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Heavy metal removal from industrial wastewater using membrane filtration techniques and bacterial biosorption

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ABSTRACT

This study justifies the use of nanofiltration (NF) and reverse osmosis (RO) membranes according to their high selectivity and efficient removal of heavy metals, at low concentrations in comparison to other conventional methods such as chemical precipitation. The NF system treated laboratory scale wastewater that contained Ni(II) Cr(VI) and Cu(II) at concentrations of 100 to 300 ppm. It is found that the NF system was able to remove more than 87%, 79% and 71% of Cr(VI), Cu(II) and Ni(II) respectively. In comparison, the RO system eliminated 93% of Cu(II), 85% of Cr(VI) and 80% of Ni(II). The permeate flux varied, from 17 to 65 L/m²•hr. In parallel biosorption of Cr(VI) Cu(II) and Ni(II) using *Pseudomonas* sp. was investigated. The experiment used a metal concentration of 100 ppm. *Pseudomonas* sp. was able to remove Cr(VI), Cu(II) and Ni(II) with an efficiency of 93%, 88% and 91% respectively. Consequently, this research aligns directly with United Nations Sustainable Development Goal 6 (Clean Water and Sanitation) by demonstrating effective technologies for improving water quality, minimizing hazardous chemical release, and facilitating safe water reuse.

Keywords: industrial wastewater, heavy metal, nanofiltration, water treatment, membrane filtration, reverse osmosis, biosorption.

INTRODUCTION

The presence of heavy metals in wastewater is a growing global concern due to their persistence, toxicity, and potential for bioaccumulation, creating serious hazards for ecosystems and human health. Industrial and urban discharges remain the major sources of heavy metal contamination in surface waters and threaten aquatic life and public health, according to recent reviews and international guidelines (Fu and Shi, 2020). The rapid industrialization and urban growth have resulted in an urgent need for efficient, cost-effective, and sustainable wastewater treatment technologies. The World Health Organization (WHO) has set strict limits for heavy metals in drinking water, soil, and agricultural sectors in order to minimize their potential hazards (WHO, 2022). Common industrial effluents typically have metals (nickel, chromium, copper, etc.) above these limits, requiring treatment before they can be discharged or reused. Conventional methods, such as chemical precipitation, ion exchange, and adsorption treat highly concentrated wastewater but have severe drawbacks at lower concentrations of metals (generally below 100 ppm). These limitations include lower removal performance, high operating expenses, secondary waste production, and performance degradation in complex multi-contaminant processes (Sharma, Nagpal and Kaur, 2018). Membrane-based separation methods, such as nanofiltration (NF) and reverse osmosis (RO) could be promising candidates for heavy metal removal at low to moderate concentrations. High selectivity, consistent effluent quality, and increasingly stringent discharge standards can be met by these technologies. NF and RO have made recent advances in industrial wastewater treatment based on successful feasibility and rapid industrial adoption (Fu and Xi, 2020; Wang et al., 2024). The performance of nanofiltration technologies shows a striking balance between operational simplicity, costs, as well as high rejection efficiency and can be very helpful in industrial applications (Algureiri and Abdulmajeed, 2016). At the same time, biological treatment approaches, namely bacterial biosorption, have been identified as low-energy and environmentally friendly methods for heavy metal removal. Biosorption takes advantage of the intrinsic affinity of microbial cell walls for metal ions through surface complexation, ion exchange, bioaccumulation, biotransformation, and bioprecipitation (Huang et al., 2018; Wang et al., 2021). Many bacterial species have demonstrated high metal uptake capacities, even at low metal concentrations, such as *Lactobacillus acidophilus*, *Rhodococcus opacus*, and *Pseudomonas species* (Calfa and Torem, 2008; Singh et al., 2010; Gialamouidis, Mitrakas and Liakopoulou-Kyriakides, 2009). Even though the literature on membrane filtration and biosorption as standalone treatment approaches is sufficient, comparisons and evaluations under standard as well as comparable operating conditions have not been carried out. Specifically, there is little systematic analysis of how the operational parameters determine the relative performance of physical and biological approaches relative to commonly occurring industrial heavy metals. Thus, the objective of this study was to comparatively evaluate nanofiltration, reverse osmosis, and bacterial biosorption with Pseudomonas sp. for the removal of Ni(II), Cr(VI), and Cu(II) from industrial wastewater-associated aqueous media. Such parameters as metal concentration, pressure, temperature, pH, flow rate, and contact time are systematically studied for influence. The evidence here provides for comparison of the advantages and disadvantages of the various methods as well as provides information on development of sustainable and efficient heavy metal removal strategies in the realization of water reuse and environmental protection objectives (Table 1).

EXPERIMENTAL PROCEDURE

Physical approach

The investigation in this study focused on heavy metals Ni(II), Cr(VI), and Cu(II). To make sure the concentration, pressure, temperature, pH, and flow rate were all right for each experiment, a certain amount of heavy metal salts were dissolved in deionized water to make the feed solution. After that, the feed tank was filled with the prepared feed.

The feed water was pumped out of the tank and changed the pressure. The operating pressure of each run was fine-tuned by slowly closing the reject valve (but not completely closing it) and keeping an eye on the pressure gauge that was set up before the membrane unit. A control valve was placed upstream of the membrane and downstream of the pump to adjust the feed flow rate as required. Table 2 provides a summary of the main physical and chemical characteristics of Ni(II), Cr(VI), and Cu(II). Table 3 lists the chemicals that are used to clean the membrane and adjust the pH.

To find the best membrane for the process, two types of nanofiltration and reverse osmosis membranes were tested. Before testing with solutions containing the heavy metal ions, the experiments were carried out using pure water. In each case, the

Table 1. Heavy metals' limits, uses, and toxicity

Chemical symbol	Oxidation state	Permissible limit (ppm)	Uses	Toxicity and health effects
Pb (lead)	+2	0.01	Construction, batteries, bullets	Negatively affects plant growth, human health, and the nervous system.
Cu (copper)	+2	0.1	Electrical conductors, construction materials, alloys	Toxic due to redox reactions, may damage DNA.
Fe (iron)	+2, +3	0.3	Various industries, pipes, wire drawing, steel mills	Osteoporosis, liver cirrhosis, heart and gland disorders.
Ni (nickel)	+2	0.02	Stainless steel, batteries, electronics	Liver damage, weight loss, heart and skin disorders at high doses.
Zn (zinc)	+2	3	Galvanization, alloy preparation, construction, batteries	Excess causes nausea, vomiting, stomach pain, and poisoning symptoms.
Cr (chromium)	+6	0.05	Leather industry, plating, metallurgy, pigments	Highly toxic, carcinogenic, damages liver, kidneys, and respiratory system.

