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CONTENTS

PHYSICS

CHEMISTRY

МАЗМҰНЫ

ФИЗИКА

ХИМИЯ

СОДЕРЖАНИЕ

ФИЗИКА

ХИМИЯ

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ACTIVATED-CARBON-ENHANCED POLYMERIC MEMBRANES FOR EFFICIENT ELIMINATION OF EMERGING CONTAMINANTS

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Abstract. The removal of contaminants of emerging concern (CECs) from wastewater remains one of the key challenges in water treatment, especially in countries with limited water resources and partially outdated infrastructure, including Kazakhstan. This study investigates polymeric membranes based on polyvinylidene fluoride (PVDF) modified with activated carbon of plant origin (AC-CN) to assess their structural characteristics and potential for further use in the removal of organic pollutants. AC-CN activated carbon was characterized by BET, SEM and FT-IR methods, which showed a developed microporous structure (S_{BET} =462 $м^2 \cdot g^{-1}$) and the presence of oxygen-containing functional groups. The membranes were formed by phase inversion using distilled water and a 70/30 ratio of distilled water and isopropanol, respectively, as a coagulation bath. Under continuous-flow conditions (C_0 = 10 mg/L, flow 0.5 mL/min, pH - 6.8), PVDF membranes loaded with AC-CN showed markedly different performance depending on the coagulation bath: the water-coagulated AC-CN_membrane removed 13.8% of paracetamol and 40.9% of 4-nitrophenol, whereas the H_2O/IPA (70:30)-coagulated AC-

CN-IPA membrane achieved substantially higher paracetamol removal (60–64% at 60 min) and an initial 4-nitrophenol removal of 37.7% with sustained retention of 33.0% to 21.7% over 20–60 min. All measurements were performed in triplicate (n = 3) and are reported as mean; the relative standard deviation did not exceed 1%, indicating good repeatability of the analytical method. These findings indicate that coagulation bath composition critically controls membrane morphology and access to AC-CN sorption sites, supporting further optimization of these materials for sustainable wastewater treatment.

Keywords: membranes, activated carbons, adsorption; paracetamol, 4-nitrophenol

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АЛАҢДАУШЫЛЫҚ ТУДЫРАТЫН ЛАСТАУШЫ ЗАТТАРДЫ ТИІМДІ ЖОЮ ҮШІН БЕЛСЕНДІРІЛГЕН КӨМІР ПОЛИМЕРЛІ МЕМБРАНАЛАР

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Аннотация. Ағынды сулардан ерекше алаңдаушылық тудыратын ластаушы заттарды (CECs) шығару, әсіресе су ресурстары шектеулі және ішінара ескірген инфрақұрылымы бар елдерде, соның ішінде Қазақстанда суды тазарту саласындағы негізгі міндеттердің бірі болып қала береді. Бұл зерттеу олардың құрылымдық сипаттамаларын және органикалық ластаушы заттарды жоюда одан әрі пайдалану әлеуетін бағалау мақсатында өсімдік тектес белсендірілген көмірмен (AC-CN) толтырылған поливинилиденфторид (PVDF) негізіндегі полимерлі мембраналарды зерттейді. Белсендірілген AC-CN көмірі BET, SEM және FT-IR әдістерімен сипатталды, олар дамыған микро-кеуекті құрылымды (S_{BET}=462м^2·г$^{-1}$) және құрамында оттегі бар функционалды топтардың болуын көрсетті. Мембраналар дистилденген суды және коагуляциялық ванна ретінде 70/30 дистилденген су мен изопропанол қоспасын пайдаланып фазалық инверсия арқылы түзілді. Үздіксіз ағын жағдайында (c = 10 мг/л, ағын жылдамдығы 0,5 мл/мин, pH - 6,8) AC-CN жүктелген PVDF мембраналары коагуляциялық ваннаға байланысты айтарлықтай әртүрлі сипаттамаларды көрсетті: сумен коагуляцияланған AC-CN мембранасы 13,8% парацетамолды және 40,9% 4-нитрофенол, ал H_2O/IPA (70:30) коагуляцияланған AC-CN мембранасы парацетамолды (60 минут ішінде 60-64%) және 37,7% 4-нитрофенолды 20-60 минут ішінде тұрақты ұстаумен 33,0% -дан 21,7% дейін жойып тастады. Барлық өлшемдер үш рет орындалды (n = 3) және орташа мәндер ретінде ұсынылды; салыстырмалы стандартты ауытқу 1% - дан аспады, бұл аналитикалық әдістің жақсы қайталануын көрсетеді. Бұл нәтижелер коагуляциялық ваннаның құрамы мембрананың морфологиясына және AC-CN сорбциялық орындарына қол жеткізуге сыни әсер ететінін көрсетеді, бұл ағынды суларды тұрақты тазарту үшін осы материалдарды одан әрі оңтайландырудың орындылығын растайды.

