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TECHNICAL REVIEW AND INTELLECTUAL PROPERTY ASPECTS OF INNOVATIVE MEMBRANE TECHNOLOGIES IN JUICE PRODUCTION

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This article presents an analytical and review study of membrane processes and equipment used for juice purification and concentration in the food industry. Special attention is given to technological innovations and the role of intellectual property in protecting membrane solutions. The paper highlights current trends, practical applications, and patent landscape relevant to membrane technologies in juice processing.

Keywords: *membrane technologies, juice production, intellectual property, juice purification, concentration.*

ТЕХНІЧНИЙ ОГЛЯД ТА АСПЕКТИ ІНТЕЛЕКТУАЛЬНОЇ ВЛАСНОСТІ ІННОВАЦІЙНИХ МЕМБРАННИХ ТЕХНОЛОГІЙ У ВИРОБНИЦТВІ СОКІВ

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У статті проведено аналітичне та оглядове дослідження сучасних мембранних процесів і відповідного обладнання, що використовуються для очищення та концентрування соків у харчовій промисловості. Мембранні технології, серед яких основними є мікрофільтрація, ультрафільтрація, нанофільтрація та зворотний осмос, відіграють дедалі важливішу роль у підвищенні ефективності технологічних процесів. Їх застосування дає змогу значно покращити якість кінцевого продукту без необхідності використання високотемпературних методів обробки, що сприяє збереженню корисних речовин, смакових характеристик і натурального кольору соків. У роботі висвітлено принципи дії зазначених процесів, особливості їх реалізації у виробничих умовах, а також класифікацію та властивості мембран, що використовуються у харчових технологіях. Окремо розглянуто технічні характеристики мембранного обладнання, зокрема матеріали виготовлення,

конструктивні рішення, модульність систем, параметри продуктивності та енергоспоживання.

Проведено порівняльний аналіз мембранних методів із традиційними технологіями очищення та концентрації, підкреслено переваги таких рішень у контексті енергоефективності, екологічної безпеки, простоти автоматизації та масштабованості виробництва. Значну увагу приділено аналізу стану інтелектуальної власності у сфері мембранних технологій, що використовуються для обробки соків. На основі патентного пошуку проаналізовано поточний стан патентування інноваційних рішень у цій галузі, визначено провідні країни та компанії, що активно займаються розробкою мембранного обладнання. Встановлено, що патентна активність зростає, що свідчить про інтенсивний розвиток технологій та високу конкурентність ринку.

Розглянуто значення правової охорони інтелектуальної власності для забезпечення комерційного успіху підприємств та стимулювання інноваційної діяльності. Зроблено висновки щодо доцільності впровадження мембранних процесів у виробництво соків та необхідності врахування патентної ситуації при розробці нових технологічних рішень.

Ключові слова: мембранні технології, виробництво соків, інтелектуальна власність, очищення соків, концентрація

Statement of the problem. In the current context of the food industry's development, one of the key challenges is to ensure high product quality while simultaneously reducing energy consumption, optimizing production processes, and complying with environmental standards. This is particularly relevant in juice production, where it is essential to preserve the natural composition, taste, and aroma of raw materials during processing [1]. Traditional methods such as thermal treatment, pasteurization, sedimentation, or mechanical filtration often lead to the degradation of vitamins, loss of biologically active compounds, increased energy use, and the generation of significant by-products [2].

In this regard, innovative membrane technologies are gaining widespread adoption, enabling the physicochemical treatment of juices at the molecular level without the use of high temperatures. Among these, ultrafiltration, microfiltration, nanofiltration, and reverse osmosis are considered the most promising processes [3]. They provide high-quality end products, preserve organoleptic properties, and significantly reduce operational costs. Membrane processes effectively remove suspended solids, microorganisms, and undesirable impurities from juice, while concentrating valuable components [4]. This opens up extensive possibilities for their application in the production of natural juices, nectars, concentrates, and functional beverages [5].

Despite numerous technical advantages, the large-scale implementation of such technologies in industrial production faces several challenges. One of the critical issues is the need to protect intellectual property, encompassing the patenting of membrane designs, modules, process schemes, and methods of integration into production lines. Given the increasing number of patent applications in the field of membrane technologies globally, it is crucial to timely identify emerging technical solutions, analyze patent data, and ensure legal protection of innovations in both national and international jurisdictions [6].

Thus, at the intersection of technical efficiency and legal protection mechanisms lies an urgent problem: identifying the potential of innovative membrane technologies in juice production while simultaneously addressing intellectual property considerations. Solving this issue will not only improve production processes but also enhance the competitiveness of enterprises by safeguarding technological innovations.

Review of the latest research and publications. Over the past few decades, membrane technologies have become a key component in juice processing, increasingly replacing traditional methods such as thermal treatment and evaporation. These innovative approaches allow for the preservation of organoleptic properties and bioactive compounds while reducing energy consumption, aligning with modern demands for product quality and sustainable production [7].

Ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are widely used for the clarification, concentration, and stabilization of fruit juices. A study conducted at Lund University demonstrated that combining RO and evaporation in apple juice processing can reduce energy consumption by 25–40% compared to conventional evaporation methods, while achieving concentrations up to 75 °Brix and retaining 98–99% of sugars and acids [8].

Integrated membrane systems that combine UF, NF, RO, membrane distillation (MD), and osmotic distillation (OD) have enabled the development of compact and energy-efficient production lines. These systems allow for simultaneous filtration, concentration, and aroma recovery, reducing losses of bioactive components [9].

Recent advancements such as electrodialysis with filtration membranes (EDFM) show potential in enriching juices with anthocyanins. A study demonstrated that treatment time significantly influences juice composition, process efficiency, and membrane fouling, with minimal anthocyanin accumulation on cation-exchange membranes and structural changes observed in anion-exchange membranes [10].

Membrane surface modifications, including the application of graphene oxide layers or TiO₂ nanoparticles, have been shown to improve

hydrophilicity, reduce fouling, and enhance selectivity. For example, the use of modified membranes in apple juice treatment resulted in improved anti-scaling properties, color retention, and increased antioxidant activity [11].

In terms of intellectual property, there has been a notable increase in patent activity related to membrane technologies for juice processing. U.S. Patent US4959237A, describes a multi-stage RO system using high-rejection polyamide membranes for juice concentration, improving the flavor profile of the final product. Another patent, WO2021167970A1, presents a juice filtration system that effectively reduces calories and sugar content while enhancing taste by removing bitter compounds [12].

These studies and patent developments emphasize the importance of integrating technological innovation with legal protection mechanisms to enhance the competitiveness and resilience of juice production systems in the global market.

The objective of the research. The purpose of this article is to conduct a comprehensive technical review of modern innovative membrane technologies used in juice production, alongside an analysis of intellectual property aspects related to their development, implementation, and legal protection.

Presentation of the research material. In modern juice production, various membrane filtration methods play a crucial role in ensuring efficient purification, stabilization, and preservation of the product's quality characteristics. Among the most common approaches are dead-end and cross-flow filtration, each with its own features, advantages, and drawbacks. The choice of filtration method directly affects the efficiency of the technological process, the level of equipment contamination, the duration of production cycles, and the final quality of the juice [13]. At the same time, an important aspect of applying innovative membrane technologies is their patent protection and the regulation of intellectual property rights. In juice production practice, intellectual property not only serves the function of legal protection of technical solutions but also acts as a strategic tool for monetizing innovations, establishing partnerships, and commercializing research achievements. This is especially relevant for new types of membranes, purification methods, automated filtration control systems, and combined technological schemes [14].

Dead-end filtration involves the flow of liquid perpendicular to the membrane surface. In this process, all particles larger than the membrane pore size accumulate on the surface, forming a filtration layer. This layer becomes denser over time, reducing membrane productivity. The main advantage of dead-end filtration is the simplicity of equipment design and relatively low initial implementation costs. It works effectively for filtering liquids with a

low content of solid impurities, ensuring a high degree of purification. This approach is suitable for small-scale production or laboratory conditions. However, the use of specific membrane designs in dead-end filtration is the subject of numerous patents, which may limit the use of certain technologies without appropriate licensing or permission from rights holders [15].

Nevertheless, dead-end filtration also has significant disadvantages. Firstly, membranes become contaminated quickly, requiring frequent cleaning or replacement. This reduces the duration of continuous system operation and increases operational costs. Secondly, the formation of the filtration layer decreases system productivity, potentially affecting overall process efficiency. As a result, dead-end filtration is rarely used on an industrial scale without additional membrane cleaning solutions, such as backflushing or chemical agents. These engineering solutions are often patented, providing competitive advantages to their owners and income opportunities through licensing [16].

In contrast, cross-flow filtration involves the flow moving parallel to the membrane surface, which minimizes particle accumulation and reduces the risk of fouling. In this case, part of the liquid passes through the membrane to form the permeate, while the rest continues to flow parallel to the membrane, carrying retained substances to the waste stream [17]. This approach ensures higher system productivity, allows effective operation with liquids containing a large number of suspended solids, and extends membrane lifespan. Patents for cross-flow modules cover new materials, structural solutions, and flow regimes, forming a legal basis for commercial exploitation and intellectual property protection of innovative solutions.

The advantages of cross-flow filtration include stable operation under high loads, reduced need for frequent membrane replacement, and the possibility of prolonged continuous use. This method provides more uniform pressure distribution across the membrane surface, reducing mechanical stress and promoting equipment durability. However, cross-flow filtration requires a more complex system design, greater investment in equipment, and higher energy consumption to maintain the necessary pressure and flow velocity. Nevertheless, these costs are offset by stable operation, reduced production downtime, and improved final product quality. Intellectual property in this field is a key to monetizing innovations through licensing, technology sales, or partnership agreements [18].