Table 2. Chemistry and physical characteristics of heavy metals

Heavy metals. Ion	Chemical formula	Molecular weight (g/mol)	The density g/cm³	Solubility in water (molal)	Purity %
Ni(II)	$NiSO_4 \cdot 6H_2O$	262.58	1.948	77.5 at 30 °C	99.8
Cu(II)	$CuSO_4 \cdot 5H_2O$	249.7	2.286	1.502 at 30 °C	99.8
Cr(VI)	$K_2Cr_2O_7$	294.18	2.68	12.5 at 25 °C	99.9

Table 3. Auxiliary chemical and physical characteristics

Material	Molecular weight (g/mol)	Density (g/cm³)
Sodium chloride	58.4	2.17
Hydrochloric acid	36.5	1.18
Sodium hydroxide	39.9	2.13

removal rate and permeate flux were measured and also it was evaluated how operating pressure affected the performance of the membrane.

In Figure 1, a simplified diagram of the membrane process can be seen. This figure shows the three streams involved in the membrane process: the concentrate (retentate) of the feed stream, the product stream and the feed stream. Water flux describes the water flow through the membrane. How substances move across or through a membrane, or the transport mechanism, is crucial to the performance of the membrane.

The process setup for RO and NF is analyzed in Figure 2. In order to clean the membrane before and after each test and determine the flux coefficient, pure water was circulated. The system required at least four minutes to reach steady-state after the operational parameters, such as pressure and flow rate, were adjusted. Preliminary testing had already established this stabilization period.

During this equilibration phase, both the permeate and reject streams were recirculated back into the feed tank to maintain a consistent feed concentration. After reaching steady state, samples of

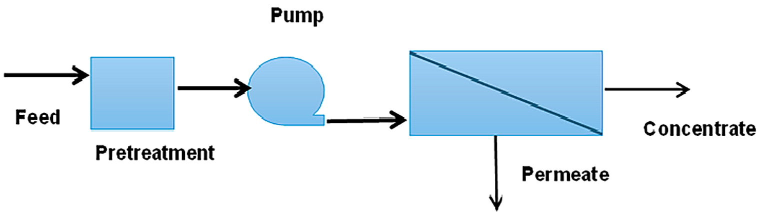

Figure 1. A schematic representation of the membrane process

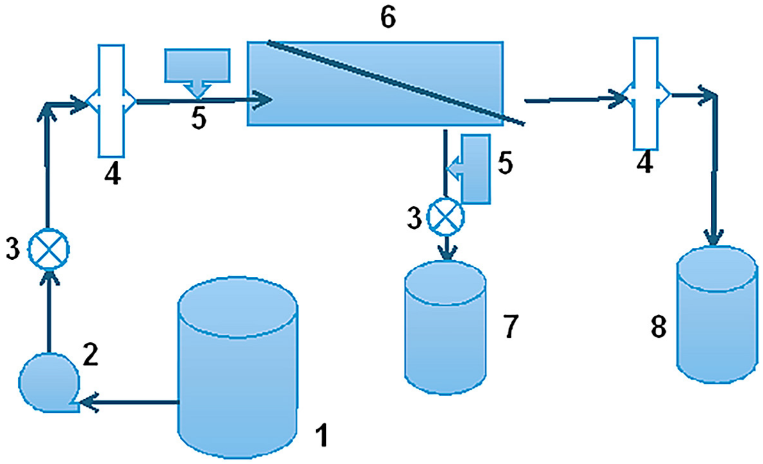

Figure 2. Schematic diagram of membrane process, 1 – feed tank, 2 – pump, 3 – valve, 4 – rotameter, 5 – pressure gage, 6 – membrane, 7– reject water tank, 8 – product

the permeate were collected to calculate the heavy metals concentration, the membrane rejection rate and the permeate flow rate, which in turn allowed for the calculation of membrane flux.

Membrane specifications, including manufacturer and model, as well as cleaning protocol details, are provided in Tables 4 and 5 supplementary materials, to ensure reproducibility and transparency. All experiments were conducted in triplicate to ensure reproduction. Results are reported as mean ± standard deviation, and statistical variability is represented by error bars in all relevant figures.

Biological approach

Bacterial preparation

Pseudomonas sp. strain was isolated from contaminated soil collected near automobile repair workshops in Baghdad, Iraq. Isolation and preliminary identification were carried out in the Microbial Laboratory, College of Agriculture, University of Baghdad, following morphological and biochemical criteria described by Gialamouidis, Mitrakas and Liakopoulou-Kyriakides (2009). Although molecular identification was not performed, the strain exhibited phenotypic characteristics consistent with the *Pseudomonas* genus.

Bacterial culture was grown in Luria-Bertani (LB) broth (Scharlau Chemie, Barcelona, Spain) at 25 °C under continuous shaking at 100 rpm to ensure adequate oxygen transfer. After reaching the exponential growth phase, bacterial cells were harvested by centrifugation at 4500 rpm for 20 min, washed twice with deionized water to remove residual growth medium, and used immediately in biosorption experiments.

Preparation of metal solution

Aqueous solutions containing single metal ions Ni(II), Cu(II) or Cr(VI) were prepared at an initial concentration of 100 ppm using analytical grade metal salts dissolved in deionized water. This concentration was selected to reflect normal concentrations obtained from industrial wastewater and suitable for the laboratory-scale biosorption assessment. The pH of each solution was adjusted to the desired value using either 0.01 M HCl or 0.01 M NaOH solution before biosorption experiments.