Түйін сөздер: мембраналар, белсендірілген көмір, адсорбция, парацетамол, 4-нитрофенол

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ПОЛИМЕРНЫЕ МЕМБРАНЫ С АКТИВИРОВАННЫМ УГЛЕМ ДЛЯ ЭФФЕКТИВНОГО УДАЛЕНИЯ ЗАГРЯЗНЯЮЩИХ ВЕЩЕСТВ ВЫЗЫВАЮЩИХ ОБЕСПОКЕННОСТЬ

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Аннотация. Удаление загрязняющих веществ, вызывающих особую озабоченность (CEC), из сточных вод остается одной из ключевых задач в области водоочистки, особенно в странах с ограниченными водными ресурсами и частично устаревшей инфраструктурой, включая Казахстан. В данном исследовании рассматриваются полимерные мембраны на основе поливинилиденфторида (PVDF), модифицированные активированным углем растительного происхождения (AC-CN), с целью оценки их структурных характеристик и потенциала для последующего применения при удалении органических загрязняющих веществ. Активированный уголь AC-CN был охарактеризован методами BET, SEM и FT-IR, которые показали развитую микропористую структуру (S_BET = 462 м²/г) и наличие кислородсодержащих функциональных групп. Мембраны формировали методом фазовой инверсии с использованием в качестве коагуляционной ванны дистиллированной воды, а также смеси дистиллированной воды и изопропанола в соотношении 70/30. В условиях непрерывного потока (C_0 = 10 мг/л, расход 0,5 мл/мин, pH ≈ 6,8) мембраны из PVDF, модифицированные AC-CN, продемонстрировали заметные различия в характеристиках в зависимости от состава коагуляционной ванны. Так, мембрана AC-CN, коагулированная в воде, обеспечила удаление 13,8 % парацетамола и 40,9 % 4-нитрофенола, тогда как мембрана AC-CN, коагулированная в системе H_2O/IPA (70:30), показала значительно более высокую степень удаления парацетамола (60–64 % за 60 мин) и 37,7 % 4-нитрофенола при устойчивом удерживании в диапазоне от 33,0 до 21,7 % в течение 20–60 мин. Все измерения были выполнены в трех повторностях (n = 3) и представлены в виде средних значений; относительное стандартное отклонение не превышало 1 %, что свидетельствует о хорошей воспроизводимости аналитического метода. Полученные результаты указывают на то, что состав коагуляционной ванны оказывает критическое влияние на морфологию мембраны и доступность сорбционных центров AC-CN, что подтверждает целесообразность дальнейшей оптимизации данных материалов для устойчивой очистки сточных вод.

Ключевые слова: мембраны, активированный уголь, адсорбция, парацетамол, 4-нитрофенол

Introduction. Wastewater treatment is a critical environmental and public health issue, drawing increasing attention to advanced technologies for removing contaminants of concern (CECs). Like many countries, Kazakhstan faces the need to modernise its wastewater treatment networks and implement innovative solutions due

to outdated infrastructure and growing requirements for the quality of discharged water (Kalmakhanova et al., 2025).

Currently, Kazakhstan mainly relies on traditional wastewater treatment methods, such as mechanical and biological processes (e.g. activated sludge systems and sedimentation tanks). Many of these facilities were built decades ago and are experiencing problems related to equipment wear and tear, changes in the composition and volume of incoming wastewater, and a lack of investment in modernisation. These factors lead to reduced treatment efficiency and increased environmental risks, particularly in large cities such as Almaty (Ospanov et al., 2022). More modern solutions are also being adopted in practice, such as the use of electrical discharges to neutralise and remove heavy metals at industrial sites, and sedimentation and suspension bioreactors for small treatment plants (Abdykadyrov et al., 2025). However, large-scale implementation of these innovations is limited by economic and infrastructural barriers (Bekenova et al., 2024).

Literature review. There has been a global shift towards advanced and hybrid technological solutions to combat water scarcity, recover resources and remove persistent pollutants. Membrane-based processes such as ultrafiltration, nanofiltration and reverse osmosis, combined with adsorption, are becoming increasingly popular due to their high efficiency and selectivity, and their potential for water reuse (Álvarez-Torrellas S. et al., 2016). Patent analysis indicates a trend away from individual technological units towards integrated systems that combine physical, chemical and biological approaches, emphasising automation and energy efficiency (Mao et al., 2021). Combinations of membrane bioreactors, advanced oxidation processes and adsorption are recognised as being particularly effective in removing CEC (Ahmed et al., 2022).

Polymeric membranes modified with activated carbon (AC) show great promise for the comprehensive removal of organic and inorganic pollutants. Incorporating AC into the polymer membrane matrix enhances hydrophilicity, sorption capacity and selectivity towards micro- and nano-pollutants, while reducing pore clogging and facilitating flow recovery (Arabloo and Javadpour, 2025; Moraes et al., 2023). These hybrid structures have been shown to perform well in the removal of heavy metals, phenolic compounds and CECs, with some studies reporting removal efficiencies of over 90% for individual compounds (Sherugar et al., 2022; Moraes et al., 2023).

