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Enhancing Wastewater Reuse in Phosphate Mining: Nanofiltration-Based Removal of Silica and Chloride Ions

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Abstract

High silica and chloride content make phosphate-mining wastewater hard to treat: both drive scaling, fouling, and corrosion in downstream equipment. Here, a ceramic nanofiltration (NF) membrane was tested against this problem, targeting silica (Si^{4+}) and chloride (Cl^{-}) removal from synthetic SiCl_4 solutions and from real effluent supplied by the Jordan Phosphate Mines Company (JPMC), with transmembrane pressure (TMP), ion concentration, and pH all varied to see how each affected rejection. The best performance came from the real JPMC effluent: 97.1% Si^{4+} rejection and 99.9% Cl^{-} rejection at 5 bar TMP. The two feedwaters behaved differently. In the synthetic solutions, electrostatic repulsion between the positively charged membrane surface and the cationic Si^{4+} dominated, so Si^{4+} rejection came out higher; in the real wastewater, a more complex ionic matrix shifted that balance toward Cl^{-} , pointing to a change in the underlying separation mechanism. Fouling rose with SiCl_4 concentration, but a NaOH cleaning cycle reversed it fully and restored membrane permeability. Together, these results indicate that ceramic NF can treat phosphate-mining wastewater well enough to support water reuse, lower treatment costs, and reduce environmental discharge.

Keywords: Silica Removal, Nanofiltration, Chloride Rejection, Water Treatment, Phosphate Mining

1. Introduction

Jordan's freshwater supply is already limited, and population growth, environmental degradation, and climate change are squeezing it further. One practical response is to recover water from sources that would otherwise go to waste, industrial wastewater included [1]. Industry sits on both sides of the problem: it is a major consumer of water and a significant source of pollution. That double role is why treating and reusing industrial wastewater is turning from a nice-to-have into a near-necessity, as freshwater grows scarcer, regulations tighten, and treatment costs climb. Mining is one of the largest industrial water users, and phosphate mining in Jordan is no exception. The Jordan Phosphate Mines Company (JPMC) holds roughly 6% of the global phosphate-rock market and depends heavily on water throughout its production process [2]. Its wastewater, however, carries silica and chloride, both of which drive scaling, corrosion, and environmental damage, so JPMC needs a treatment method that is effective, affordable, and environmentally sound.

Membrane technologies are widely used for municipal and industrial water reuse because they can produce high-quality water, are relatively easy to operate, and can be combined with other treatment processes (He et al., October) [1]. These technologies have been successfully applied in many sectors, including the chemical, textile, pulp and paper, metal-finishing, and food industries. Wastewater with high silica content, however, is difficult to treat with membrane systems. Silica, commonly present as silicon dioxide, occurs naturally in rocks, minerals, and sand, and once it enters a membrane system it tends to deposit on membrane surfaces and equipment. These deposits drive scaling and fouling, degrade membrane performance, and make cleaning harder; silica and silicate precipitation are, in fact, among the main constraints on high-recovery membrane operation, which is why effective silica-scaling control remains an open research problem [3].

JPMC relies on reverse osmosis (RO). It works well for desalination and removes many dissolved ions, but high silica concentrations are its weak point and causes trouble further down the line. Nanofiltration (NF) looks like a better fit: it runs at lower pressure than RO yet still removes a wide range of dissolved contaminants, reason enough to test it directly against JPMC's silica problem. The core question here is whether NF can separate silica (Si^{4+}) and chloride (Cl^{-}) ions out of the water and wastewater coming out of JPMC's operations. Both ions matter in practice, silica (Si^{4+}) by scaling and fouling pipes and equipment, chloride (Cl^{-}) by raising the water's corrosivity. What follows is an assessment of how well NF performs against this specific feedwater, and what that performance means for water quality, water reuse, environmental impact, and JPMC's broader treatment strategy.

1.1. Nanofiltration

Nanofiltration (NF) membranes date back to the late 1980s and occupy the separation range between ultrafiltration (UF) and reverse osmosis (RO): pore sizes typically run 0.2-2 nm, corresponding to a molecular weight cut-off of 200-1000 Da [4]. NF shares its basic separation principle with RO but uses larger pores and offers lower membrane resistance, which lets it remove a wide range of contaminants, including silica and other dissolved ions. It remains a comparatively young technology, but its use in mining has grown steadily as its effectiveness and environmental profile have become clearer [5].