Biosorption experiments

Biosorption experiments were conducted using *Pseudomonas sp.* to determine the optimum pH range and equilibrium contact time for the removal of Ni(II), Cu(II) and Cr(VI) ions. The starting metal concentration for all tests was maintained at 100 ppm. The effect of pH in the range 3.0–7.0 and the contact time (0–120 min) were investigated. Metal uptake kinetics and equilibrium conditions were examined by collecting samples every 15 min. After biosorption, the suspension was centrifuged, and the remaining metal content in the supernatant was determined using a flame atomic absorption spectrophotometer (Perkin-Elmer). Nickel concentrations were measured at 232 nM, copper at 324.8

Table 4. Specification of RO & NF membranes

Parameter	NF membrane	RO membrane
Membrane type	Nanofiltration (NF)	Low pressure reverse osmosis (LP-RO)
Average pore diameter (nm)	0.5–2.0	< 0.5
Active layer material	PPSU / PES / PSf (TFC optional)	Thin film composite (Polyamide)
Dope composition (wt %)	PPSU/NMP (20–30 : 70–80)	Polyamide (thin active layer)
Bore fluid composition (NMP/water)	0 / 100	0 / 100
Operating pressure (bar)	2–10	1–6
Coagulation bath temperature (°C)	25–40	20–30
Salt rejection (%)	20–80 (NaCl) 80–99 (divalent salts)	90–99.5
Water flux (LMH)	50–120	30–70
Energy consumption	Low	Low–Moderate
Typical applications	Water softening, dye removal, wastewater treatment	Drinking water production, low-TDS desalination
Example manufacturer	DuPont (FilmTec™)	DuPont (FilmTec™)
Example model	NF270 / NF90	BW30-400 ULP
Zeta potential at pH 7	−10 to −30 mV	−5 to −20 mV

Table 5. Specification of MF & UF membranes

Parameter	MF membrane	UF membrane
Membrane type	Microfiltration (MF)	Ultrafiltration (UF)
Average pore diameter (nm)	100–10.000	2–100
Active layer material	PVDF / PP / PTFE	PES / PSf / PVDF
Dope composition (wt %)	PVDF/NMP (15–25 : 75–85)	PES/NMP (15–25 : 75–85)
Bore fluid composition (NMP/water)	0 / 100	0 / 100
Operating pressure (bar)	0.1–2	0.5–5
Coagulation bath temperature (°C)	20–30	20–35
Salt rejection (%)	< 5	< 10
Water flux (LMH)	200–2000	100–500
Energy consumption	Very low	Low
Typical applications	Suspended solids removal, bacteria removal, pretreatment	Virus removal, protein separation, wastewater treatment
Example manufacturer	Toray	SUEZ
Example model	TMF-101	ZeeWeed® 500
Zeta potential at pH 7	−5 to −15 mV	−10 to −25 mV

nM and chromium at 357.9 nM as per standard analytical procedures. The efficiency (%R) of metal ions was measured according to the equation:

$$\%R = (Co - C)/Co \times 100 = (1 - C/Co) \times 100 \quad (1)$$

where: $\%R$ – the percent removal, Co – the initial metal concentration (ppm), C – the metal concentration at a specific time (ppm).

Triplicate biosorption experiments were performed in order to achieve reproducibility. Results are expressed as mean ± standard deviation, and they are consistent with statistical variation through error bars included in all applicable figures.

RESULTS AND DISCUSSION

Physical approaches

Performance of two types of membranes

The removal efficiencies of heavy metals by two types of membranes at an operating pressure of 1 bar are illustrated in Figure 3. The observed removal rates were 76.6% for NF and 85% for RO. At a higher pressure of 4 bars, the removal percentage increased to 86% for NF and 90% for RO.

Figure 4 compares the permeate fluxes achieved by the two membranes. At 1 bar, the

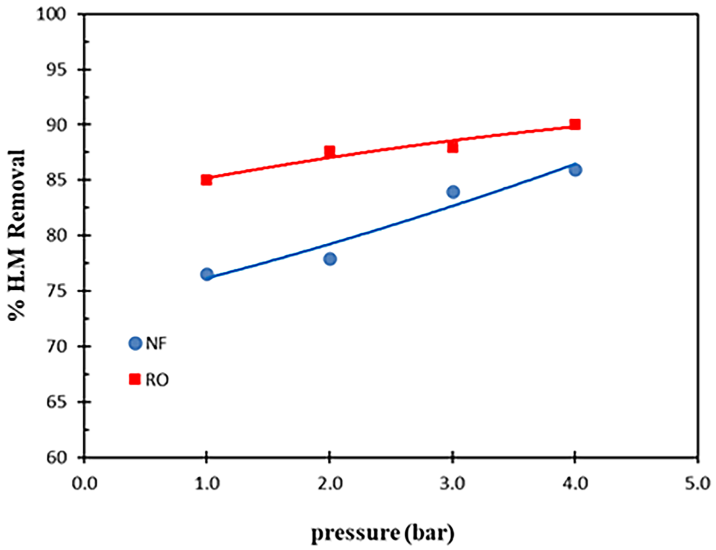

Figure 3. The effect of pressure (bar) on the percentage of Cr(VI) removal at various membrane types (concentrations 200 ppm, flow rate = 4 L/hr, pH 5 and temperature 35 °C)

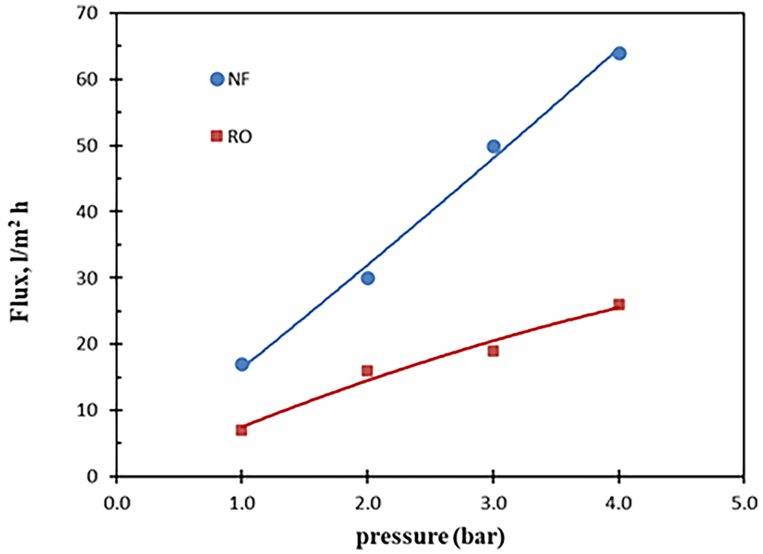

Figure 4. The pressure's impact on the permeate flux of Cr(VI) at several types of membranes. (concentrations 200 ppm, flow rate = 4 L/hr, pH 5 and temperature 35 °C)

permeate flux values were 17 L/m²·hr for NF and 7 L/m²·hr for RO. When the operating pressure was raised to 4 bar, the fluxes increased to 64 L/m²·hr for NF and 26 L/m²·hr for RO.

