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MEMBRANE PROCESSING OF APPLE JUICE AS AN INNOVATIVE DIRECTION IN THE FOOD INDUSTRY

Summary. The article considers the application of membrane technologies in the production of apple juice as an innovative direction of development of the food industry. A comprehensive analysis of modern membrane processing methods, in particular microfiltration, ultrafiltration, nanofiltration and reverse osmosis, is carried out, which allow to ensure transparency, stability and high organoleptic quality of the product. Special attention is paid to the problem of membrane fouling, which is the main technical challenge in the processing of apple juice, and methods for its minimization are considered, including enzymatic preparation of raw materials, optimization of hydrodynamic modes and the use of ceramic membranes. The analysis shows that membrane processes allow to preserve a high content of biologically active components, such as vitamin C, polyphenols and volatile aromatic substances, and also provide energy savings and a reduction in the use of chemical reagents compared to traditional methods of concentration and clarification. The prospects for integrating membrane stages into combined technological schemes are considered, which contributes to increasing the productivity and quality of the final product. The economic and environmental aspects of the implementation of membrane technologies at industrial enterprises are highlighted. The conclusions of the article indicate that membrane processing of apple juice is an effective and environmentally safe innovative solution capable of ensuring the competitiveness of enterprises and high organoleptic and biological characteristics of the product.

Keywords: membrane treatment, apple juice, microfiltration, ultrafiltration, nanofiltration, reverse osmosis, biologically active substances, environmental safety, innovative technologies.

Formulation of the problem. The modern food industry is in the process of actively searching for new technological solutions that can improve product quality, preserve its natural properties and simultaneously reduce production costs. Juice production, in particular apple juice, is one of the most dynamic industries in the world, because apples are one of the most common and affordable fruits, and their processed products occupy a significant share of the beverage market.

However, traditional methods of processing apple juice (clarification, stabilization, concentration) have a number of significant disadvantages associated with high energy costs, the use of excipients and partial loss of biologically active components. In particular, classical methods of clarifying apple juice involve the use of adsorbents, enzymes, gelatin, bentonite or other substances, which not only increase the cost of the finished product, but also cause additional difficulties in cleaning production lines and waste disposal. Thermal pasteurization and evaporation during juice concentration cause the destruction of thermolabile vitamins, aromatic and polyphenolic compounds, which reduces the nutritional and functional value of the product. In addition, traditional processing methods do not

always guarantee a sufficient level of microbiological stability without significant impact on organoleptic properties [1].

In response to these challenges, interest in membrane technologies is growing, which have already found wide application in water treatment, pharmaceutical and biotechnology industries. Their feature lies in the possibility of selective separation of components of multicomponent systems through the use of semipermeable membranes. In the food industry, membrane processes, in particular microfiltration, ultrafiltration, nanofiltration and reverse osmosis, demonstrate significant potential for juice processing. They allow for the effective removal of colloidal particles, microorganisms, macromolecules without the use of chemical reagents and without significant losses of nutrients.

Membrane technologies are of particular importance for apple juice, as this product is characterized by a high content of polyphenols, organic acids, aromatic components that are sensitive to heat treatment. The use of membrane treatment allows you to preserve the natural taste, color and nutritional value of the juice, while ensuring its microbiological stability and long shelf life. Such advantages correspond to modern trends in the food industry, where products with minimal processing and high natural quality are becoming increasingly popular [2].

At the same time, the introduction of membrane technologies in the production of apple juices is accompanied by a number of problems and tasks that need to be solved. One of the main ones is ensuring stable operation of membranes and preventing their contamination (fouling). The accumulation of colloidal particles, pectin substances, proteins and microorganisms on the surface of the membranes significantly reduces the productivity of the process and requires frequent washing or replacement of membrane modules. This, in turn, affects the economic feasibility of using the technology on an industrial scale [3].

In addition, there is a need to develop optimal filtration modes and select appropriate membrane materials that will ensure maximum selectivity and durability. An important aspect is also the energy efficiency of membrane processes: although they are characterized by lower heat consumption, they require significant energy resources to create the necessary pressure during nanofiltration or reverse osmosis [4].