Contact with an aqueous solution is enough to charge an NF membrane's surface, either through adsorption of charged solutes or dissociation of the membrane's own surface functional groups. In polymeric NF membranes, that charge typically comes from carboxylic or sulphonic acid groups exposed at the surface (Bush, Vanneste, and Cath, 2019). Ceramic membranes work differently: their surface charge is intrinsic to the material itself, though the feed solution's ionic composition can still shift it. Because that charge depends on what's in the water, testing ceramic NF membranes directly against JPMC's feedwater is worth doing.

NF already has a track record in mining. At the Collahuasi mine in Chile, NF membranes stripped impurities and contaminants from process water, helping the site conserve more than 40% of its freshwater supply (Wang, 2018) [2]. At Peru's Yanacocha gold mine, the same technology recovered up to 95% of valuable minerals from wastewater while cutting water consumption by 30% (Miranda, Latour, and Blanco, 2021) [3]. Coal mine drainage is another proving ground: it typically carries heavy concentrations of salts, heavy metals, and suspended solids that threaten nearby ecosystems, and NF has been used to strip these out and bring the water within discharge limits [6].

Fouling is what limits NF's long-term performance. It reduces permeate flux, forces higher operating pressures, and eventually drives up both cost and compromises product quality [7,8]. Keeping the membrane clean is therefore not optional, it is central to sustaining performance, usually through some combination of high-pressure flushing, chemical treatment, or mechanical

cleaning.

1.2. Problem of the Study

JPMC is one of the largest mining and processing operations in Jordan and the wider region. Its scale carries a proportional cost: large volumes of wastewater that must be adequately treated before discharge. Silica (Si^{4+}) ion is the most persistent pollutant in that wastewater stream. It shows up in several forms, fouls equipment, cuts process efficiency, and is especially damaging to membrane-based treatment because it drives scaling and fouling. Left untreated, it degrades process-water quality, complicates downstream treatment, and puts equipment at risk of damage. It does not dissolve readily, and it resists conventional filtration, which is exactly why removing it is so difficult [2].

Chloride (Cl^{-}) ion adds a second problem: elevated concentrations make the water more corrosive, accelerating wear on industrial infrastructure and posing risks to the surrounding ecosystem [3]. JPMC's current treatment approach is both costly and insufficient for Si^{4+} ion removal. The result is that a meaningful share of its wastewater still reaches local water bodies carrying a high Si^{4+} ion load, raising both pollution and public-health concerns.

NF is a promising response to this gap. Under favorable conditions, NF membranes have removed up to 95% of Si^{4+} in prior studies, though what performs well in the laboratory does not automatically translate to industrial conditions, and no study to date has examined NF performance specifically against JPMC's wastewater and local operating context [9]. This study was designed to close that gap. Its central aim: evaluate how effectively NF removes Si^{4+} and Cl^{-} ions from water associated with JPMC's operations, with the broader goal of informing a more sustainable water-treatment strategy for both the company and the surrounding environment [10]. To get there, ion rejection was measured across a range of silicon tetrachloride (SiCl_4) concentrations and transmembrane pressures (TMP), characterizing performance under realistic operating conditions.

2. Experimental Procedure

Si^{4+} ion rejection was evaluated by passing silica-containing solutions through a ceramic nanofiltration (NF) membrane and measuring the resulting Si^{4+} rejection. Feed samples came from two sources: some supplied directly by JPMC, others prepared in-house from solid silicon tetrachloride (SiCl_4). Three stock solutions were made up this way, at 0.1, 0.5, and 1.5 M, by dissolving the appropriate mass of SiCl_4 in 5 L of distilled water. Before filtration began, the pH, conductivity, and ion concentrations of each sample were recorded as a baseline. Figure 1 outlines the experimental setup. The procedure started with loading the solution into the feed tank, then switching on the pump and letting it run for a few minutes until flow is steady state. The transmembrane pressure (TMP) was obtained by changing the feed and retentate flow pressures. The TMP were obtained as follows