The applied pressure range for RO (1–4 bar) was selected due to the relatively low osmotic pressure of the feed solutions. For brackish or seawater feeds, higher pressures would be necessary, but for the studied synthetic wastewater, effective removal was achieved with the stated pressures. The membrane type used was a commercial low-pressure RO, as specified in the Materials section.

Effect of feed concentration in membrane systems

Typical concentrations that are usually used in industrial wastewater, 100, 200, and 300 ppm were chosen as the feed concentrations for all the metals that were tested. With all other parameters maintained constant (pressure at 1 bar, pH at 5, flow rate at 4 L/hr, and temperature at 35 °C), Figure 5 shows that increasing the concentration of Cu(II), Cr(VI), and Ni(II) in the feed reduces removal efficiency for the NF system. The removal rates for copper (II), chromium (VI), and nickel

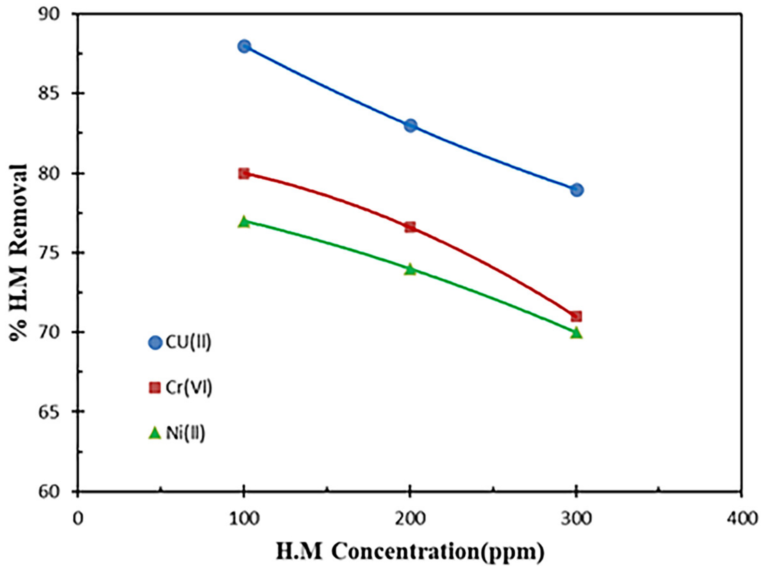

Figure 5. Impact of concentration on the removal percentage of heavy metals at the nanofiltration membrane (pressure = 1 bar, temperature = 35 °C, pH = 5, and rate of flow = 4 L/hr)

(II) were 88%, 80.1%, and 77.2%, respectively, at a concentration of 100 ppm. At 300 ppm, the removal rates for copper (II), chromium (VI), and nickel (II) were 79.8%, 72%, and 71%, respectively, in that order.

The effect on permeate flux of raising the feed concentration is shown in Figure 6. The flux drops marginally from 19.5 L/m²·hr at 100 ppm to 15 L/m²·hr at 300 ppm, proportional to the increase in heavy metal concentration.

The decrease in removal and flux is primarily attributed to concentration polarization, ionic shielding, and increased osmotic pressure, as metal concentration increases. These factors reduce the driving force across the membrane and increase resistance to mass transfer, resulting in lower removal efficiency and flux. The explanation was revised for mechanistic accuracy.

Previous studies have reached similar conclusions. As an illustration, it was found by (Wang et al., 2008) that the removal efficiency and permeate flux of $CuSO_4$ through polybenzimidazole (PBI) nanofiltration hollow fiber membranes declined with increasing concentrations of metal ions. In a similar vein (Johnson et al., 2018) discovered that at low concentrations, the removal of copper ions was 90% when using an NF270 membrane at a concentration of 1000 ppm, pressure of 4 bar, and pH of 1.5 ± 0.2. However, at higher concentrations, this percentage dropped to 58%. Under the same circumstances, lead ions were removed at a rate of 74%, cadmium ions at 99%, and manganese ions at 89%.

Effect of pressure in membrane systems

The pressure differential is sensitive to the type and concentration of contaminants. That makes the operating pressure is an important factor in how well an NF membrane system functions. The change in removal efficiency according to the change in pressure is shown in Figure 7. For these tests, the following parameters were used: starting concentration = 200 ppm, pH = 5, temperature = 35 °C, and flow rate = 4 L/hr. From 83% to 91%, 86% to 88%, and 77% to 74.5 percent, respectively, for Cu(II), Cr(VI), and Ni(II), the removal rates improved as the pressure increased from 1 bar to 4 bar. An increase in driving force across the membrane, leading to a stronger rejection of metal ions, is the likely explanation for the improved removal at higher pressures. Unfortunately, some heavy metal ions will still be able to pass through the membranes, because they are not impermeable. Water flux increases at a faster rate than heavy metal ion transport at higher pressures, leading to improved removal efficiencies up to a certain limit (Figure 8, 9).

Effect of temperatures in membrane systems

The effect of temperature on the NF system's removal efficiency of Cu(II), Cr(VI), and Ni(II) ions was 80.1%, 74%, and 71%, respectively. Raised to 45 °C, the Cu(II)/Cr(VI)/Ni(II) removal efficiencies were 88.1%, 81.2%, and 79%, respectively. These changes in permeate flux are shown in Figure 10 with the temperature

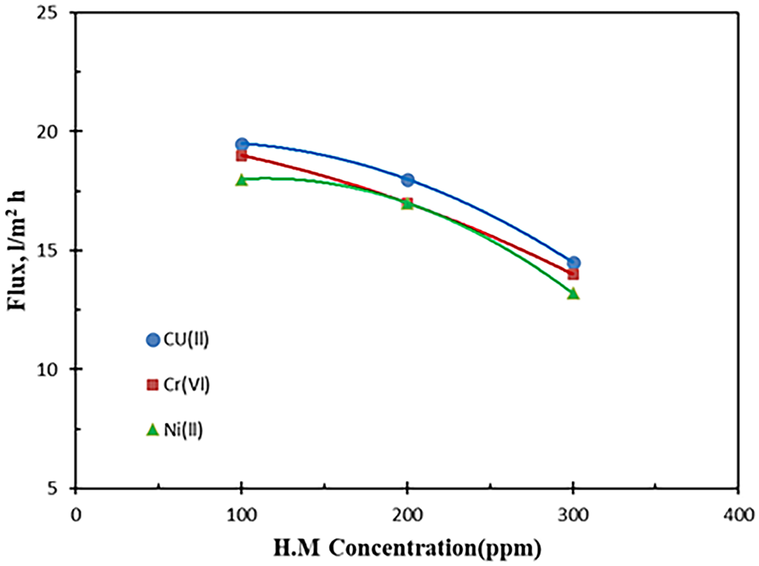

Figure 6. Influence of concentration on permeate flux of heavy metals at nanofiltration membrane (pressure = 1 bar, temperature

