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DEVELOPMENT AND APPLICATION OF BIOPOLYMER MEMBRANES FOR WATER PURIFICATION FROM HEAVY METALS

[1*]Kabylbekova A., [2]Khaldun M.A.

[1]Miras University, Shymkent, Kazakhstan
[2]University of Jordan, Jordan
**Corresponding author e-mail:aika_kabil@mail.ru*

Authors information:
Kabylbekova Aisulu, Miras University, Shymkent, Kazakhstan, e-mail: aika_kabil@mail.ru. ORCID: https://orcid.org/0000-0003-4167-6800;
Khaldun Mohammad Al Azzam, Department of Chemistry, School of Science, University of Jordan, Jordan. e-mail: k.alazzam@ju.edu.jo ORCID: https://orcid.org/0000-0003-4097-6991.

Abstract — This article discusses biopolymer membranes as an effective method for removing heavy metals from water and wastewater. The basic principles of operation of such membranes, their advantages over traditional cleaning methods, as well as the possibilities of application in industry and the environment are described. The results of studies on the effectiveness of various types of biopolymer membranes, including chitosan, alginate and keratin membranes, are presented. Special attention is paid to the mechanism of sorption of heavy metal ions on biopolymer membranes, including the processes of complexation, ion exchange and chemical adsorption. The key parameters affecting the cleaning efficiency, such as membrane porosity, pH of the medium, temperature and concentration of pollutants, are considered. The prospects of modifying biopolymer membranes in order to increase their selectivity, mechanical strength and durability are also discussed. Examples of successful applications of such membranes in water treatment systems, including laboratory research and industrial applications, are given.
Keywords — biopolymer membranes, heavy metals, water purification, wastewater, chitosan, alginate, keratin, sorption, filtration.

СУДЫ АУЫР МЕТАЛДАРДАН ТАЗАРТУ ҮШІН БИОПОЛИМЕРЛІ МЕМБРАНАЛАРДЫ ЖАСАУ ЖӘНЕ ҚОЛДАНУ

[1*]Кабылбекова А.Т., [2]Кхалдун М.А.

[1]«Мирас Университеті», Шымкент, Қазақстан
[2]Иордания университеті, Иордания
**Автор-корреспондент e-mail: aika_kabil@mail.ru*

Авторлар туралы ақпарат:
Кабылбекова Айсулу Тенелхановна, «Мирас Университеті», Шымкент, Қазақстан, e-mail: aika_kabil@mail.ru. ORCID: https://orcid.org/0000-0003-4167-6800;
Кхалдун Мохаммад Әл-Аззам, Химия кафедрасы, Ғылым мектебі, Иордания университеті, Иордания. e-mail: k.alazzam@ju.edu.jo ORCID: https://orcid.org/0000-0003-4097-6991.

Аңдатпа — Бұл мақалада биополимерлі мембраналар су мен ағынды сулардан ауыр металдарды кетірудің тиімді әдісі ретінде қарастырылады. Мұндай мембраналардың жұмысының негізгі принциптері, олардың дәстүрлі тазарту әдістерінен артықшылығы, сондай-ақ өнеркәсіп пен экологияда қолдану мүмкіндіктері сипатталған. Биополимерлі мембраналардың әртүрлі түрлерінің, соның ішінде хитозан, альгинат және кератин мембраналарының тиімділігі туралы зерттеу нәтижелері ұсынылған. Күрделі түзілу, ион алмасу және химиялық адсорбция процестерін қоса алғанда, биополимерлі мембраналардағы ауыр металл иондарының сорбция механизміне ерекше назар аударылады. Мембрананың кеуектілігі, ортаның pH, температура және ластаушы заттардың концентрациясы сияқты тазалау тиімділігіне әсер ететін негізгі параметрлер қарастырылады. Биополимерлі мембраналардың селективтілігін, механикалық беріктігі мен беріктігін арттыру мақсатында оларды өзгерту перспективалары да талқыланады. Мұндай мембраналарды суды тазарту жүйелерінде, соның ішінде зертханалық зерттеулер мен өнеркәсіптік енгізулерде сәтті қолдану мысалдары келтірілген.