$$TMP = \left(\frac{P_{out} - P_{in}}{2} \right) \quad (1)$$

Were P_{out} being the retentate pressure (bar), and P_{in} is the feed pressure (bar). TMP was increased to 1 bar and held until steady-state flow was reached, at which point a permeate sample was collected over a set time period. This was repeated at TMP values ranging between 2 to 5 bar. For each TMP value, the permeate sample volume and mass were measured. These data were used in calculating the permeate volumetric and mass flow rate. Also, the pH, conductivity, and temperature of each permeate, feed and retentate samples were checked — these stayed essentially constant throughout. Once the runs were complete, Si^{4+} and Cl^{-} concentrations in the permeate were measured so that rejection values could be calculated for both ions. To check for fouling, the same procedure was repeated using plain distilled water instead of the $SiCl_4$ solution. Ion rejection was calculated using

$$R = \left(1 - \frac{c_p}{c_f}\right) \quad (2)$$

where R is the rejection, c_p is the permeate ion concentration (M), and c_f is the feed ion concentration (M). After each experiment the membrane was cleaned by using a 1.0 M sodium hydroxide (NaOH) solution in three stages. First, distilled water was flushed through the system to clear any residual material from the pipes and feed tank. Second, the NaOH solution was circulated through the system for two hours. Finally, distilled water was run through again until the effluent reached a neutral pH, confirmed using a pH meter. For reference, the membrane's pore diameter was 0.8 nm, and ions diameter of 0.04 nm for Si^{4+} and 0.167 nm for Cl^{-} . Si^{4+} ion concentration was measured using UV-Vis Spectrophotometer / Silica Analyzer, and Cl^{-} ion concentration was measured using ion selective electrode (ISE).

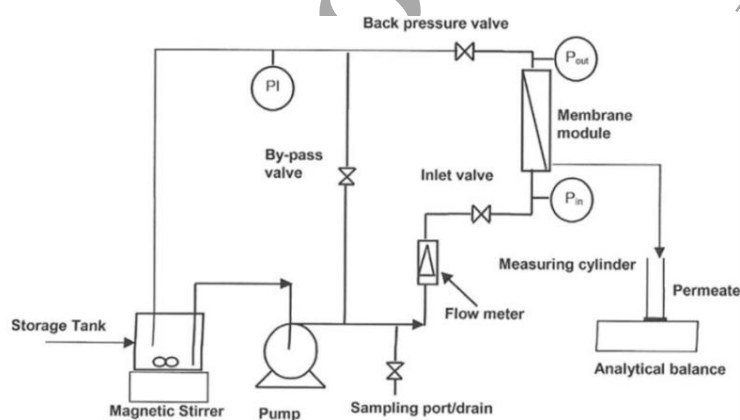


Figure 1: Experimental Setup Flow Chart

3. Results and Discussion

3.1. Synthetic $SiCl_4$ Solutions

For synthetic solutions, the rejection of Si^{4+} was generally higher than that of Cl^{-} . Maximum rejections reached approximately 99% for both ions at optimal conditions. Rejection rates for both Si^{4+} and Cl^{-} increased with increasing TMP (Figures 2-4) but decreased with increasing feed concentration. At a TMP of 1 bar, Si^{4+} rejection was 94% for the 0.1 M solution, 84.5% for the 0.5 M solution, and 47.6% for the 1.5 M solution. Similarly, Cl^{-} rejection at 1 bar was 92.7% (0.1 M), 89.7% (0.5 M) and 63.1% for the 1.5 M solution (Figures 2-4).

The higher rejection of Si^{4+} follows from the positive charge on the ceramic membrane surface, which electrostatically repels the cationic ion; the anionic Cl^{-} , by contrast, is drawn toward the membrane surface and passes through more readily, giving it a lower rejection. As concentration rises, concentration polarization weakens this effective surface charge and, with it, the repulsion driving Si^{4+} rejection. Above 3 bar TMP, size exclusion (steric hindrance) takes over as the dominant mechanism, since ions accumulating at the surface begin to block membrane pores and raise rejection for both species. Solution pH also fell as $SiCl_4$ concentration increased, and this decline tracked with lower ion rejection overall, so both concentration and pH moved together to suppress rejection of Si^{4+} and Cl^{-} at the higher feed strengths.