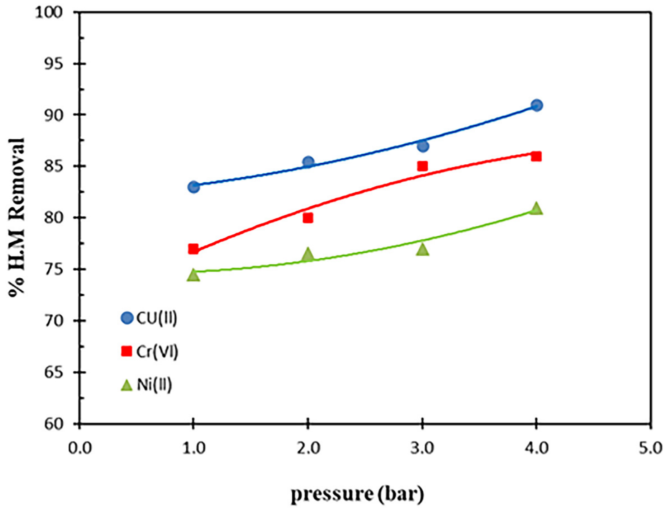

Figure 7. Influence of pressure on the removal percentage of heavy metals at the nanofiltration membrane (concentration = 200 ppm, temp = 35 °C, pH = 5, and rate of flow = 4 L/hr)

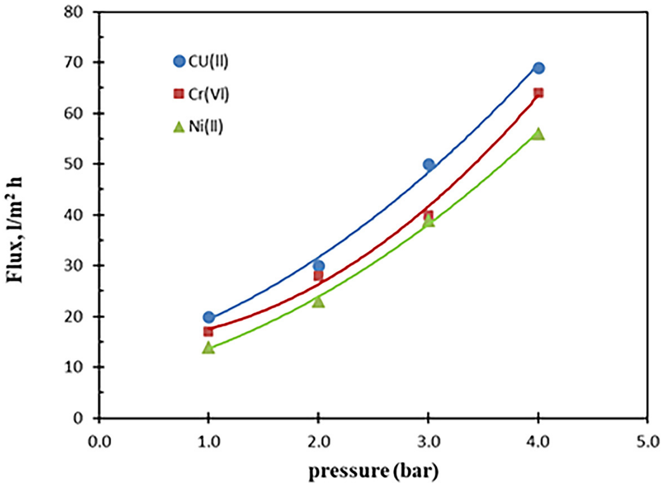

Figure 8. Influence of pressure on permeate flux of heavy metals at the nanofiltration membrane (concentration = 200 ppm, temperature = 35 °C, pH = 5, and rate of flow = 4 L/hr)

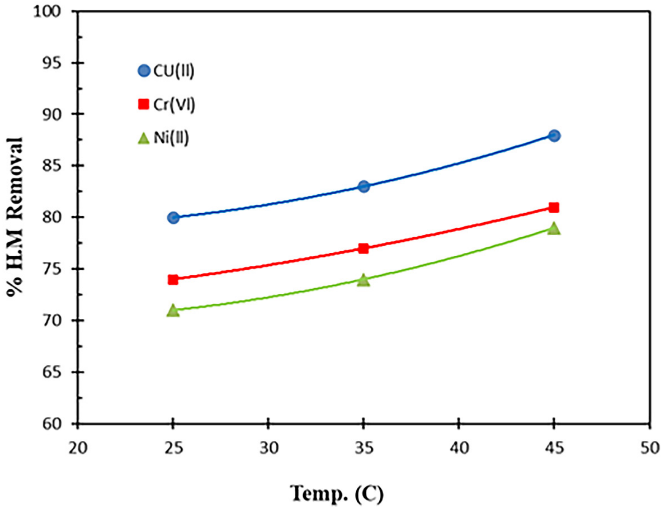

Figure 9. Effect of temperature on the percentage removal of heavy metals using a nanofiltration membrane (pressure = 1 bar, concentration = 200 ppm, pH = 5, flow rate = 4 L/hr)

difference. The permeate fluxes corresponding to Cu(II), Cr(VI), and Ni(II) were 14, 13, and 11 L/m²•hr at 25 °C. At 45 °C, rates of Cu(II), Cr(VI), and Ni(II) increased drastically up to 27, 23, and 21.1 L/m²•hr, respectively. At higher temperatures, the water molecules are diffusive, and their viscosity drops and the permeate flux increases. The pore sizes of the polymeric membrane may also expand slightly at high temperatures, which would increase flux by further allowing more water through (Abod et al., 2019).

Impact of pH on heavy metal removal and permeate flux

The removal of heavy metals like Cu(II), Cr(VI), Ni(II) and so forth is also influenced by pH (see Figure 11). Through the experiment, it can be seen that removal efficiencies significantly improved with increasing pH. At pH 4 the removal rates of Cu(II), Cr(VI) and Ni(II) were 77%, 71% and 69%, respectively. Up to pH 6, removal rates of 90.2% for Cu(II), 87% for Cr(VI), and 82% for Ni(II) were enhanced. Permeate flux in Figure 12 is manipulated by pH. Flux values for Cu(II), Cr(VI), and Ni(II) for the most favorable pH 6 were 24, 20, and 19 L/m²•hr, respectively. Flow rates of these ions reached their minimum at pH 4 of 17, 14.9, and 13 L/m²•hr. Experimental measurements of membrane surface charge and zeta potential at a range of pH values were prepared. The effect of pH on surface charge and rejection is consistent with the chemistry of the selected membrane.