Түйін сөздер — биополимерлі мембраналар, ауыр металдар, суды тазарту, ағынды сулар, хитозан, альгинат, кератин, сорбция, сүзу.

РАЗРАБОТКА И ПРИМЕНЕНИЕ БИОПОЛИМЕРНЫХ МЕМБРАН ДЛЯ ОЧИСТКИ ВОДЫ ОТ ТЯЖЕЛЫХ МЕТАЛЛОВ

[1*]Кабылбекова А.Т., [2]Кхалдун М.А.

[1]«Мирас университет», Шымкент, Казахстан
[2]Иорданский университет, Иордания
**Автор-корреспондент e-mail: aika_kabil@mail.ru*

Информация об авторе:
Кабылбекова Айсулу Тенелхановна, «Мирас университет», Шымкент, Казахстан, e-mail: aika_kabil@mail.ru. ORCID: https://orcid.org/0000-0003-4167-6800;
Халдун Мохаммад Аль-Аззам, Кафедра химии, Школа наук, Иорданский университет, Иордания. e-mail: k.alazzam@ju.edu.jo ORCID: https://orcid.org/0000-0003-4097-6991.

Аннотация — В данной статье рассматриваются биополимерные мембраны как эффективный метод удаления тяжелых металлов из воды и сточных вод. Описаны основные принципы работы таких мембран, их преимущества перед традиционными методами очистки, а также возможности применения в промышленности и экологии. Представлены результаты исследований по эффективности различных типов биополимерных мембран, включая хитозановые, альгинатные и кератиновые мембраны. Особое внимание уделяется механизму сорбции ионов тяжелых металлов на биополимерных мембранах, включая процессы комплексообразования, ионного обмена и химической адсорбции. Рассматриваются ключевые параметры, влияющие на эффективность очистки, такие как пористость мембраны, pH среды, температура и концентрация загрязняющих веществ. Также обсуждаются перспективы модификации биополимерных мембран с целью повышения их селективности, механической прочности и долговечности. Приведены примеры успешного применения таких мембран в системах водоочистки, включая лабораторные исследования и промышленные внедрения.

Ключевые слова — биополимерные мембраны, тяжелые металлы, очистка воды, сточные воды, хитозан, альгинат, кератин, сорбция, фильтрация.

MAIN PROVISION

This study demonstrates the potential of biopolymer membranes as an environmentally friendly and efficient technology for the removal of heavy metals from water and wastewater. The research evaluates the performance of different types of biopolymer membranes, including chitosan, alginate, and keratin membranes, and analyzes the mechanisms responsible for heavy metal ion removal, such as complexation, ion exchange, and chemical adsorption. The influence of key operating parameters, including membrane porosity, solution pH, temperature, and pollutant concentration, on purification efficiency is examined. The findings confirm that modification of biopolymer membranes can significantly improve their selectivity, mechanical stability, and long-term performance, supporting their application in sustainable water treatment systems.

INTRODUCTION

Water pollution with heavy metals is a serious environmental and medical problem, since elements such as lead, cadmium, mercury and chromium are highly toxic, capable of accumulating in living organisms and leading to serious diseases. Traditional purification methods such as coagulation, ion exchange, and reverse osmosis have a number of disadvantages, including high operating costs, difficulty in application, and the formation of toxic waste requiring additional disposal.

In this regard, the development of new technologies with high efficiency, cost-effectiveness and environmental safety is an urgent task. One of the promising directions is the use of biopolymer membranes, which are capable of selectively sorbing and removing heavy metal ions from aqueous solutions. These membranes are made on the basis of natural polymers such as chitosan, alginate, keratin and cellulose, which have high biocompatibility, chemical resistance and the ability to bind heavy metals due to functional groups such as amino groups, carboxyl and hydroxyl groups.

Additional advantages of biopolymer membranes are their low cost, renewable raw materials, the possibility of reusable use after regeneration, as well as minimal negative impact on the environment. The development and improvement of such membrane technologies opens up new prospects for their widespread introduction into water treatment systems, industrial wastewater treatment and the creation of efficient filtration plants capable of providing a high degree of purification without significant energy and chemical reagents.