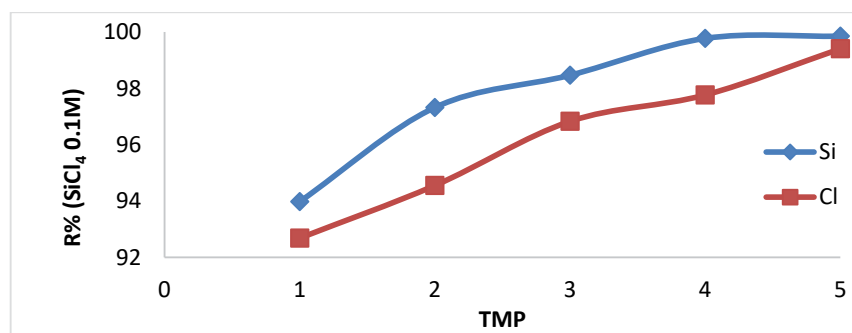


Figure 2: SiCl₄ Rejection (R%) Versus TMP (SiCl₄ Concentration 0.1 M).

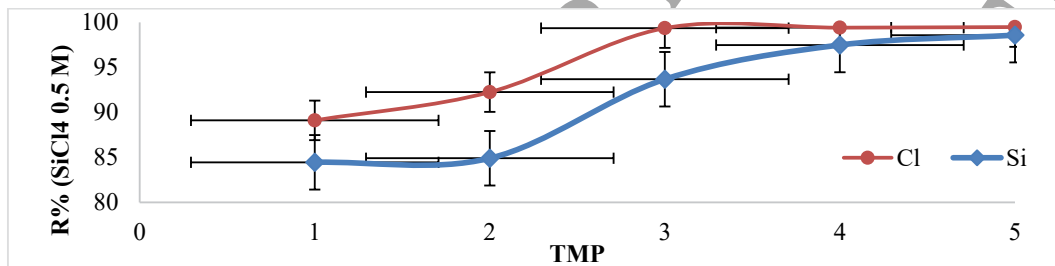


Figure 3: SiCl₄ Rejection (R%) Versus TMP (SiCl₄ Concentration 0.5 M).

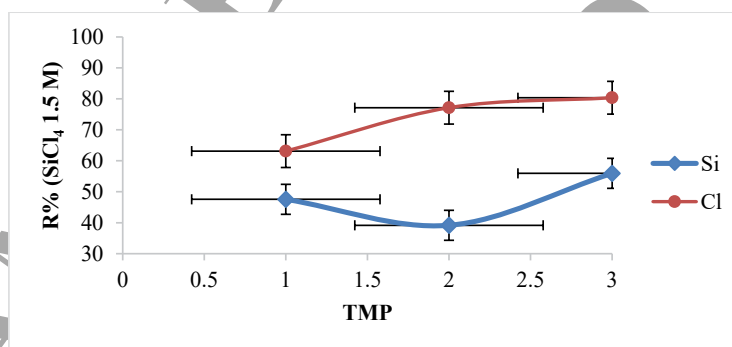


Figure 4: SiCl₄ Rejection (R%) Versus TMP (SiCl₄ Concentration 1.5 M).

3.2. JPMC Wastewater

With the real JPMC effluent, Cl⁻ rejection exceeded Si⁴⁺ rejection at every TMP tested. Rejection for both ions increased with TMP. At 1 bar, Si⁴⁺ rejection was 89.6% and Cl⁻ rejection was 99%. At 5

bar, Si⁴⁺ rejection reached 97.1% and Cl⁻ rejection reached 99.9% (Figure 5). The high rejection efficiency in the JPMC wastewater, which had a neutral to slightly basic pH (7-8), underscores the effectiveness of NF for real industrial applications.