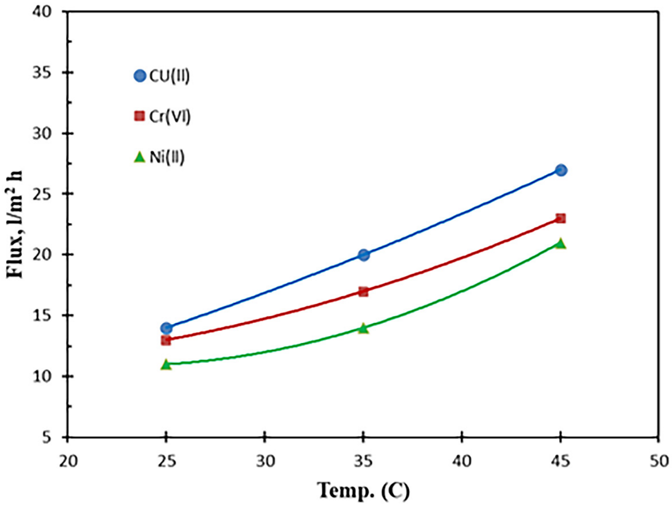

Figure 10. Influence of temperature on permeate flux of heavy metals at nanofiltration membrane (pH = 5, concentration = 200 ppm, pressure = 1 bar, and rate of flow = 4 L/hr.)

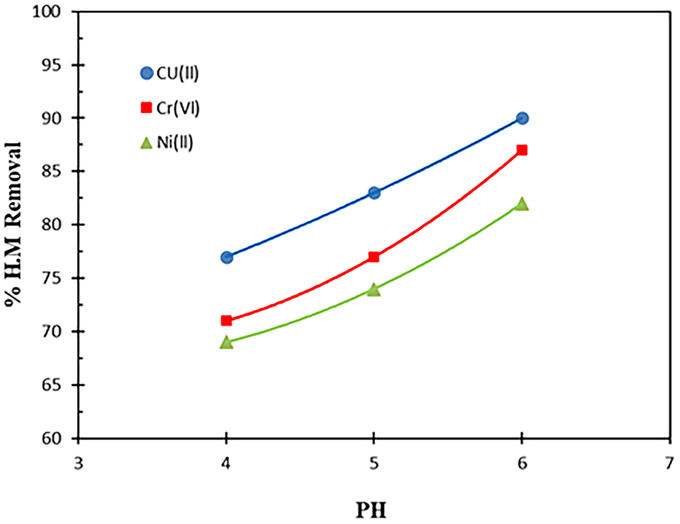

Figure 11. Impact of pH on the removal percentage of heavy metals at the nanofiltration membrane (pressure = 1 bar, concentration = 200 ppm, temp = 35 °C, and the rate of flow = 4 L/hr)

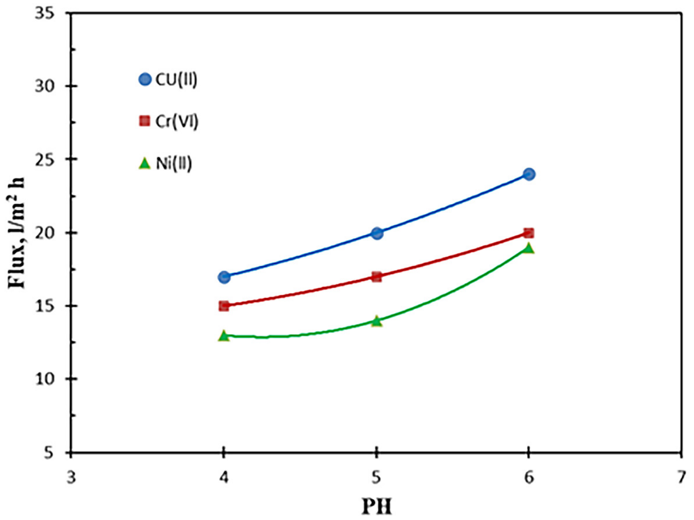

Figure 12. Influence of pH on permeate flux of heavy metals at nanofiltration membrane (pressure = 1 bar, concentration = 200 ppm, temp = 35 °C, and the rate of flow = 4 L/hr)

Effect of feed flow rate in membrane systems

Higher currents not only decrease layer fouling on the surface but also increase the efficiency of removing heavy metal and flux. The diaphragm should not be driven out of mechanical strength; such an action can impact the filtration efficiency or possibly to the end of the device damage, again depending on the design and form of the device. The lower concentration of heavy metal permeate is a result of the increased feed flow rate into the NF membrane, as shown in Figure 13. For example, at a feed flow rate of 3 L/h, the removal efficiencies for Cu(II), Cr(VI), and Ni(II) were 80.2%, 75%, and 72%, respectively. When the flow rate was increased to 5 l/h, the removal percentage of Cu(II), Cr(VI) and Ni(II) increased to 85.1%, 79.9% and 78%, respectively.

The effect of feed flow rate on permeate flux is shown in Figure 14. A permeate flux of 10, 8, and 7 L/m²·hr was measured for Cu(II), Cr(VI), and Ni(II), respectively, at 3 L/hr. The fluxes for Cu(II), Cr(VI), and Ni(II) were 27, 23, and 22 L/m²·hr, respectively, when the feed flow rate was increased to 5 L/hr. The decrease in concentration polarization at the membrane surface is responsible for this improvement. At higher feed flow rates, turbulence increases near the membrane, the boundary layer thickness decreases, and the local solute concentration drops (Al-Alawy, Ramy, 2019; Mthethwa, 2014).

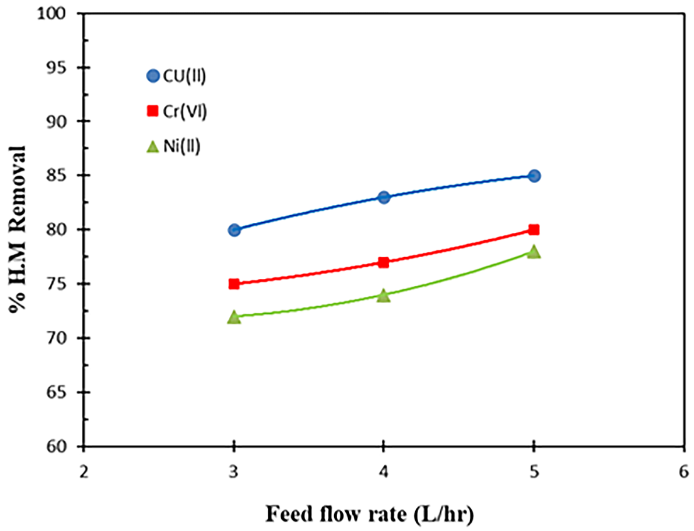

Figure 13. Influence of feed flow rate on the removal % of heavy metals at the nanofiltration membrane (pressure = 1 bar, concentration = 200 ppm, temperature = 35 °C, and pH = 5)