Combined systems that use membrane filtration alongside activated carbon adsorption and other methods, such as ultrasound and photocatalysis, can achieve almost complete removal of pharmaceutical compounds and other persistent CECs (Secondes et al., 2014). Activated carbon is still one of the most effective adsorbents thanks to its large surface area and the fact that it can be modified; using adsorbents derived from agricultural waste makes solutions more sustainable and cost-effective (Ntone et al., 2025).

This study presents a novel approach to developing polymeric membranes for efficient contaminant removal by incorporating biomass-derived activated carbon (AC-CN). The scientific novelty lies in:

− Investigating the critical role of coagulation bath composition (distilled water

vs. H2O/IPA mixture) in controlling the membrane's porous structure and surface properties, directly impacting the accessibility of activated carbon's sorption sites.

− Establishing a direct link between membrane fabrication parameters, resulting morphology, and adsorption performance for model emerging contaminants (paracetamol and 4-nitrophenol).

− Demonstrating significantly improved and sustained removal efficiencies for paracetamol and 4-nitrophenol using AC-CN-modified PVDF membranes coagulated in an H_2O/IPA bath, showcasing their potential for advanced wastewater treatment applications.

− This research differentiates itself by not only synthesizing and characterizing AC-CN but also by systematically evaluating the influence of the membrane formation process on overall contaminant removal efficiency, offering a more holistic understanding for designing advanced filtration materials.

Materials and methods. *Materials.* Paracetamol, also known as acetominophen (PCM, ≥99%), and acetonitrile (HPLC grading, ≥99.9%) were purchased from Sigma-Aldrich (Merck KGaA, Germany) and used without further purification. Polyvinylpyrrolidone (PVP; MW: 40,000 g mol^{-1}), 1-methyl-2-pyrrolidone (NMP; 99.5 wt.%) and poly (vinylidene fluoride) (PVDF; MW: 275,000 g mol^{-1}), from Sigma-Aldrich, were used for membrane fabrication.

All chemicals were of analytical or chromatographic purity and were used directly in working solutions.

Methods for obtaining activated carbon as a filler for polymeric membranes. The synthesis of the activated carbons was adapted from the work of F. Bibi et al. (2023), as described elsewhere. In this study, agro-industrial waste such as corn cobs was used as the raw material. To obtain activated carbon, the raw material was thoroughly washed with ultrapure water and then pre-carbonised at 450 °C in a vertical furnace under a nitrogen flow of 0.2 mL/min. The material was pre-washed with a diluted HCl solution to remove residual non-carbon impurities. It was then activated by impregnation with an acid solution (HNO_3) of a specified concentration. Finally, the material was washed with ultrapure water until a neutral pH was achieved in the washing water. The carbonisation process was then carried out at 600°C under the same N_2 flow rate (0.2 ml/min) as during pre-carbonisation. (See Figure 1.) The material was labelled AC-CN: the first letter denotes the precursor. C: *corn cob;* and the second letter indicates the activating agent used: N: *HNO_3*.

Figure 1 - Scheme of the procedure of the activated carbons preparation
(I - Biomass (corn cob), II - Pre-carbonization in a nitrogen atmosphere (oven) at 450 °C, III - Acid wash (HCl) with heating,
IV - Activation step (impregnation/activation using a shaker), V - Rinse with ultrapure water, VI – Drying, VII - Final activated carbon material obtained)

Methods for preparing polymeric membranes. To prepare the membranes, 1.3 g of PVP, 11.5 mL of NMP and 2.5 g of activated carbon (AC-CN) were sequentially added to the solution and dispersed in an ultrasonic bath for 3 hours until a homogeneous suspension was obtained. Then, 1.25 g of PVDC was added and stirred on a magnetic stirrer at 40°C and 200 rpm for 48 hours. After that, the solution was left overnight at room temperature without external influence for degassing and stabilization. The prepared solution was applied to a glass substrate and spread with a precision applicator with a blade thickness of 300 μm, after which the membrane was subjected to coagulation (Ribeiro R.S. et al, 2022). In the first variant, coagulation was carried out in ultrapure water, and the resulting sample was designated as AC-CN_membrane. In the second variant, a coagulation bath containing a mixture of ultrapure water and isopropanol in a ratio of 70/30 was used; after exposure for 20 minutes, the membrane was transferred to fresh ultrapure water and left overnight. This sample was designated AC-CN_IPA and further stored in ultrapure water at 3 °C (Wang Y., et al., 2020). Figure 2 shows the membrane preparation process in detail.