An equally urgent problem is the lack of standardized technological schemes for membrane processing of apple juice, which complicates their widespread implementation at enterprises of various scales. Scientifically based recommendations are needed for the selection of technological parameters, integration of membrane processes into existing production lines, economic justification and environmental assessment of their application [5].

Given the growing consumer demand for natural, environmentally safe and high-quality juices, the use of membrane technologies can be considered as an innovative direction in the development of the food industry. However, for its implementation it is necessary to comprehensively solve a number of scientific and technical problems: from studying the processes of interaction of juice components with membrane materials to optimizing the design of membrane plants and developing recommendations for industrial use [6].

Thus, the problem is to find effective solutions for the implementation of membrane technologies in the apple juice processing process, taking into account the quality of the final product, economic feasibility and environmental safety. Solving this problem will significantly increase the competitiveness of domestic enterprises, promote the development of innovative technologies in the food industry and ensure the production of products that meet modern consumer requirements and world quality standards.

Analysis of recent research and publications. Recent years have been marked by intensive development and in-depth study of membrane technologies for processing fruit juices, in particular apple juice. General reviews of the literature emphasize that membrane processes (microfiltration – MF,

ultrafiltration – UF, nanofiltration – NF, reverse osmosis – RO) are considered as promising non-thermal methods that allow combining clarification, stabilization and partial concentration of juice with minimal losses of biologically active compounds and organoleptic properties. Thus, comparative reviews of recent years note an increase in the number of studies aimed at optimizing filtration modes, selecting membrane materials and integrating membrane stages into combined technological schemes.

A separate line of research is devoted to the problem of fouling – the accumulation of colloids, pectins, proteins and microorganisms on the surface of membranes, which causes a decrease in throughput and deterioration of operational characteristics. A number of recent works have analyzed in detail the mechanisms of fouling in apple juice processing and proposed strategies to minimize it: preliminary enzymatic degradation of pectin, optimization of hydrodynamics (mainly cross flow and high tangential velocity), periodic backwashing, use of diafiltration, and selection of membranes with low hydrophobicity or modified surface. Reviews emphasize that the combination of technological approaches gives the greatest effect in increasing the stability of the flow and the duration of inter-cleaning. Another important trend is the active study and implementation of ceramic membranes. The advantages of ceramics (higher chemical and thermal resistance, the possibility of aggressive washing regime, longer service life) make it attractive for industrial conditions where precise and regular cleaning is critical. The 2023–2024 reviews summarize experimental results on the use of ceramic MF/UF membranes for clarification and cold sterilization of apple products: high removal of cellular impurities and microorganisms is demonstrated while preserving dissolved aromatic and polyphenolic components, although the issues of energy costs and initial capital investment remain the subject of economic analysis [7].

Studies aimed at concentrating and preserving aromatics show that NF and RO processes can be used not only to reduce water content, but also to selectively concentrate certain low-molecular compounds – in particular, sugars and aromatic components. Laboratory and pilot experiments indicate a complex balance between the restoration of the flavor profile and the behavior of solutes; optimal operating parameters and the selection of membranes with appropriate pore size and surface-chemical properties critically affect the final composition of the retentate and permeate. Some works also demonstrate the potential of integrating membrane stages with aroma recovery technologies (e.g., using steam or adsorption systems after membrane concentration) to compensate for possible losses of volatile compounds [8].

New publications in recent years also focus on integrated schemes: the combination of MF/UF for pre-clarification and colloid removal followed by NF/RO for concentration or selective separation of components has shown good results in preserving color, aroma and antioxidant activity while achieving microbiological stability. Extensive experiments with a combination of pressure membrane processes and osmotic/piezocomponent methods allow obtaining concentrates with a high content of target compounds, as well as using the permeate to create low-calorie drinks or for further fermentation [9].

At the same time, considerable attention is paid to non-traditional approaches to raw material preparation: pre-membrane treatments (enzymatic depectinization, cold plasma modifications, ultrasonic treatment) show varying degrees of effectiveness in reducing fouling and improving membrane permeability. Some experiments show that the combination of enzymatic treatment with ultrafiltration allows to significantly increase the initial flow and reduce the rate of thickening of the layer on the membrane, although the issues of optimizing enzyme doses and treatment time require further clarification [10].