Research gap. Although biopolymer membranes have attracted considerable attention as sustainable materials for water treatment, there is still insufficient comparative information on the performance of different biopolymer membranes for the removal of heavy metals under varying operating conditions. Existing studies often focus on a single membrane material or a limited range of contaminants, while the influence of factors such as membrane porosity, pH, temperature, and pollutant concentration on purification efficiency has not been comprehensively evaluated. Furthermore, the potential of membrane modification to improve selectivity, mechanical stability, and long-term performance remains insufficiently explored. This study addresses these gaps by comparatively evaluating different biopolymer membranes and analyzing the key parameters affecting their efficiency in heavy metal removal from water.

Novelty statement. The novelty of this study lies in the comprehensive evaluation of different biopolymer membranes, including chitosan, alginate, and keratin membranes, for the removal of heavy metals from water. Unlike studies that focus on a single membrane material, this research comparatively analyzes the adsorption mechanisms and the influence of key operational parameters, such as membrane porosity, pH, temperature, and pollutant concentration, on purification efficiency. In addition, the study highlights the potential of membrane modification to enhance selectivity, mechanical strength, and durability, providing new insights into the development of sustainable and high-performance biopolymer membrane technologies for water purification.

METODOLOGY

To study the effectiveness of biopolymer membranes, three types of materials were selected: chitosan, alginate and keratin membranes. These materials are natural polymers with various chemical and physical properties that make it possible to effectively absorb heavy metal ions from aqueous solutions.

Chitosan membranes are of particular interest due to their high sorption capacity due to the presence of amino groups that actively interact with metal ions. Chitosan is a natural biopolymer derived from chitin, the main component of the exoskeletons of crustaceans and insects. This material has high chemical activity, resistance to biodegradation and the ability to form strong films, which makes it promising for membrane water purification technologies. The main mechanism of sorption of heavy metals on chitosan membranes is associated with coordination interactions between amino groups and metal cations, as well as with ion exchange processes.

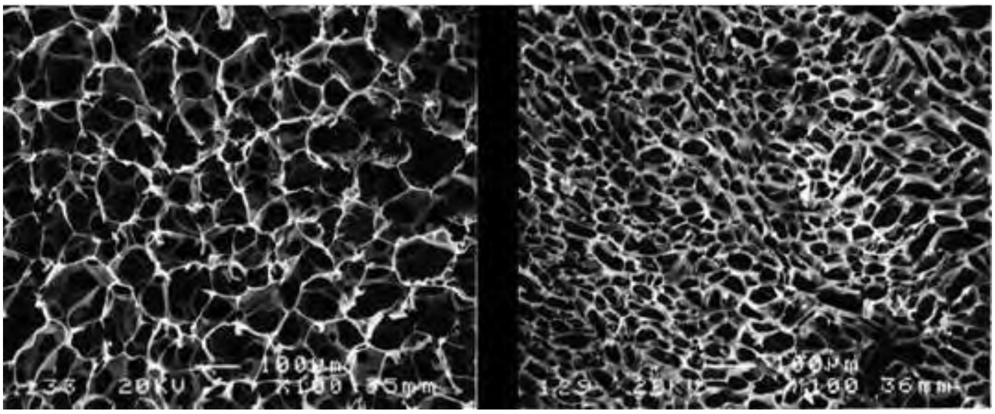

Fig. 1 – Microstructure of chitosan membranes

Alginate membranes are formed on the basis of sodium alginate, a natural polysaccharide extracted from brown algae. They have high hydrophilicity, which contributes to the uniform distribution of aqueous solutions in the membrane structure and effective contact with pollutants. Alginates contain carboxyl groups that are involved in the sorption of heavy metals, forming strong complexes with ions.

One of the significant advantages of alginate membranes is their ability to gel in the presence of divalent ions, which can contribute to additional retention of pollutants in the membrane structure.