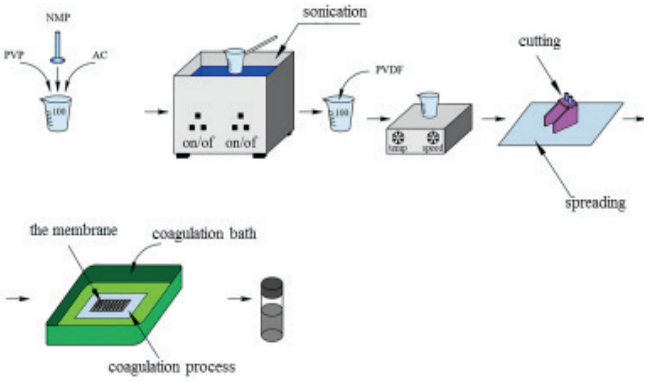


Figure 2 - Scheme of the membrane preparation process

Polymeric mixed matrix membranes in a continuous system. To evaluate the effectiveness of the obtained membrane in removing contaminants, a reactor containing the membranes (AC-CN_membrane and AC-CN_IPA) was connected to a peristaltic pump to create a continuous system. The following conditions were used to conduct the experiment: The contaminant (paracetamol) at a concentration of 10 mg/L was connected to the pump at a flow rate of 0.5 mL/min. This fed the contaminant through the reactor inlet, passing it through the polymeric membrane installed in the reactor (see Figure 3). Samples (2 ml) were taken at 0, 3, 6, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 minutes during filtration. All measurements were performed in triplicate (n = 3) and reported as mean standard deviation. The filtered samples were analysed by HPLC and UV spectrophotometry. The samples were then centrifuged and filtered through 0.45 μm nylon membrane filters before being analysed using a JASCO High-Performance Liquid Chromatograph equipped with a UV-4575 detector. Separation was performed using an Inertsil ODS-3 column (250 × 4.6 mm, 5 μm). The mobile phase

consisted of acetonitrile and ultrapure water (45:55 v/v) adjusted to pH 2.5. The flow rate was maintained at 1.0 mL/min and detection was carried out at 254 nm.

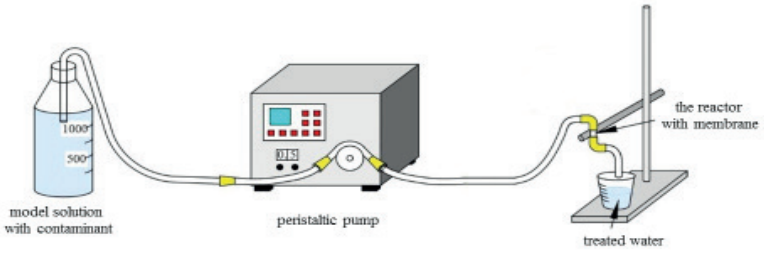


Figure 3 - Experimental set-up for adsorption tests using membrane materials

Equations (1) and (2) were used to process the results.

$$residue\% = \frac{C_{in} \cdot 100\%}{C_{exp}} \quad (1)$$

$$purified\% = 100\% - residue\% \quad (2)$$

where, residue% - is the unadsorbed residue in the solution; purified% - is the purified result, C_{in} - is the initial concentration of the model solution, C_{exp} - is the experimental data of the model solution during the experiments.

Results and discussions. *Material characteristics.* Of the synthesised carbons, the AC-CN membrane matrix showed the most promising characteristics, combining the highest specific surface area (according to BET analysis) with the best adsorption capacity for PCM (20.26 mg/g). Consequently, it was chosen for membrane fabrication.

Table 1 - Textural properties of the synthesized activated carbons.

Material	S_{BET} (m^2/g)	V_{Total} (cm^3/g)	V_{micro} (cm^3/g)	V_{meso} (cm^3/g)	V_{micro}/V_{Total}	d_{pore} (Á)
AC-CN	462	0.224	0.182	0.042	0.81	19.4

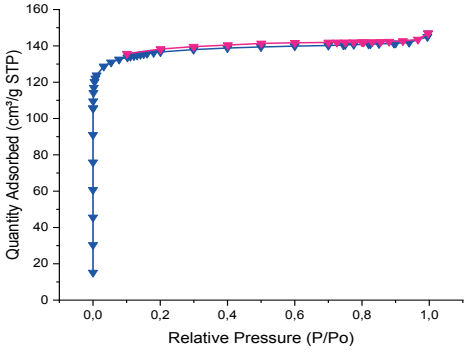


Figure 4 - N_2 adsorption-desorption isotherms at 77K of the activated carbon obtained from corncob (AC-CN).

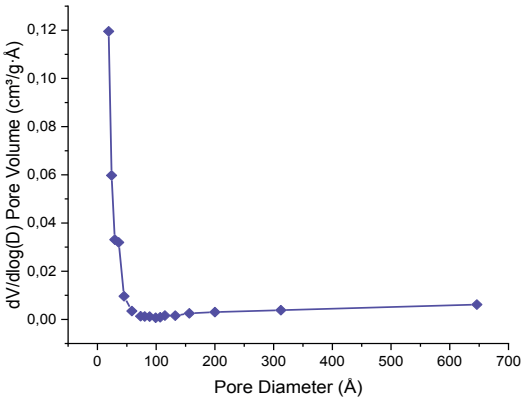


Figure 5 - Pores size distributions of the activated carbon obtained from corncob (AC-CN).