Economic and environmental aspects remain key for industrial implementation: modern review articles emphasize the need for comprehensive life-cycle assessments, comparing capital investments and operating costs compared to traditional technologies, taking into account the costs of washing

reagents and energy resources. Many researchers state that membrane solutions can already be competitive for medium and large plants today, provided that the regimes are optimized and effective measures are implemented to combat fouling.

Based on the analysis of recent publications, it is clear: scientific interest is shifting from confirming the fundamental suitability of membranes for apple juice processing to solving practical engineering problems – reducing fouling, increasing membrane durability, developing integrated schemes for preserving aroma and nutrients, as well as the economic feasibility of implementation. Further research should focus on scaling up successful laboratory-pilot solutions, standardizing process schemes, and conducting detailed economic and environmental assessments for broad industrial application.

Formulation of the purpose of the article. The purpose of the article is to comprehensively analyze and justify the feasibility of using membrane technologies in the process of apple juice processing as an innovative direction of development of the food industry. In particular, the impact of membrane processes on the quality characteristics of juice, their advantages compared to traditional clarification and concentration methods, and the key problems and prospects for the implementation of these technologies on an industrial scale are investigated.

Presentation of the main research material. Membrane technologies have become widespread in the food industry in recent decades due to their versatility, energy efficiency and ability to ensure a high level of quality of the final product. They are especially relevant in the field of juice production, where the requirements for transparency, stability, taste and aroma characteristics, as well as the preservation of biologically active substances are key criteria for consumers. Traditional methods of clarification and concentration of juices, such as the use of excipients, heating, centrifugation or vacuum evaporation, although time-tested, are often accompanied by significant energy costs, a decrease in the nutritional and biological value of the product, and a partial loss of vitamins and volatile aromatic components. In this context, the introduction of membrane processes into the technology of apple juice processing is considered a promising innovative direction, capable not only of improving product quality, but also of optimizing economic and environmental parameters of production [11].

The use of microfiltration allows for pre-cleaning and removal of suspended particles, cell debris and microorganisms, ensuring basic product transparency without the use of centrifugation or auxiliary filter media. At the next stage, ultrafiltration contributes to deep clarification and stabilization of apple juice by removing pectin substances and high-molecular proteins, which are responsible for turbidity and reduced stability [12].

Membrane processes are physical methods of separating liquid media based on the selective passage of molecules and particles through semipermeable membranes under the influence of pressure, concentration or potential differences. In the case of juice processing, microfiltration, ultrafiltration, nanofiltration and reverse osmosis are the most widely used. Each of these methods has its own specific properties that determine the scope of application in apple juice processing technology. For clarity, their characteristics can be summarized in the table 1.

Nanofiltration provides selective separation of low-molecular impurities and partial desalting, which helps preserve taste and biological value. Reverse osmosis is used to concentrate juice without heating, which is a key advantage in preserving aromatic and vitamin substances. One of the most significant challenges in the application of membrane technologies in the production of apple juice is the phenomenon of fouling, i.e. the formation of deposits of colloids, proteins, pectins and microorganisms on the surface of membranes. This leads to a decrease in membrane productivity, increased energy consumption and the need for frequent cleaning. A number of strategies for combating fouling have been described in the scientific literature. One of the most effective approaches is the enzymatic pretreatment of apple juice with pectolytic enzymes, which destroy high-molecular complexes and reduce their accumulation on the membrane. In addition, the use of cross-flow during filtration and

maintaining an optimal liquid circulation rate significantly reduces the formation of sediment on the membrane surface. In practice, periodic backwashing and diafiltration are also used, which increases the stability of the process. Significant results have been obtained through the use of ceramic membranes, which are characterized by high chemical and thermal resistance, which allows the use of more intensive cleaning modes and increases the service life of the membranes [13].