Special attention in the context of juice production is given to methods such as microfiltration and ultrafiltration. Microfiltration uses membranes with pore sizes ranging from 0.1 to 10 microns, effectively removing bacteria, suspended particles, and some colloids. This method is widely used at the juice pre-treatment stage, ensuring the removal of unwanted solids without

altering the product's organoleptic properties. Due to operation at low pressure, microfiltration is an energy-efficient technology that reduces operational costs and the risk of thermal damage to sensitive juice components. Recent developments in microfiltration include membranes made from nanostructured polymers, which are the subject of numerous international patents, reflecting high innovation activity in this field [19].

The advantages of microfiltration include the preservation of taste, aroma, and color of the beverage, ease of membrane maintenance, and the ability to integrate into existing processing lines. However, the effectiveness of this method is limited. Microfiltration cannot remove dissolved substances, viruses, and small molecules, which reduces the degree of product stabilization. Additionally, membranes may become quickly fouled when processing liquids with a high colloid content, requiring additional regeneration measures. Legal protection of such solutions enables developers to ensure exclusivity, strengthen market positions, and receive royalties from the commercial use of technologies [20].

Ultrafiltration, in turn, uses membranes with smaller pores 0.01 to 0.1 microns allowing the removal of even fine-dispersed particles, viruses, and protein compounds. This ensures high purification efficiency and biological stability of the final product. Ultrafiltration allows the preservation of vitamins and biologically active substances while reducing microbiological load. The use of ultrafiltration contributes to extending the shelf life of beverages without preservatives, meeting modern requirements for naturalness and environmental friendliness of food products. Companies developing new types of ultrafiltration membranes actively patent their innovations to protect the market, attract investors, and build a high-tech image on the international stage.

Figure 1 shows the technical equipment of the tangential filtration process.

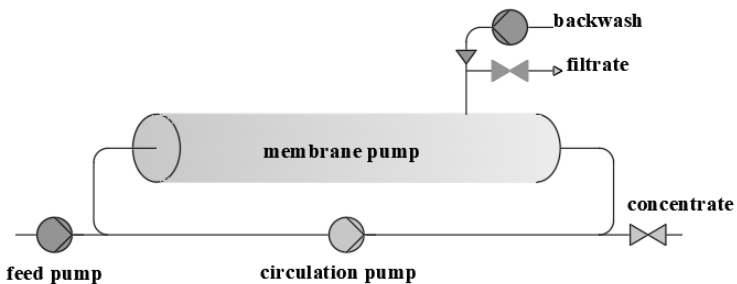


Fig. 1. Technical equipment of the tangential filtration process

The advantages of ultrafiltration include a high degree of purification, the ability to control product composition, and consistent quality over an extended period. However, this method also has certain drawbacks. High equipment and maintenance costs, the need for juice pre-treatment to prevent rapid membrane fouling, and the complexity of process control can limit its application in enterprises with small-scale production. However, obtaining patents for pre-treatment and automatic membrane cleaning processes is a way to ensure technological advantage and legal protection of intellectual property, which is critically important for commercializing research results.

In industrial practice, combined approaches to membrane filtration are increasingly used, combining the benefits of microfiltration and ultrafiltration and optimizing filtration modes (e.g., switching from dead-end to cross-flow depending on working conditions). Such an integrated approach allows not only to ensure high final product quality but also to increase production profitability by reducing losses, energy consumption, and membrane replacement frequency. Furthermore, the use of automated filtration process monitoring and control systems, often developed as part of patented technologies, helps reduce human error and ensures the stability of technological parameters. These technical solutions highlight the importance of legal protection of innovations and the need for strategic management of intellectual property in the agro-industrial sector.

Thus, the choice between dead-end and cross-flow filtration, as well as between microfiltration and ultrafiltration, should be based on an analysis of final product quality requirements, the enterprise's technological capabilities, economic feasibility, and legal aspects of intellectual property. In modern juice production, combinations of these methods are increasingly used to optimize purification processes and preserve the natural properties of beverages. Future development prospects lie in improving membrane materials, increasing their chemical and mechanical resistance, and applying advanced approaches to intelligent filtration process management based on big data analysis and machine learning, with appropriate patent protection to stimulate innovation activity.

Conclusion. In conclusion, membrane filtration technologies represent not only a technical foundation for high-quality juice production but also a dynamic sphere of intellectual property development. Their use ensures high product quality and meets consumer demands for natural, preservative-free beverages. Innovations in filtration methods, supported by patents, contribute to increased production efficiency and competitiveness. The rapidly growing patent landscape encompassing membrane materials, designs, and automated control systems underscores the importance of protecting technological advances. Enterprises that strategically manage their

intellectual property portfolios can capitalize on licensing opportunities, attract investment, and ensure long-term market presence. Therefore, integrating filtration innovations with legal safeguards is essential for sustainable development in the juice processing industry.

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