AC-CN exhibits a clearly pronounced microporous structure with a high specific surface area. SBET is approximately 462 462 $m^2 \cdot g^{-1}$ and the total pore volume is approximately 0.224 $cm^3 \cdot g\wedge^1$. The micropore volume is approximately 0.182 $cm^3 \cdot g\wedge(-1)$, corresponding to a microporosity fraction is approximately 0,182 $cm^3 \cdot g^{-1}$, of the total pore volume. The average effective pore size is calculated to be ≈19.4 Å (≈1.94 nm). These parameters indicate the predominance of micropores and the presence of a narrow mesopore contribution (see Figures 4 and 5). The adsorption isotherm in Figure 4 is of Type I, which is characteristic of microporous solids. However, because the theoretical assumptions underlying the Brunauer–Emmett–Teller (BET) model are not fully met for strictly microporous materials, the reported BET surface area must be considered an apparent value. Rigorous assessment of microporosity and pore size distribution therefore requires complementary analyses. Chemical activation (KOH, H_3PO_4, $ZnCl_2$) and process parameters (temperature, time and impregnation coefficient) play a key role in forming textural characteristics (Sousa et al., 2022; Bedane et al., 2023). The composition of the starting precursor (e.g. cellulose, hemicellulose, lignin and ash content) also significantly influences the development of the porous structure and the final properties of the activated carbon (AC) (Santos et al., 2020).

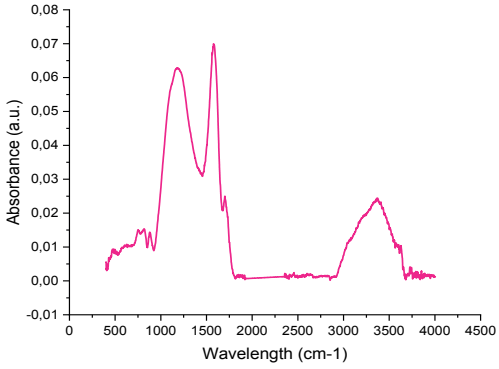


Figure 6 - FT-IR spectra of the synthesized activated carbon prepared from corncob (AC-CN).

The FT-IR spectrum of AC-CN shows the presence of several key functional groups that form the surface chemistry of activated carbon: a broad band in the region of ~3400 cm^{-1}, corresponding to ν(O–H) (hydroxyl/adsorbed water molecules); bands in the region of ~1700–1650 cm^{-1}, associated with carbonyl ν(C=O); bands ~1200–1000 cm^{-1}, indicating ν(C–O) of ether/phenolic groups; as well as characteristic bands of aromatic C=C in the region of ~1600 cm^{-1} (Figure 6). This combination of oxygen-containing functional groups and aromatic structure is typical for chemically activated biochar and determines a polar, slightly acidic surface with the possibility of multiple types of intermolecular interactions (Ţucureanu et al., 2016).