Table 1

Properties of membrane juice processing processes

Process	Membrane pore size	Pressure, mpa	Main purpose in apple juice processing
Microfiltration	0,1…1,0 microns	0,1…0,3	removal of suspended particles, cells, colloids, initial clarification
Ultrafiltration	1…100 nm	0,1…0,5	removal of pectins, proteins, colloids; deep clarification and stabilization
Nanofiltration	0,5…2 nm	0,4…1,0	Partial desalting, retention of sugars and phenolic compounds, concentration
Reverse osmosis	< 0,5 nm	1,0…7,0	Concentration of juice by removing water, obtaining high-quality concentrates

The issue of energy efficiency and economic feasibility of membrane processes also attracts considerable attention from researchers and manufacturers. Compared to traditional concentration methods, such as vacuum evaporation, reverse osmosis is characterized by significantly lower energy costs, since the process occurs at room temperatures and does not require significant thermal resources. This allows not only to preserve the volatile aromatic components and vitamin composition of apple juice, but also to significantly reduce the cost of production in the long term. At the same time, the high cost of membrane equipment and the need for regular replacement or cleaning of membranes can act as a deterrent for enterprises with small production capacities. Another important advantage of membrane technologies in the production of apple juice is the ability to integrate different processes into a single technological scheme. For example, the combination of microfiltration and ultrafiltration allows to achieve a high degree of transparency and stability of the product, while the subsequent use of nanofiltration or reverse osmosis contributes to the production of high-quality concentrates. This approach allows to maximally preserve the natural taste, color and aroma of apple juice, while ensuring its microbiological safety and long-term stability during storage [14].

In the practical plane, studies aimed at assessing the impact of membrane processes on the preservation of biologically active compounds of apple juice are of great importance. It has been established that the use of ultrafiltration and nanofiltration allows to preserve the majority of polyphenolic compounds that determine the antioxidant activity of the product. In the case of reverse osmosis, high efficiency is observed in concentrating sugars and phenolic substances while simultaneously reducing the loss of volatile components, which is especially important for the formation of aroma and taste. However, to achieve maximum results, careful adjustment of process parameters is required, in particular, pressure, temperature and flow rate, which requires a high level of technological competence of personnel.

Figure 1 shows a diagram of the equipment for membrane juice processing.

From an environmental point of view, membrane technologies also have significant advantages. They allow for a reduction in the use of auxiliary substances traditionally used for juice clarification (e.g. bentonite or gelatin), which reduces the burden on the environment and facilitates waste disposal. In addition, reducing energy consumption in the juice concentration process contributes to a reduction in carbon dioxide emissions, which is in line with current trends in sustainable development and environmental responsibility of the food industry. Among the promising areas of development

of membrane technologies for the production of apple juice, one can single out the improvement of membrane materials. Scientific research focuses on the creation of membranes with a modified surface, which are characterized by increased resistance to fouling and microbiological contamination. There is considerable interest in combining membrane processes with non-traditional methods of raw material pre-treatment, such as ultrasonic cavitation or cold plasma treatment, which can provide even higher filtration efficiency. It is also important to integrate membrane processes into complex production systems with the recovery of aromatic components and secondary use of permeate, for example, for the production of low-calorie drinks or for biotechnological processes.