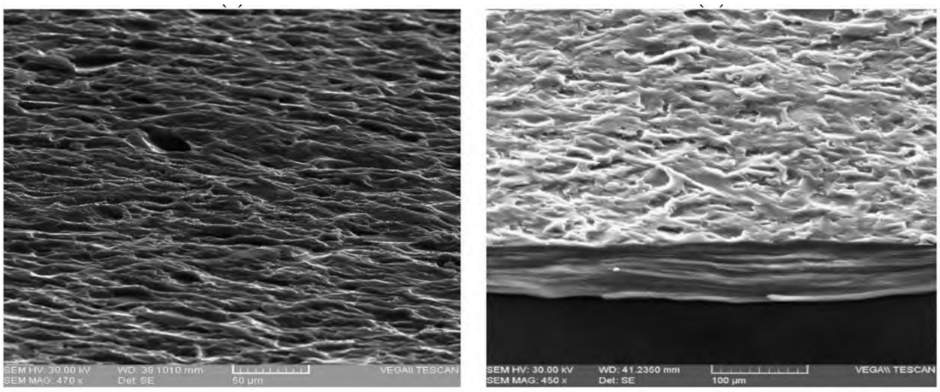

Fig. 2 – Microstructure of alginate membranes

Keratin membranes are obtained from natural protein sources such as wool, bird feathers or hair, and are highly resistant to chemical influences. Keratin is a complex fibrillar protein containing a large number of disulfide bonds that provide mechanical strength and stability of the material. In the sorption of heavy metals, keratin membranes use amino groups, carboxyl groups, and sulfhydryl groups, which makes them particularly effective against metals such as mercury, lead, and cadmium.

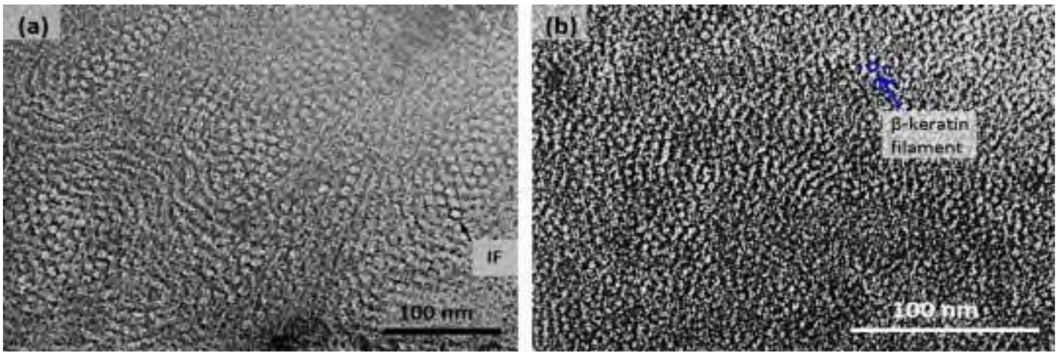

Fig. 3 – Microstructure of keratin membranes

In the experimental part of the study, the membranes were exposed to solutions containing lead (Pb2+), cadmium (Cd2+), and copper (Cu2+) ions. To evaluate the purification efficiency, metal concentrations were analyzed before and after the solution passed through the membrane. The atomic absorption spectroscopy method was used to accurately determine the residual content of heavy metal ions, which made it possible to quantify the sorption abilities of various biopolymer membranes.

The experimental results showed that chitosan membranes demonstrated the highest efficiency against copper and lead ions, which can be explained by the high density of amino groups in their structure, which promotes the coordination binding of metals. Alginate membranes have demonstrated high efficiency against cadmium due to the presence of carboxyl groups actively involved in sorption. Keratin membranes have shown the greatest stability in conditions of varying pH of the medium, which makes them promising for use in conditions of complex industrial wastewater.

Additionally, the membranes were regenerated to assess their reuse. Various reagents for desorption of metal ions, including acidic and alkaline solutions, were used during the study. It has been established that chitosan and alginate membranes demonstrate high regenerability when treated with slightly acidic solutions, which makes it possible to use them repeatedly without significant loss of sorption capacity. Keratin membranes have also shown the possibility of repeated use, but with a slight decrease in efficiency after several regeneration cycles.

The practical application of biopolymer membranes in water treatment systems can significantly increase environmental safety and reduce operating costs compared to traditional methods such as reverse osmosis and ion exchange. The main advantages of such membranes include biodegradability, low cost of raw materials, the ability to scale production and adapt to various operating conditions. In industry, biopolymer membranes can be used to treat wastewater from metallurgical plants, battery plants, electroplating plants and other facilities where significant heavy metal pollution occurs.