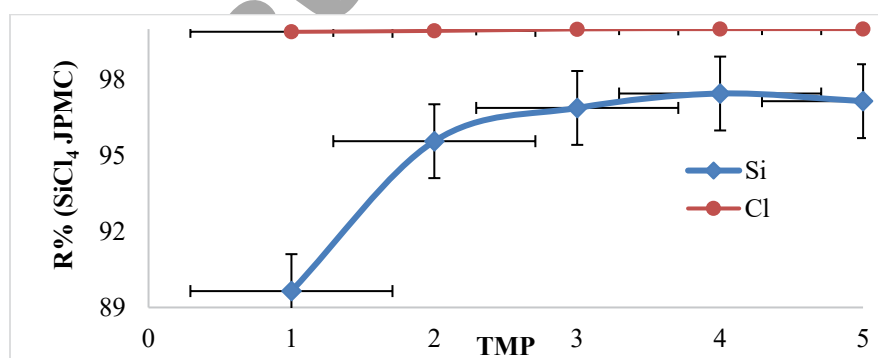


Figure 5: SiCl₄ Rejection (R%) Versus TMP (SiCl₄ Solution from JPMC).

TMP and ions concentration gradient were investigated. It was found that both parameters had an effect on the volumetric flux (J_v) and the ions rejection ($R\%$). The increase in pressure lead to an increase in the permeate flux. Also, the increase in the ions concentration led to decrease in the rejection rate, which in turn leads to improved silica removal efficiency. Nanofiltration membrane effectively separated silica and chlorine from the water due to their respective properties. Silica, being a large molecule, with a charge opposite to the membrane surface charge was separated from water. Chlorine ions rejection at lower concentration was less than the rejection of silica ions. Thus, as the ions concentration increased Si^{4+} rejection decreased and Cl^{-} rejection increased. This would be as a result of ions polarization on the membrane surface at higher ions concentration; were the membrane effective charge would be neutralized by Cl^{-} ions. Decrease in the repulsion force between the membrane surface effective charge and Si^{4+} ions; and as a result, decreasing Si^{4+} ions rejection. As the polarization layer thickness increases, then the layer would cause an extra resistance for the ions to pass through the membrane causing the rejection of Si^{4+} and Cl^{-} ions to increase. Such separating mechanisms made Nanofiltration membrane successful in removing Si^{4+} and Cl^{-} ions from water. The separation of Si^{4+} and Cl^{-} ions produces clean water that suitable is for industrial use.

Taken together, these results show that ceramic nanofiltration is an effective, practical option for JPMC's water-treatment problem. Rejection rates of up to 97.1% for Si^{4+} and 99.9% for Cl^{-} under optimal conditions represent a clear improvement over JPMC's existing treatment train, which by the company's own account struggles to remove silica adequately.

One of the more informative results here is the reversal in rejection behavior between the synthetic solutions and the real effluent. In the synthetic SiCl_4 solutions, Si^{4+} 's higher rejection relative to Cl^{-} fits the Donnan exclusion picture: the positively charged ceramic surface repels the similarly charged cation. Change the feedwater, though, and the pattern reverses too, in the real JPMC wastewater, Cl^{-} rejection came out higher, which points to the effluent's complex matrix altering the membrane's surface charge and, with it, the dominant separation mechanism. Co-existing ions,

natural organic matter, and pH most likely shift the membrane's zeta potential enough to move the controlling mechanism from electrostatic repulsion toward steric hindrance (size exclusion), consistent with So et al.'s (2023) findings on how strongly feedwater composition governs NF performance.

Membrane science has a well-established explanation for the inverse relationship between ion concentration and rejection: concentration polarization. As ions build up near the membrane surface, they weaken the effective driving force and can shield charged ions from the membrane's electrostatic field, lowering rejection. A parallel drop in pH, driven by SiCl_4 hydrolysis, reinforces this, lower pH tends to protonate the membrane's surface groups, reducing its positive charge and, with it, its ability to repel Si^{4+} , a pattern Kuan and Hu (2009) also reported in their coagulation work [12].

3.3. Membrane Fouling and Cleaning

Fouling developed faster at higher SiCl_4 concentrations and lower TMP values. The distilled water flux tests conducted before and after the SiCl_4 experiments confirmed that fouling was not permanent. The volumetric flux for distilled water was consistently higher than for SiCl_4 solutions and increased linearly with TMP. After chemical cleaning with NaOH, the membrane's water flux recovered to its initial values, indicating that the cleaning protocol successfully restored membrane performance (Figure 6).