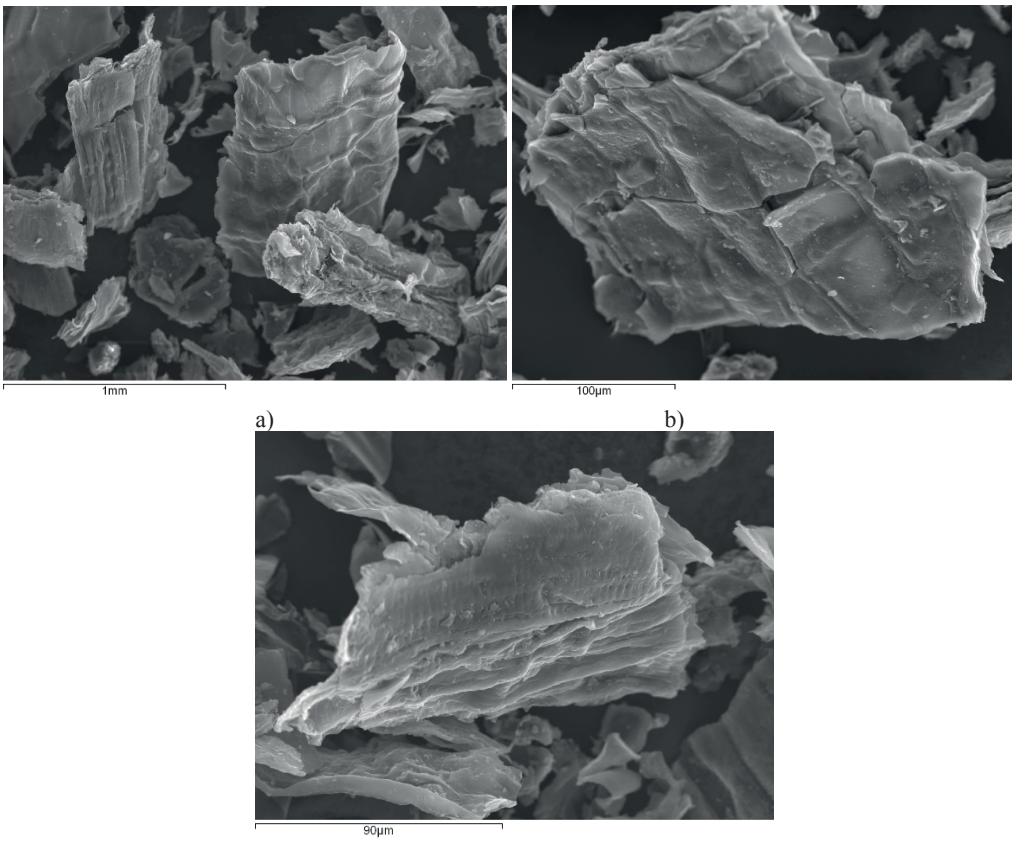
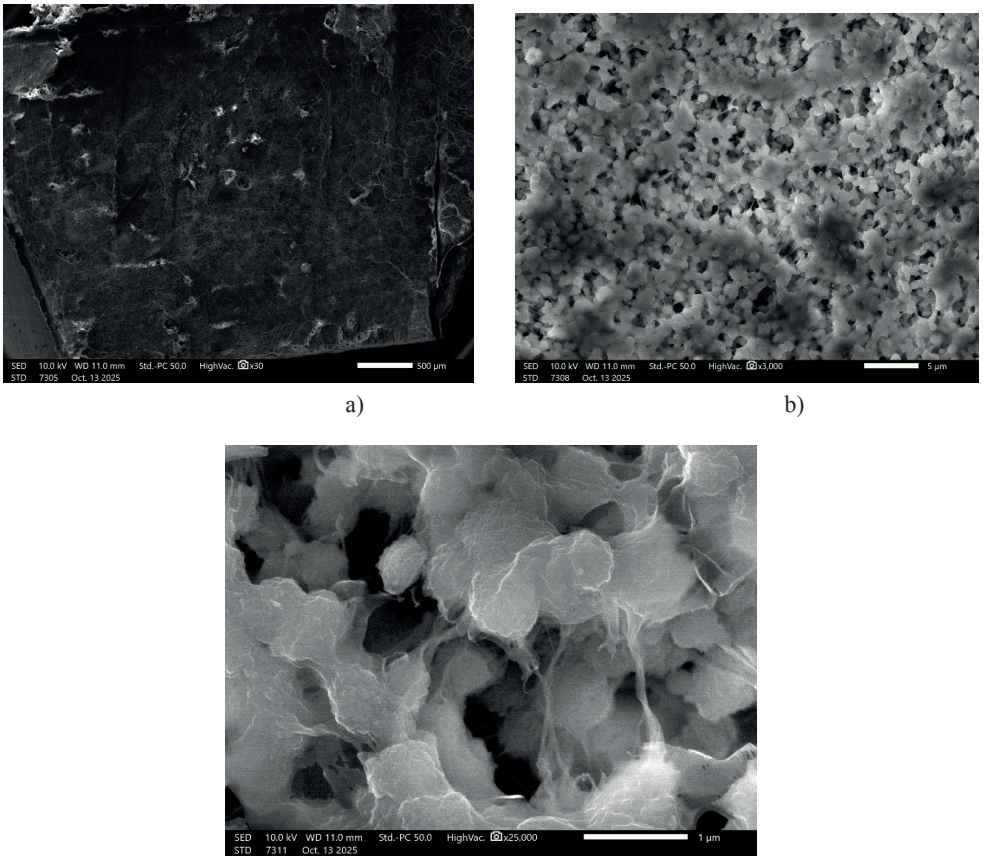


Figure 7 - SEM micrographs of the synthesized activated carbons from corncob (AC-CN) a) x250, b) x370 c) x600.

SEM images of AC-CN powder show a rough, highly textured particle surface: irregularities, cellular structures and local depressions/cracks are visible. Such a surface is typical for activated materials with pronounced microporosity and enlarged external irregularities, which provide additional external surface area. The images (Figure 7) also show thin ‘plates’ and microcracks, which can occur during carbonization/activation and indicate the layered nature of the original precursor (Portillo E., et al, 2025).



a) b)

c)

Figure 8 - SEM micrographs of the synthesized membranes with AC matrix (AC-CN_membrane) a) x30, b) x3000 c) x2500.

Scanning electron microscope (SEM) images of the water-coagulated membrane demonstrate the typical morphology of rapid phase separation: a dense 'skin crust' on the surface and a more porous sub-threshold layer. The surface is relatively smooth with isolated irregularities and rare protrusions, indicating the onset of surface sealing during coagulation. Cross-sections clearly show the contrast between the thin, dense surface film and the porous sub-layer. The pores under the crust are often narrow and partially closed, which indicates limited connectivity of the pore network on the surface (Ribeiro R. S. et al., 2022; Y. Wang et al., 2020).

The distribution of AC-CN particles in the matrix is heterogeneous; both uniformly encapsulated particles in close contact with the polymer and local agglomerates are present. At low magnification (Figure 8a), the textured outer surface can be seen, which is caused by the irregular external surfaces of the carbon particles and the peculiarities of phase inversion. At higher magnifications (Figures 8b and 8c), fine cracks and micron-sized depressions typical of carbon particles after heat treatment and the carbonisation of the raw material are visible.