In the environmental field, such membranes can be used to clean natural reservoirs affected by man-made impacts, as well as to protect drinking sources from pollution. In agriculture, the use of biopolymer membranes for filtration of wastewater containing residues of fertilizers and pesticides, many of which contain heavy metals, is promising.

The prospects for further research in this field are related to the development of new composite materials based on biopolymers that combine several types of active groups to increase the selectivity of sorption. Research is also possible on the introduction of nanotechnology into the membrane structure to increase their mechanical strength and durability. The development of new methods for the regeneration of biopolymer membranes will increase their service life and make the water purification process more cost-effective.

Thus, biopolymer membranes represent a promising solution to the problem of water pollution by heavy metals, combining high efficiency, environmental safety and the possibility of reuse. Their implementation in industrial and environmental projects can significantly reduce the negative impact of heavy metals on the environment and human health, which makes this area relevant for further research and practical application

RESULTS AND DISCUSSION

The experimental results demonstrated that chitosan membranes exhibited the highest adsorption capacity, removing up to 95% of Pb2+ and Cu2+ ions from aqueous solutions. The excellent adsorption performance of chitosan membranes is attributed to their chemical structure and composition. Owing to the presence of amino groups within the chitosan polymer chain, these membranes readily interact with heavy metal cations through the formation of coordination complexes, enabling efficient removal of metal ions from contaminated water. Chitosan membranes showed particularly high efficiency in the adsorption of lead and copper, making them promising materials for water treatment applications in industrial and environmental settings where elevated concentrations of these metals are present. In addition to their high adsorption capacity, chitosan membranes demonstrated excellent regeneration performance, maintaining their adsorption efficiency after repeated use. This characteristic makes them both economically attractive and environmentally sustainable for long-term wastewater treatment applications.

Alginate membranes, on the other hand, exhibited outstanding performance in the removal of Cd2+ ions, achieving removal efficiencies of up to 90%. Sodium alginate, a naturally occurring polysaccharide, possesses high hydrophilicity and abundant carboxyl functional groups that readily interact with metal ions, forming stable adsorption complexes with high sorption capacity. These membranes were particularly effective in removing cadmium due to their strong affinity for divalent metal ions such as Cd^{2+}. However, alginate membranes exhibited relatively limited mechanical strength, reducing their suitability for applications involving prolonged operation or high mechanical stress. Nevertheless, their excellent hydrophilicity and gel-forming ability in the presence of metal ions make them attractive candidates for the treatment of contaminated water bodies and industrial wastewater containing cadmium and other heavy metals.

Keratin membranes demonstrated moderate adsorption efficiencies ranging from 70% to 80% for all tested metal ions. Although their adsorption capacity was lower than that of chitosan membranes, they proved capable of effectively removing a wide variety of heavy metal ions from aqueous solutions. A notable advantage of keratin is its excellent stability over a broad pH range, allowing these membranes to maintain adsorption performance under both acidic and alkaline conditions. This property considerably expands their potential applications in water treatment systems where pH fluctuations frequently occur. Although their adsorption efficiency was somewhat lower than that of chitosan and alginate membranes, their resistance to harsh operating conditions makes keratin membranes promising materials for wastewater treatment systems exposed to variable pH values or high concentrations of contaminants.

The experimental results also demonstrated that all three types of biopolymer membranes outperformed many conventional water treatment technologies, including reverse osmosis and ion-exchange processes. Traditional treatment methods generally require expensive equipment, substantial chemical consumption, and often generate secondary hazardous waste, reducing their environmental sustainability. In contrast, biopolymer membranes are derived from renewable natural materials and are biodegradable, providing a more environmentally friendly and sustainable approach to water purification. Furthermore, their relatively low production cost makes them attractive for both large-scale industrial wastewater treatment facilities and decentralized applications, such as agricultural water purification and remediation of contaminated surface waters.