Distilled water was used before cleaning the membrane in order to check if fouling occurred during running SiCl_4 solution experiment. While running the experiments it was noticed that as the concentration of SiCl_4 solution increased, fouling starts to form fast at lower TMP values. Distilled water was used to observe if complete fouling occurred. Before and after SiCl_4 solution experiments, an experiment using distilled water was run. Thus, it was found that the volumetric flux for distilled water increased as the TMP increased. In addition, distilled water volumetric flux was higher than the volumetric flux of SiCl_4 solution. It can be concluded that; complete fouling did not occur and the membrane returned to its original condition after cleaning the membrane. See figure 6.

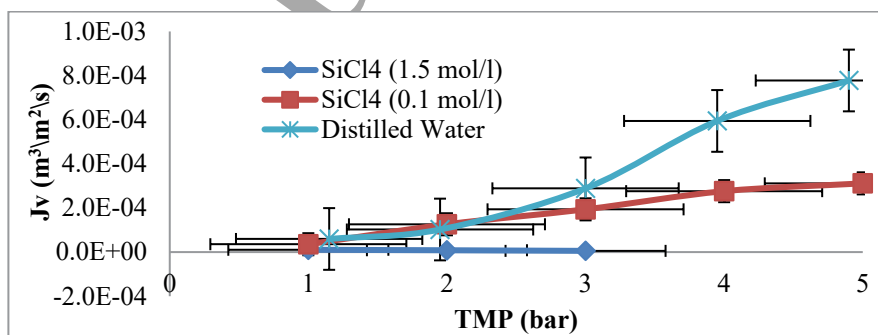


Figure 6: Volumetric Flux Versus TMP.

Fouling is one of the central concerns for any industrial membrane system. On that front, the results here are encouraging: the silica-related fouling observed was largely reversible through a standard NaOH cleaning cycle. Distilled-water flux returned to its original values after cleaning, which suggests the fouling was superficial rather than the kind that permanently plugs or degrades the membrane, a distinction that matters economically as well as technically. It implies periodic cleaning cycles, not membrane replacement, are enough to sustain performance, removing one of the larger cost barriers to running this system at scale (Wang, 2018) [2].

Volumetric flux (J_v) rose with TMP across every feed solution, exactly as expected when higher pressure pushes more permeate through the membrane, visible in Figure 6 as an upward curve in every case. Distilled water showed the clearest gain, climbing from $1.0\text{E-}04 \text{ m}^3/\text{m}^2.\text{s}$ at 1 bar to $8.0\text{E-}04 \text{ m}^3/\text{m}^2.\text{s}$ at 5 bar, close to linear growth. The 1.5 mol/l SiCl_4 solution lagged well behind, reaching only $4.0\text{E-}04 \text{ m}^3/\text{m}^2.\text{s}$ at 5 bar, about half the distilled-water value at the same pressure [10].

Higher SiCl_4 concentrations reduced flux at every TMP tested, and 1.5 mol/l consistently underperformed 0.1 mol/l : the added resistance from ion accumulation and fouling simply outweighs the pressure-driven gain. Concentration affected the two ions differently, too. As SiCl_4 concentration rose, Si^{4+} rejection fell while Cl^- rejection rose, two trends moving in opposite directions even as overall flux declined [11].

The overall ranking, distilled water flux above 0.1 mol/l SiCl_4 , which in turn stayed above 1.5 mol/l SiCl_4 , confirms that dissolved ions add resistance through concentration-polarization layers, and that this effect is strong enough at low TMP and high concentration to flatten the flux curve early on. At 5 bar, flux measured $8.0\text{E-}04 \text{ m}^3/\text{m}^2.\text{s}$ for distilled water, $5.0\text{E-}04 \text{ m}^3/\text{m}^2.\text{s}$ for the 0.1 mol/l solution, and $4.0\text{E-}04 \text{ m}^3/\text{m}^2.\text{s}$ for the 1.5 mol/l solution, roughly 50% lower than distilled water at the same pressure. Cleaning with NaOH brought flux back to distilled-water levels afterward, and pre- and post-experiment distilled-water runs showed the same linear increase with TMP, together confirming that the fouling was reversible rather than permanent pore blockage [13].