Polymeric mixed matrix membranes in a continuous system. The synthesised AC-CN filler demonstrated a high specific surface area (S_{BET} ≈ 462 m²/g) and significant adsorption capacities in powder form (PCM ≈ 20.26 mg/g), which justified its selection for the preparation of mixed membrane matrices. However, the transfer of the powder's adsorption properties to the membrane structure was limited — when testing a circular section of the membrane (area 2.10 cm²), the total percentage removal of paracetamol was low (≈13.8%), which indicates the limited availability of activated carbon mass in the section involved in the experiment. The results for adsorption of paracetamol and 4-nitrophenol with the AC-CN_membrane are presented in Figures 9 and 10.

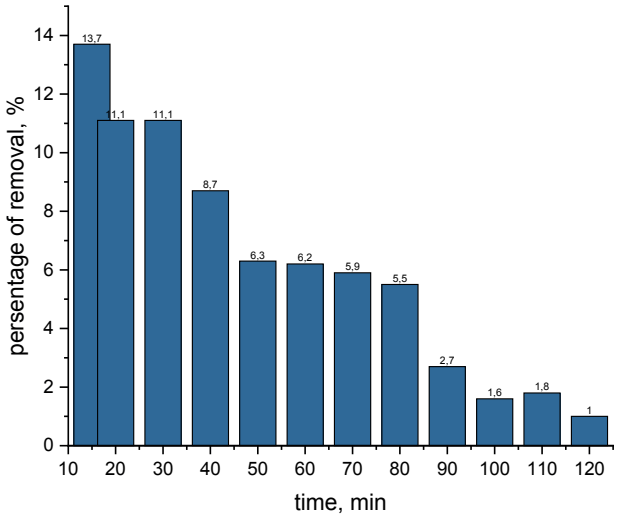


Figure 9 - Continuous experiments with AC-CN_membrane for paracetamol adsorption
Conditions: C_0 = 10 mg/L, flow= 0.5 mL/min, pH = 6.8, T= room temperature.

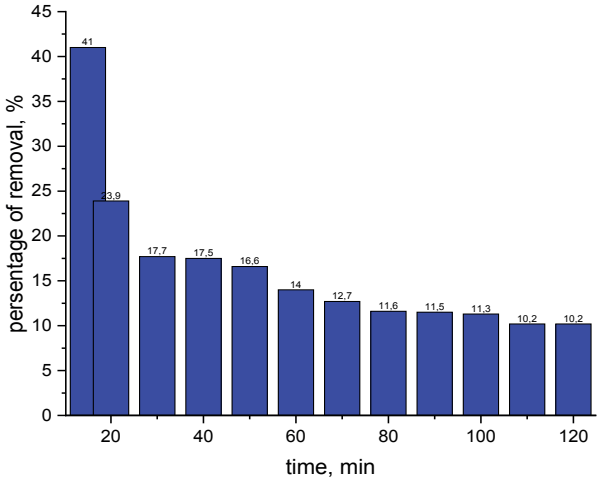


Figure 10 - Continuous experiments with AC-CN_membrane for 4-nitrophenol adsorption
Conditions: C_0 = 10 mg/L, flow = 0.5 mL/min, pH = 6.8, T= room temperature.

The results for adsorption paracetamol and 4-nitrophenol with AC-CN_IPA are presented in Figures 11 and 12.

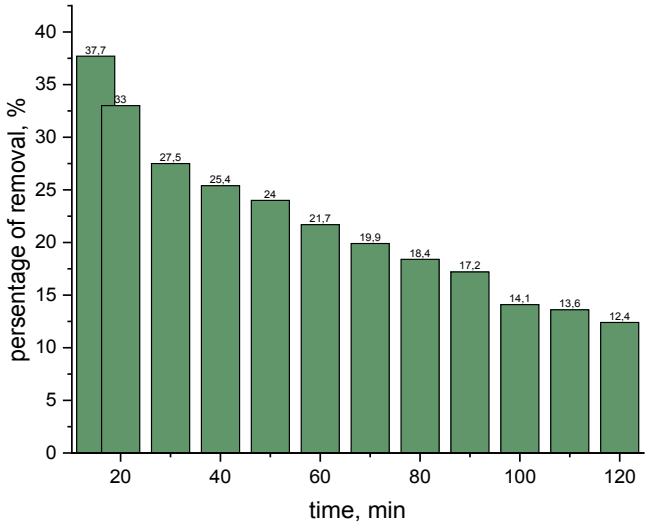


Figure 11 - Continuous experiments with AC-CN_IPA for 4-nitrophenol adsorption
Conditions: C_0 = 10 mg/L, flow = 0.5 mL/min, pH = 6.8, T= room temperature.

