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TECHNOLOGICAL ASPECTS AND PROSPECTS FOR THE DEVELOPMENT OF ULTRAFILTRATION IN MEMBRANE SYSTEMS

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The article considers the technological aspects of ultrafiltration in membrane systems for cleaning and concentrating juices. The main process parameters, fouling problems and modern approaches to increasing efficiency are analyzed. The prospects for using innovative membrane materials and combined technologies are determined. The directions of process optimization for improving the quality of juice products and reducing energy costs are substantiated.

Keywords: *ultrafiltration, membrane technologies, juices, concentration, purification, fouling, membrane equipment, innovations, food industry, energy efficiency.*

ТЕХНОЛОГІЧНІ АСПЕКТИ ТА ПЕРСПЕКТИВИ РОЗВИТКУ УЛЬТРАФІЛЬТРАЦІЇ В МЕМБРАННИХ СИСТЕМАХ

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У статті розглянуто сучасні технологічні аспекти ультрафільтрації як одного з ключових мембранних методів очищення та концентрування соків у харчовій промисловості. Проаналізовано особливості процесу розділення компонентів соків без використання високих температур, що дозволяє зберігати їхні природні властивості, включаючи біологічно активні речовини, аромат і колір.

Визначено основні параметри, що впливають на ефективність ультрафільтрації, зокрема трансмембранний тиск, гідродинамічні умови та характеристики мембран. Окрему увагу приділено проблемі фолінгу, який є основним обмежуючим фактором стабільної роботи мембранних систем і призводить до зниження продуктивності процесу.

Розглянуто сучасні підходи до підвищення ефективності ультрафільтрації, включаючи попередню обробку сировини, застосування ферментативних методів, використання модифікованих мембран та оптимізацію гідродинамічних режимів. Проаналізовано перспективи інтеграції ультрафільтрації з іншими мембранними технологіями для досягнення більш високого ступеня очищення та концентрування соків.

Обґрунтовано доцільність подальших досліджень у напрямі вдосконалення мембранного обладнання, підвищення його енергоефективності

та зменшення впливу фолінгу. Отримані результати можуть бути використані для розвитку інноваційних технологій у виробництві сокової продукції та підвищення її якості.

Ключові слова: *ультрафільтрація, мембранні технології, соки, концентрування, очищення, фолінг, мембранне обладнання, інновації, харчова промисловість, енергоефективність.*

Statement of the problem. The modern development of the food industry, in particular the juice production sector, is accompanied by increasing requirements for the quality of finished products, their nutritional value and safety. Traditional methods of concentrating and purifying juices, in particular thermal evaporation and filtration, have significant disadvantages, including high energy consumption, partial loss of biologically active substances, changes in organoleptic indicators and a decrease in the content of vitamins. In this regard, it is urgent to search for and implement alternative technological solutions that allow minimizing the negative impact on product quality and increasing production efficiency [1].

One of the promising areas is the use of membrane methods, in particular ultrafiltration, which ensure the separation of juice components at the molecular level without the use of high temperatures. This makes it possible to preserve the natural properties of the product, including aroma, color and content of nutrients [2]. However, despite its significant advantages, the widespread introduction of ultrafiltration into technological processes of the juice industry is hampered by a number of technical and economic problems [3].

The main ones include the phenomena of concentration polarization and membrane fouling (fouling), which lead to a decrease in equipment productivity, increased energy consumption and the need for frequent cleaning or replacement of membrane elements [4]. In addition, there are limitations on the selectivity of membranes, which makes it difficult to achieve the optimal degree of purification and concentration without losing valuable juice components. The issues of optimizing hydrodynamic modes, choosing membrane materials and integrating ultrafiltration with other technological processes remain insufficiently studied [5].

Thus, there is a need for a comprehensive study of the technological aspects of ultrafiltration in membrane systems for juice processing, aimed at increasing the efficiency of concentration and purification processes, reducing operating costs and ensuring stable quality of the finished product. Solving these problems is an important task both from a scientific and practical point of view, which determines the relevance of further research in this direction.

