of Food Science & Technology*. 2014. Vol. 49 (9). P. 2052–2060. https://doi.org/10.1111/ijfs.12505

14. Hameed K.W. Concentration of Orange Juice Using Forward Osmosis Membrane Process. *Iraqi Journal of Chemical and Petroleum Engineering*. 2013. Vol. 14(4). P. 71–79. https://doi.org/10.31699/IJCPE.2013.4.8

15. Apaydın A.S., Bağcı P.O. Applications of membrane separation techniques in fruit juice processing. *GIDA – The Journal of Food*. 2025. Vol. 50(3). P. 442–465. https://doi.org/10.15237/gida.GD25027

16. Surur Fahmi M. M., Qun W. FO-based integrated system for juice concentration: system design and experimental investigation. *Distilat: Jurnal Teknologi Separasi*. 2025. Vol. 11 (1). P. 84–97. https://doi.org/10.33795/distilat.v11i1.6875

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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ПРОЦЕСУ МЕМБРАННОЇ ФІЛЬТРАЦІЇ У ВИРОБНИЦТВІ ПЛОДОВОЯГІДНИХ СОКІВ

Анотація

У статті досліджено шляхи підвищення ефективності процесу мембранної фільтрації у виробництві плодовоягідних соків. Розглянуто переваги застосування мембранних технологій як енергоощадного й екологічно безпечного методу очищення, що дає змогу отримати високоякісні соки без втрати природних властивостей. Описано основні етапи технологічної схеми: підготовку сировини, ферментативну обробку, попереднє фільтрування, основну мембранну фільтрацію, промивання мембран і стабілізацію готового продукту. Проведено аналіз впливу ключових технологічних параметрів – тиску, температури, швидкості потоку та типу мембрани – на швидкість і стабільність процесу. Встановлено, що оптимальні умови для ультрафільтрації становлять тиск 0,3…0,6 МПа і температуру 25…35 °С, що забезпечує високу продуктивність та мінімальне забруднення мембран. Зазначено, що попередня ферментативна обробка сировини підвищує ефективність процесу, а використання антифолінгових мембран сприяє продовженню їх терміну служби. Результати дослідження підтверджують ефективність комплексного підходу до вдосконалення мембранної фільтрації, який дає можливість покращити якість соків, зменшити енергоспоживання та підвищити екологічну стійкість виробництва.

***Ключові слова*:** мембранна фільтрація, плодовоягідні соки, ультрафільтрація, очищення, селективність мембран, якість продукту, технологічні параметри.