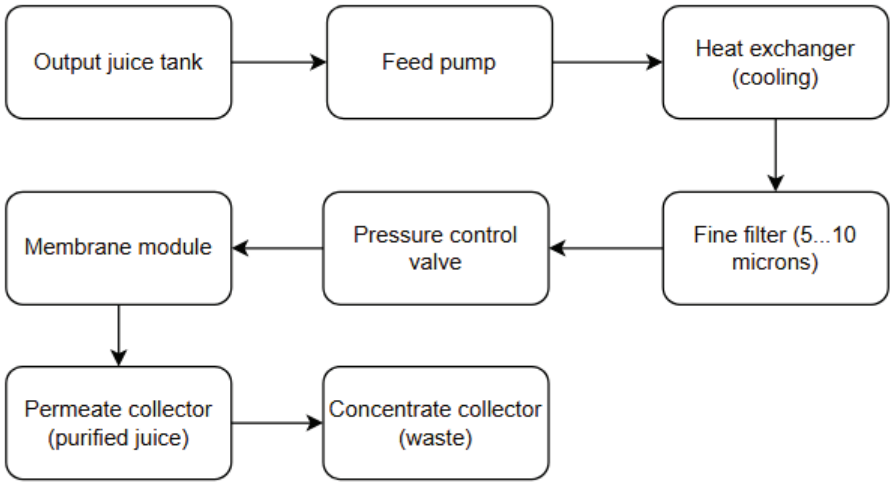

Fig. 1. Schematic diagram of equipment for membrane juice processing

Thus, the analysis of the current state and trends in the development of membrane technologies in the production of apple juice indicates their high efficiency and feasibility of implementation as an innovative direction in the food industry. The use of microfiltration, ultrafiltration, nanofiltration and reverse osmosis allows you to obtain high-quality products while preserving natural properties, reduce energy costs and environmental impact, and increase the economic competitiveness of production. Despite the existing challenges associated with the phenomenon of fouling, the high cost of equipment and the need for specialized maintenance, the development of materials science, optimization of technological modes and integration of various methods allow you to gradually overcome these limitations. In the future, we can expect further spread of membrane processes in the juice industry, in particular apple juice, which will contribute to improving product quality, expanding the range and ensuring sustainable development of food enterprises.

Conclusions. The analysis of the features of the application of membrane technologies in the production of apple juice allows us to conclude that they are a promising innovative tool capable of ensuring high product quality, increasing the economic efficiency of production and reducing its environmental impact. The use of microfiltration and ultrafiltration provides reliable clarification and stabilization of juice, while nanofiltration and reverse osmosis allow us to obtain concentrates with maximally preserved taste and aromatic properties. Of particular importance is the fact that these processes occur without thermal effects, which allows us to preserve vitamins, polyphenols and other biologically active substances. Despite the existence of problems associated with membrane fouling, the high cost of equipment and the need for careful adjustment of modes, modern research and development are aimed at overcoming them by creating new membrane materials, improving technological schemes and integrating various processing methods. Given the global trends towards sustainable

development of the food industry, membrane processes have all the prerequisites for widespread industrial implementation in the production of apple juice, ensuring the competitiveness of enterprises and high quality of the final product.

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МЕМБРАННА ОБРОБКА ЯБЛУЧНОГО СОКУ ЯК ІННОВАЦІЙНИЙ НАПРЯМ У ХАРЧОВІЙ ПРОМИСЛОВОСТІ

Анотація

У статті розглянуто застосування мембранних технологій у виробництві яблучного соку як інноваційного та перспективного напряму розвитку харчової промисловості. Проаналізовано основні методи обробки, зокрема мікрофільтрацію, ультрафільтрацію, нанофільтрацію та зворотний осмос, які забезпечують високий рівень прозорості, стабільності та органолептичних властивостей кінцевого продукту, а також сприяють збереженню біологічно активних компонентів, зокрема вітаміну С, поліфенолів та летких ароматичних речовин. Особливу увагу приділено проблемі фоулінгу мембран та методам її мінімізації, включаючи ферментативну підготовку сировини, оптимізацію гідродинамічних режимів, застосування поперечного потоку та використання керамічних мембран. Розглянуто інтеграцію мембранних етапів у комбіновані технологічні схеми, що дає змогу підвищити продуктивність процесу, економічну ефективність виробництва та екологічну безпеку. Доведено, що мембранні процеси забезпечують високу стабільність продукту без використання хімічних реагентів та нагрівання, що дає змогу зберегти натуральний смак, аромат і біологічну цінність яблучного соку. Висновки свідчать, що мембранна обробка є ефективним, екологічно безпечним і перспективним рішенням для сучасного виробництва фруктових соків, сприяє підвищенню конкурентоспроможності підприємств та задоволенню потреб споживачів у високоякісних натуральних продуктах харчування.

Ключові слова: мембранна обробка, яблучний сік, мікрофільтрація, ультрафільтрація, нанофільтрація, зворотний осмос, біологічно активні речовини, екологічна безпека, інноваційні технології.