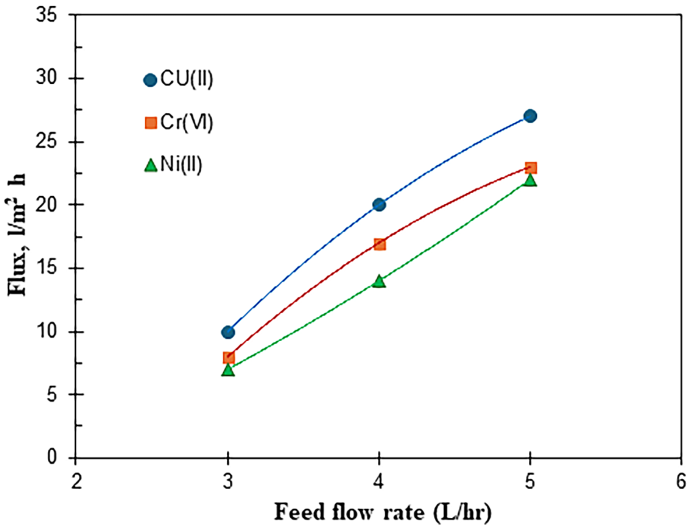

Figure 14. Influence of pH on permeate flux of heavy metals at nanofiltration membrane (pressure = 1 bar, concentration = 200 ppm, temperature = 35 °C, and pH = 4)

Biological approaches

pH effect

The pH is an important parameter, which affects the solution chemistry of metal ions and the surface functional groups of the bacterial cell wall (Long et al., 2014). The effect of pH on removal efficiency of *Pseudomonas* sp. to eliminate heavy metals is shown in Figure 15. The metal concentration is fixed at 100 ppm for the three studied elements. As it can be seen, there is an increase in removal efficiency with increasing pH value to 4 for Cr(VI) and 5 for a media containing Cu(II) and Ni(II). When pH increases above these values, the removal efficiency began to reduce dramatically. This result compatible with the finding reported by (Aryal and Liakopoulou-Kyriakides, 2015) and that could due to the repulsive forces between metal anions and negatively charged biomass surface reduce the metal removal percentage (Izadpanah and Javidnia (2012)).

Equilibrium time effect

The equilibrium time is also one of the most essential parameters that can affect the bacterial biosorbents. The time range was between 0–120 min. Figure 16 shows that generally, the increase in removal efficiency was very fast in the beginning then it started to be slower. Further increase of equilibrium time did not result in a significant increase in the adsorbed metals. The results showed significant differences between the three studied metals Ni(II), Cr(VI) and Cu(II), since the equilibrium time of those elements were 15, 90, 30 min, respectively. This finding is in agreement with earlier studies of (Ziagova et al., 2007; Gialamouidis, Mitrakas and

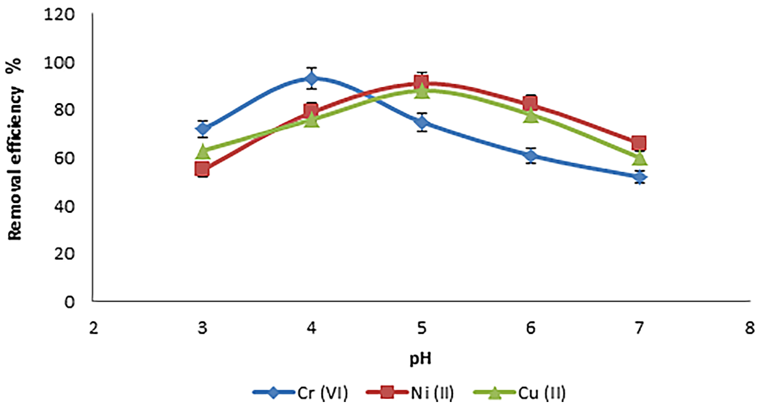

Figure 15. Effect of pH on Ni(II), Cu (II) and Cr (VI) removal efficiency of *Pseudomonas* sp. Initial metal concentration 100 mg L^{-1} and equilibrium time 120 min

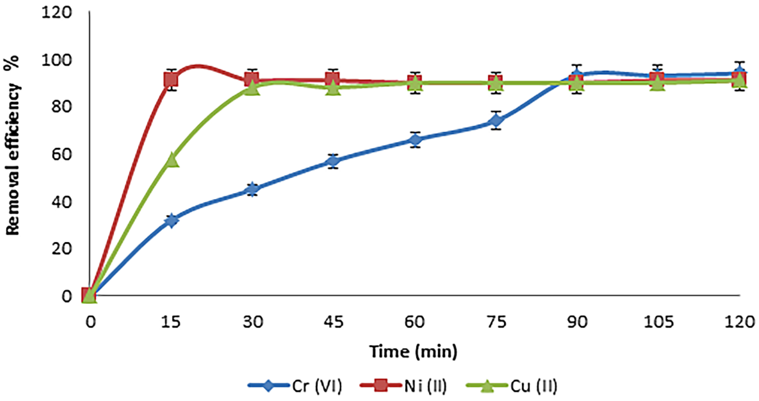

Figure 16. Effect of equilibrium time on Ni(II), Cu (II) and Cr (VI) removal efficiency of *Pseudomonas* sp. Initial metal concentration 100 mg L^{-1} and pH 5

Liakopoulou-Kyriakides, 2009). When optimum pH and equilibrium time were applied, the highest removal efficiency was 91%, 93% and 88% of Ni(II), Cr(VI) and Cu(II), respectively.

Replicate experiments were performed for each experiment. Error bars and standard deviation in all graphs are represented. The results were statistically significant ($p < 0.05$).