Review of the latest research and publications. Modern scientific research in the field of membrane technologies indicates the active development

of ultrafiltration as an effective method of cleaning and concentrating juices. Most works emphasize that the use of ultrafiltration allows to achieve a high degree of removal of colloidal particles, pectins and proteins without significant impact on the organoleptic properties of the product, which is a significant advantage compared to traditional processing methods [6].

Considerable attention is paid by researchers to the problem of membrane fouling (fouling), which is a key factor limiting the efficiency of the process. It has been established that fouling has a complex multifactorial nature and includes mechanisms of pore blocking, formation of a sedimentary layer and adsorption of juice components on the membrane surface [7]. At the same time, the main factors affecting the intensity of fouling are the properties of the raw material, process parameters (pressure, flow rate, temperature) and membrane characteristics [8].

Some studies are aimed at studying the influence of the physicochemical properties of membranes on the ultrafiltration process. In particular, it has been established that the surface charge and porosity of the membrane significantly affect the degree of its fouling and cleaning efficiency [9]. Membranes with a more pronounced negative charge may demonstrate an increased tendency to fouling, which requires optimization of their characteristics [10].

An important area of research is also the optimization of technological modes of ultrafiltration. Experimental work shows that there is an optimal range of transmembrane pressure at which the maximum permeate flux is achieved, while a further increase in pressure does not lead to an increase in productivity due to the intensification of fouling. This indicates the need for rational selection of equipment operating modes [11].

In addition, a significant number of modern publications are devoted to methods for reducing fouling. Among them, preliminary treatment of juices (in particular, enzymatic depectinization), modification of membrane surfaces, improvement of hydrodynamic conditions and the use of combined technologies are distinguished. In particular, the use of enzymatic treatment allows to reduce the duration of filtration and increase the productivity of the process, although it may be accompanied by partial losses of biologically active substances.

Thus, the analysis of modern research shows that, despite significant achievements in the development of ultrafiltration technologies for juice processing, a number of problems remain unresolved. In particular, further research is required to increase the resistance of membranes to contamination, optimize technological parameters, and develop innovative materials and

designs of membrane equipment, which will ensure increased efficiency of juice purification and concentration processes.

The objective of the research. The purpose of the article is to study the technological aspects of ultrafiltration in membrane systems during the purification and concentration of juices, as well as to identify prospects for increasing the efficiency of the process by implementing innovative solutions and optimizing equipment operating modes.

Materials and methods. The methodological basis of the study is an analytical approach to the assessment of ultrafiltration processes in membrane systems during the purification and concentration of juices. The work uses the results of modern scientific publications, experimental studies, as well as theoretical models describing mass transfer, hydrodynamics and membrane fouling phenomena. The analysis was carried out using a systems approach, which allows for a comprehensive assessment of the impact of technological parameters on the efficiency of the process [12].

The main method of the study is a comparative analysis of existing ultrafiltration technologies, in particular, taking into account different types of membranes, equipment designs and operating modes. Particular attention is paid to assessing the impact of transmembrane pressure, flow rate and temperature on the productivity of the process, as well as on the intensity of concentration polarization and fouling phenomena. For this purpose, generalized dependencies obtained as a result of processing literary sources, as well as analytical equations describing the change in permeate flow over time, were used [13].

Working hypotheses were formulated within the framework of the study to increase the efficiency of ultrafiltration of juices. In particular, it is suggested that optimizing the hydrodynamic conditions in the channels of the membrane apparatus allows to reduce the intensity of the formation of a sediment layer and increase the stability of the permeate flow. Another hypothesis is that the use of membranes with a modified surface can contribute to reducing the adsorption of colloidal particles and, accordingly, reducing the level of fouling [14].