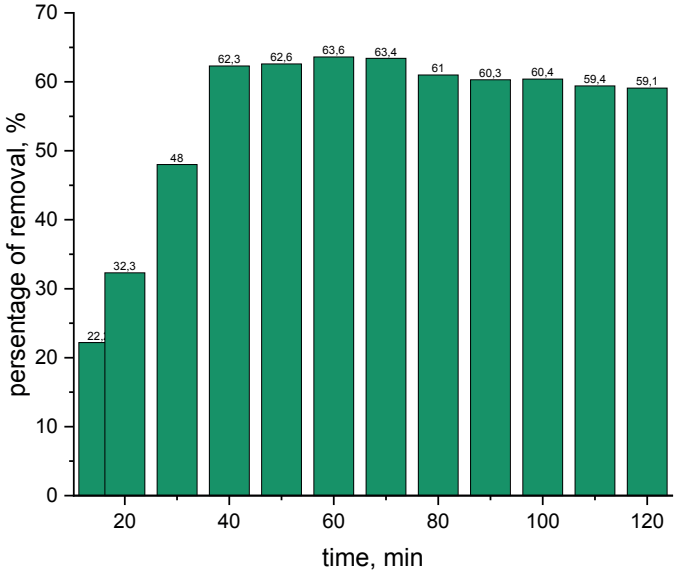


Figure 12 - Continuous experiments with AC-CN_IPA for paracetamol adsorption
Conditions: C_0 = 10 mg/L, flow = 0.5 mL/min, pH = 6.8, T= room temperature

A comparison of the two coagulation modes revealed a significant influence of the bath composition on the adsorption kinetics. Figures 10 and 11 show that in the first 15 minutes, the sample coagulated in water (AC-CN_membrane) showed a slightly

higher initial removal 'spike' (≈40.9% vs. 37.7% for AC-CN_IPA), while in the 20–60 min interval, the membrane formed in H_2O/IPA (70:30) showed a stable advantage in contaminant retention (approximately 33.0 → 21.7%), whereas the values for water coagulation fell faster (≈23.8 → 14.0%) (Moraes E., et al., 2023). A similar trend was observed for paracetamol adsorption (Figures 9 and 12): although the membrane coagulated in water (Figure 9) exhibited a limited overall removal (≈13.8%), the AC-CN-IPA membrane (Figure 12) showed a markedly improved and more stable performance, with a rapid increase in removal efficiency during the first 40–60 minutes and a plateau around 60–64% under continuous-flow conditions. This behaviour indicates that the presence of IPA in the coagulation bath enhances the effective utilisation of the carbon filler within the polymeric matrix, promoting sustained access to sorption sites even for a less strongly interacting compound such as paracetamol. This dynamic is consistent with the fact that the composition of the coagulation bath determines the morphology and pore structure of the membrane: an IPA-containing bath likely forms a more porous and open network or improves the exposure of the active centres of the carbon filler, increasing the long-term availability of sorption sites, whereas rapid coagulation in water can lead to the formation of a dense surface crust with limited internal diffusion (Wang Y. et al., 2020).

The relative standard deviation (RSD) of measurements did not exceed ≈1% and varied within approximately 0.6–1.0%, indicating good repeatability of the analytical method.

The difference in behaviour towards paracetamol and 4-nitrophenol highlights the role of the chemical nature of the contaminant: 4-nitrophenol, containing a hydroxyl group, exhibits more favourable interactions with the actiavted carbon surface (hydrogen bonds, π–π interactions), which explains the observed differences in adsorption between the two pollutant models.

Conclusion. This work successfully synthesised PVDF polymeric membranes modified with AC-CN activated carbon. The validated textural characteristics of these membranes (S_{BET} = 462 $m^2 \cdot g^{-1}$, V_{micro} = 0.182 $cm^3 \cdot g^{-1}$, micropore fraction = 81%) confirm their substantial sorption potential. The phase inversion process employing distinct coagulation baths yielded membranes with different morphologies: coagulation in distilled water produced a denser surface that limited contaminant access, whereas the H_2O/IPA (70:30) system fostered greater porosity and permeability. These structural differences directly impacted sorption efficiencies. Notably, the water-coagulated membrane exhibited minimal paracetamol removal (approximately 13.8%), whereas the AC-CN-IPA membrane achieved significantly higher and more stable paracetamol capture (approximately 60–64% within 60 minutes), suggesting improved pore accessibility. For 4-nitrophenol, the initial removal differences (40.9% vs 37.7%) were less pronounced than the sustained retention observed for the AC-CN_IPA membrane (33.0% to 21.7% over 20–60 minutes), indicating a more robust interaction. These results definitively demonstrate that the composition of the coagulation baths plays a critical role in controlling membrane morphology and consequently the accessibility of AC-CN sorption sites. Furthermore, the chemical nature of the contaminant plays

a differential role: 4-nitrophenol appears to engage in more favourable specific interactions with carbon fillers, whereas paracetamol removal is more sensitive to pore access. This study confirms the influence of coagulation bath composition on membrane structure–property relationships and validates the potential of PVDF/AC-CN composite membranes for effectively removing diverse organic pollutants, offering a promising approach to sustainable water treatment. Future research should focus on optimising these parameters further and exploring their efficacy against a broader spectrum of CECs.

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