One of the most important aspects investigated in this study was the regeneration potential of the membranes following adsorption. All three membrane types exhibited a high degree of recovery of their adsorption capacity after treatment with dilute acidic or alkaline solutions, allowing multiple reuse cycles. Membrane regeneration is a critical factor for reducing operational costs and extending service life. Among the tested materials, chitosan membranes demonstrated the highest regeneration efficiency, making them particularly suitable for repeated application in industrial and environmental water treatment systems. Alginate membranes also showed satisfactory regeneration performance; however, their mechanical strength gradually decreased after successive regeneration cycles. Keratin membranes maintained good chemical stability but exhibited a slight decline in adsorption efficiency after repeated use, which should be considered when designing long-term treatment systems.

Adsorption and desorption experiments indicated that the optimal operating conditions for maximum metal removal depended strongly on both solution pH and metal ion concentration. Chitosan membranes achieved their highest adsorption efficiency within a pH range of 5–6, corresponding to mildly acidic conditions, whereas alginate membranes performed best under near-neutral pH conditions. Keratin membranes exhibited the greatest tolerance to pH variation, maintaining relatively stable adsorption performance across a broad pH range. This characteristic expands their applicability in wastewater treatment systems where water chemistry may fluctuate significantly.

Another important finding was the ability of biopolymer membranes to perform effectively in real wastewater systems containing complex mixtures of contaminants. Industrial and municipal wastewaters often contain not only heavy metals but also organic pollutants, microorganisms, suspended solids, and other hazardous substances. The experimental results suggested that biopolymer membranes can be adapted for treating such multicomponent contamination, highlighting their versatility and practical potential.

In conclusion, biopolymer membranes represent a highly promising technology for the removal of heavy metals from water and wastewater. Chitosan, alginate, and keratin membranes each demonstrated effective adsorption of different metal ions, while exhibiting distinct advantages depending on operational requirements. Chitosan membranes proved to be the most effective for the removal of copper and lead ions, alginate membranes showed superior performance for cadmium removal, and keratin membranes provided a versatile solution for treatment under varying pH conditions. Their excellent regeneration capability and potential for repeated use further enhance their economic viability and environmental sustainability, making biopolymer membranes attractive candidates for a wide range of future water purification applications.

CONCLUSION

Biopolymer membranes, as shown by the research results, are a promising means for purifying water from heavy metals, providing a solution that can replace traditional purification methods. Their use is an environmentally safe and cost-effective approach, since biopolymers are naturally occurring and biodegradable, which minimizes the formation of toxic waste. Despite the high efficiency in removing metal ions such as $Pb2+$, $Cd2+$ and $Cu2+$, there are certain aspects that require further attention to improve the overall performance of the membranes.

Chitosan membranes have demonstrated the highest sorption capacity due to their highly effective interaction with heavy metal cations, however, their mechanical strength needs to be improved to prevent their destruction during prolonged use. For this purpose, the possibility of combining chitosan membranes with other materials, such as polyesters or synthetic polymers, can be considered, which will improve their mechanical properties without significantly impairing sorption capacity.

Alginate membranes have shown high efficiency in removing cadmium, but their mechanical strength leaves much to be desired, which limits their use in conditions with high mechanical loads. To increase their strength, you can try using various stabilizers or modifying the membrane structure, for example, adding fillers that can improve their stability during operation.

Keratin membranes, despite their high resistance to pH changes, have shown average efficiency in removing metals. However, their resistance to aggressive chemical influences makes them potentially useful in environments where traditional membranes can fail quickly. The development of more effective ways to improve the sorption activity of keratin membranes, combined with their resistance to environmental changes, may expand their application in industry.

Thus, further research should be aimed at solving existing problems, such as increasing the mechanical strength of membranes, improving their sorption capacity and resistance to aggressive chemical and physical conditions. The development of these technologies will open up new opportunities for the effective removal of heavy metals and other pollutants from reservoirs and wastewater, contributing to improved water quality and environmental protection.

AUTHOR'S CONTRIBUTION
(taxonomy CRediT):

Kabylbekova A. – Conceptualization, Investigation, Methodology, Data Curation, Writing - Original Draft.

Khaldun M.A. – Conceptualization, Validation, Methodology, Formal Analysis, Writing - Review & Editing, Supervision.

CONFLICT OF INTEREST

The author claims that there is no conflict of interest in the implementation of this study and the publication of the article.

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