In addition, the hypothesis regarding the effectiveness of combining ultrafiltration with previous methods of juice processing, such as enzymatic treatment or microfiltration, was considered, which potentially allows to improve the selectivity of the process and reduce the load on the membranes. To test these hypotheses, the method of logical-analytical generalization of the results of research by various authors and the construction of cause-and-effect relationships between the parameters of the process and its effectiveness was used [15].

The processing of the obtained data was carried out using the methods of generalization, interpretation and critical analysis, which allowed to formulate reasonable conclusions regarding the prospects for improving membrane equipment and ultrafiltration technologies in the juice industry.

Presentation of the research material. Ultrafiltration as one of the key membrane processes occupies an important place in the technologies of purification and concentration of juices, ensuring effective separation of components without significant impact on their physicochemical and organoleptic properties. Unlike traditional thermal methods, membrane processes are implemented at moderate temperatures, which allows preserving biologically active substances, in particular vitamins, phenolic compounds and aromatic components. This determines the feasibility of their use in the production of high-quality juice products.

Analysis of the technological aspects of ultrafiltration shows that the efficiency of the process largely depends on a set of parameters, among which the key ones are transmembrane pressure, flow rate and temperature of the medium. With increasing transmembrane pressure, an increase in the permeate flow is observed, but only to a certain critical value, after which the productivity stabilizes or even decreases. This is explained by the intensification of concentration polarization phenomena and the formation of a sedimentary layer on the membrane surface. Thus, pressure optimization is one of the determining factors in increasing the efficiency of the process [16].

Hydrodynamic conditions play an important role in ensuring the stability of ultrafiltration. The use of tangential filtration mode contributes to a decrease in the thickness of the boundary layer and intensification of mass transfer, which, in turn, allows maintaining a higher permeate flux for a long time. Increasing the flow circulation speed reduces the accumulation of particles on the membrane surface, but is accompanied by an increase in energy consumption, which requires finding compromise solutions between productivity and cost-effectiveness of the process [17].

One of the main problems of juice ultrafiltration is membrane fouling, which manifests itself in the form of a decrease in permeability due to pore blockage and the formation of sedimentary layers. The main components that cause contamination are pectin substances, proteins and polyphenols, which have the ability to aggregate and adsorb on the membrane surface. As a result of this process, the separation efficiency decreases, operating costs increase and the service life of the membranes is shortened.

Figure 1 shows the scheme of ultrafiltration process for juice treatment.