CONCLUSIONS

With heavy metals being one of the most difficult categories of pollutants due to their toxicity and persistence, their removal from wastewater is vital to prevent harm to the environment and to human health. This study investigated the removal of three common heavy metals Ni(II), Cr(VI), and Cu(II) utilizing two different treatment methods: membrane-based physical processes (nanofiltration and reverse osmosis) and biological biosorption using *Pseudomonas* sp. Nanofiltration and reverse osmosis were found to be highly effective for the removal of heavy metals, where reverse osmosis showed significantly higher rejection efficiencies than nanofiltration followed by better permeate fluxes. Concurrently, the high removal efficiency of bacterial biosorption under optimal pH and contact time conditions validated a low-energy, environmentally friendly treatment solution for the microbial species. The final treated water met the WHO (2022) guidelines for heavy metals in water across most operating conditions. This observation goes beyond performance and serves to underline relevant environmental aspects related to every treatment method such as concentrate management in membrane systems, biomass regeneration or waste disposal after biosorption. These are all relevant factors when evaluating general sustainability of heavy metal treatment technologies. It is important to note that the experiments were carried out at laboratory scale for single-ion aqueous solutions. However, competitive reactions of multiple ions, organic matter and long-term membrane fouling were not considered. This calls for future attention to multi-component real wastewater systems, longer operational periods, and membrane fouling behavior, in order to provide a more comprehensive evaluation of long-term performance and feasibility. Lastly, this study is a comparative laboratory comparison between physical and biological treatment methods, rather than an integrated or hybrid treatment system. Sequential or coupled processes were not studied, and the manuscript is not a claim of process integration per se. The results present a distinct performance benchmark and a scientific rationale for choosing suitable treatment methods for heavy metal removal from industry-contaminated wastewater.

REFERENCES

1. Abod, B.M. et al. (2019). Comparative bio-sorption of cadmium and nickel ions from aqueous solution onto fibers of date palm using fluidized bed column, *Rev. Chim.(Bucharest), 70*, 1507–1512.
2. Al-Rashdi, B.A.M., Johnson, D.J. and Hilal, N. (2013). Removal of heavy metal ions by nanofiltration, *Desalination, 315*, 2–17.
3. Algureiri, A.H. and Abdulmajeed, Y.R. (2016). Removal of heavy metals from industrial wastewater by using RO membrane, *Iraqi Journal of Chemical and Petroleum Engineering, 17*(4), 125–136.
4. Al-Alawy, R.M.J., Abod, B.M., Kamar, F.H.,

Nechifor, A.C. (2019). Removal of dyes from wastewater by ceramic membrane, *Revista de Chimie Open Access. 70*(5,) 1715–1719.

5. Aryal, M. and Liakopoulou-Kyriakides, M. (2015). Bioremoval of heavy metals by bacterial biomass, *Environmental monitoring and assessment, 187*(1), 4173.
6. Bakyayita, G.K. et al. (2014). Kinetic studies of Cd (II) and Pb (II) ions biosorption from aqueous media using untreated and chemically treated biosorbents, *Water science and technology, 69*(11), 2230–2236.
7. Calfa, B.A. and Torem, M.L. (2008). On the fundamentals of Cr (III) removal from liquid streams by a bacterial strain, *Minerals Engineering, 21*(1), 48–54.
8. Fu, Z. and Xi, S. (2020). The effects of heavy metals on human metabolism, *Toxicology mechanisms and methods, 30*(3), 167–176.
9. Gergely, S. (2001). Arsenic Removal from drinking water by nanofiltration, Doctoral (phD) thesis, new scientific results [Preprint].
10. Gialamouidis, D., Mitrakas, M. and Liakopoulou-Kyriakides, M. (2009). Biosorption of nickel ions from aqueous solutions by Pseudomonas sp. and Staphylococcus xylosus cells, *Desalination, 248*(1–3), 907–914.
11. Huang, Y. et al. (2018). Heavy metal pollution and health risk assessment of agricultural soils in a typical peri-urban area in southeast China, *Journal of environmental management, 207*, 159–168.
12. Izadpanah, A.A. and Javidnia, A. (2012). The ability of a nanofiltration membrane to remove hardness and ions from diluted seawater, *Water, 4*(2), 283–294.
13. Jaafarzadeh, N. et al. (2015). Biosorption of heavy metals from aqueous solutions onto chitin, *International Journal of Environmental Health Engineering, 4*(1), 7.
14. Johnson, D.J. et al. (2018). Osmotic's potential: An overview of draw solutes for forward osmosis, *Desalination, 434*, 100–120.
15. Long, J., Luo, D. and Chen, Y. (2014). Identification and biosorption characterization of a thallium-resistant strain, *Chin J App Environ Biol, 20*, 426–430.
16. Lumami Kapepula, V. et al. (2022). Evaluation of commercial reverse osmosis and nanofiltration membranes for the removal of heavy metals from surface water in the Democratic Republic of Congo, *Clean Technologies, 4*(4), 1300–1316.
17. Mthethwa, V. (2014). *Investigation of polyethersulfone (PES) hollow fiber membrane for the treatment of acid mine drainage.* Wits University.
18. Salih, M.H. et al. (2024). Green power generation from the Tigris River using pressure retarded osmosis process, *Desalination and Water Treatment, 320*, 100887.
19. Sharma, S., Nagpal, A.K. and Kaur, I. (2018). Heavy metal contamination in soil, food crops and associated health risks for residents of Ropar wetland, Punjab, India and its environs, *Food chemistry, 255*, 15–22.
20. Singh, A. et al. (2010). Risk assessment of heavy metal toxicity through contaminated vegetables from waste water irrigated area of Varanasi, India, *Tropical ecology, 51*(2), 375–387.
21. Wang, F. et al. (2021). Enhanced heavy metals sorption by modified biochars derived from pig manure, *Science of the Total Environment, 786*, 147595.
22. Wang, L.K. et al. (2008). *Membrane and desalination technologies*. Springer.
23. Wang, Y. et al. (2024). Research progress on membrane separation technology for oily wastewater treatment, *Toxics, 12*(11), 794.
24. Wierzba, S. and Latała, A. (2010). Biosorption lead (II) and nikel (II) from an aqueous solution by bacterial biomass, *Polish Journal of Chemical Technology, 12*(3), 72–78.
25. World Health Organization (WHO), 2022. *Guidelines for Drinking-water Quality*, 4th ed. (including addenda). WHO Press, Geneva, Switzerland.
26. Ziagova, M. et al. (2007). Comparative study of Cd (II) and Cr (VI) biosorption on *Staphylococcus* xylosus and *Pseudomonas* sp. in single and binary mixtures, *Bioresource technology, 98*(15), 2859–2865.