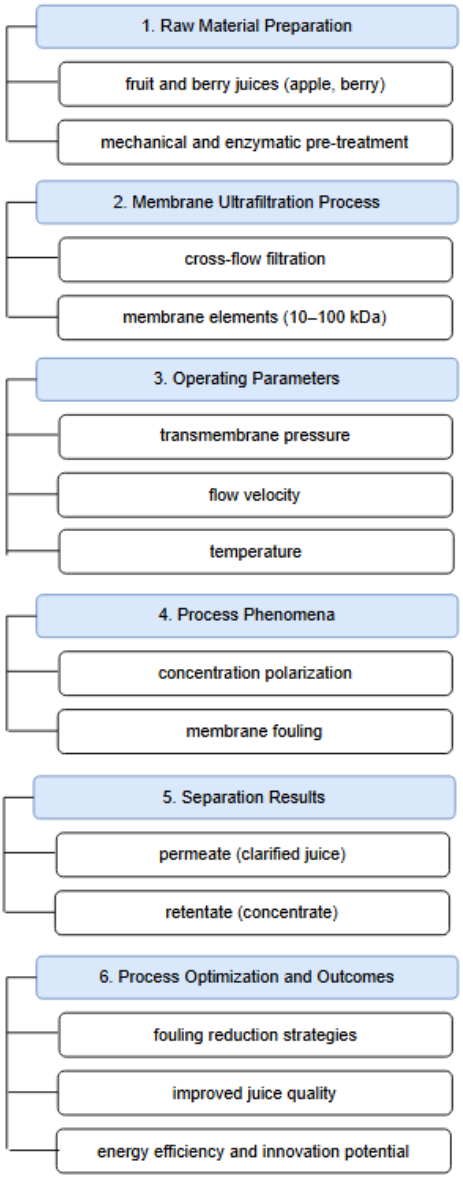

Fig. 1. Scheme of ultrafiltration process for juice treatment

The study analyzed approaches to reducing the intensity of fouling. One of the effective solutions is the preliminary enzymatic treatment of juices, aimed at the destruction of pectin structures. This helps to reduce the viscosity of the medium and reduce the number of colloidal particles, which, in turn, improves the filtration conditions. At the same time, it is necessary to take into account the possible losses of individual biologically active components, which requires optimization of enzymatic treatment modes.

Table 1 shows a comparison of juice processing methods.

Table 1

Comparison of juice processing methods

Processing Method	Principle	Advantages	Disadvantages	Impact on Juice Quality
Thermal evaporation	Water removal by heating	High productivity, simple technology	High energy consumption, degradation of vitamins	Significant loss of aroma and bioactive compounds
Mechanical filtration	Separation based on particle size	Low cost, easy operation	Low selectivity	Partial clarification, colloids remain
Ultrafiltration	Pressure-driven membrane separation	Preservation of quality, no thermal impact	Membrane fouling, need for cleaning	High quality, retention of bioactive components
Reverse osmosis	Solvent transport through semi-permeable membrane	High degree of concentration	High pressure required, expensive membranes	Very high concentration, possible taste changes
Integrated membrane processes	Combination of UF, MF, RO	High efficiency and selectivity	System complexity, high cost	Optimal product quality and stability

A promising direction is also the use of modified membranes with increased hydrophilicity and a reduced level of adsorption interaction with

juice components. Such membranes are characterized by greater resistance to contamination and the ability to provide a stable permeate flow. In addition, new composite materials are being developed that combine high selectivity and mechanical strength, which is important for long-term operation of the equipment.

Analysis of innovative solutions shows that the integration of ultrafiltration with other membrane processes, in particular microfiltration and reverse osmosis, has significant potential. Such a combined approach allows for deeper purification and effective concentration of juices while reducing the load on individual stages of the process. In particular, preliminary microfiltration helps to remove coarse particles, which reduces the intensity of fouling at the ultrafiltration stage. Special attention is paid in the study to the hypothesis regarding the influence of hydrodynamic turbulization on the efficiency of the process. It is assumed that the creation of turbulent flows in the channels of the membrane apparatus can contribute to the destruction of the boundary layer and increase the intensity of mass transfer. This can be achieved by using special turbulators or optimizing the geometry of the channels. Preliminary analysis confirms the feasibility of this approach, but requires further research to determine the optimal design solutions. Thus, the results of the study indicate that increasing the efficiency of juice ultrafiltration is possible with a comprehensive approach, which includes optimizing technological parameters, improving the design of membrane equipment and introducing innovative materials. Of particular importance is the reduction of fouling intensity and ensuring process stability, which are key factors for the widespread introduction of membrane technologies in the food industry.

Conclusion. As a result of the study, it was found that ultrafiltration is an effective method of cleaning and concentrating juices, which ensures the preservation of their qualitative and biologically valuable characteristics in comparison with traditional thermal processing methods. It was determined that the key factors affecting the efficiency of the process are transmembrane pressure, hydrodynamic conditions and membrane properties.

It was confirmed that the main limiting factor in the application of ultrafiltration is the phenomenon of fouling, which leads to a decrease in productivity and an increase in operating costs. In this regard, the feasibility of using pre-treatment of raw materials, optimization of operating modes and the use of modified membranes with increased resistance to contamination was substantiated.

The prospects of integrating ultrafiltration with other membrane processes were proven, which allows to increase the efficiency of cleaning and concentrating juices. The proposed analytical approaches and formulated hypotheses can be used for further improvement of membrane equipment and technologies aimed at increasing energy efficiency, process stability and quality of finished products.

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