As SiCl_4 concentration rises, hydrolysis lowers solution pH, and that tracks with reduced Si^{4+} and Cl^- rejection, consistent with the suppressed flux seen at higher concentrations. The synthetic solutions favored Si^{4+} rejection over Cl^- , electrostatic repulsion dominating, but the real JPMC wastewater reversed that ordering, most likely because co-existing ions and organic matter in the actual effluent change the governing separation mechanism. Broadly, this flux behavior is consistent with a pressure-driven model based on Darcy's law [14].

$$J_v = \frac{TMP}{\eta(R_m + R_{cp} + R_f)} \quad (3)$$

Here η is viscosity, R_m is membrane resistance, R_{cp} is concentration polarization resistance, and R_f is fouling resistance. As TMP increases, then TMP drives J_v to increase. As the R_{cp} and R_f increases due to dissolved ions are deposited on the membrane surface, then this causes the SiCl_4 curves to be below the distilled-water curve. At low concentration, the positively charged ceramic membrane repels cationic Si^{4+} effectively, hence Si^{4+} rejection reaching up to 97.1% under these conditions. Push the concentration higher, though, and concentration polarization neutralizes part of that surface charge with Cl^- , weakening Si^{4+} repulsion even as the thicker polarization layer raises overall rejection. In the JPMC wastewater specifically, steric hindrance (size exclusion) takes over as the dominant mechanism, consistent with Cl^- rejection reaching as high as 99.9%.

That the flux was restored after NaOH cleaning confirms the silica-related fouling was superficial and reversible, consistent with prior work on ceramic membrane cleaning [15]. The mechanism traces back to pH: SiCl_4 hydrolysis lowers it, which protonates the membrane surface, weakens charge-based rejection, and helps explain the concentration-dependent trends described above.

Conclusion

This study demonstrates that nanofiltration is a highly effective technology for removing silica and chloride from the wastewater streams of the Jordan Phosphate Mines Company. Silica removal and water distillation in Jordan Phosphate Mines Company is critical to ensure the quality of water used in mining and processing activities. The company's water may benefit from water treatment using Nanofiltration membranes. Nanofiltration membrane effectively removes silica from the water sources that is used by JPMC. Under optimal conditions, rejection rates of 97.1% for Si^{4+} and 99.9% for Cl^- were achieved using a pilot-scale ceramic NF system.

The performance of the NF membrane was significantly influenced by transmembrane pressure, ion concentration, and feed solution pH. While fouling was observed, particularly at high contaminant concentrations, it was found to be reversible with a standard NaOH cleaning procedure, allowing the membrane to regain its original permeability.

The removal of silica and chloride ions from the JPMC water was assessed using a pilot-scale Nanofiltration membrane system (Broughton 2020) [16]. The separation efficiency was optimized by using a tubular ceramic Nanofiltration membrane module at varying feed flow rates and TMP [17]. The study's findings demonstrated how successful Nanofiltration was at removing silica and chloride ions (Wang 2018). Ceramic NF is highly effective for removing Si^{4+} and Cl^- , enabling water reuse, reducing scaling/corrosion in equipment, and minimizing environmental discharge. This could save costs (e.g., less maintenance) and support sustainability goals. Optimal conditions; 5 bar TMP with real wastewater yields top rejection rates, but high concentrations require frequent cleaning to maintain flux.

The quantities of silica and chloride ions in the water obtained from the Jordan Phosphate Mines Company were lowered using Nanofiltration; the percentage of silica ions rejected was 97%, while the percentage of chloride ions rejected was 99% [6]. Where the company faces problems regarding the removal of silica ions from the discharged water. Similar work was done by Yeon So et. al. where it was concluded that the composition and the concentration of the solution would affect the rejection of Silica ions [9]. Also, it was noticed as the concentration of silicon tetrachloride (SiCl_4) solution increased then the solution pH decreased and the rejection of Si^{4+} and Cl^- ions decreased. Which is supported by Wen-Hui Kuan and Ching-Yao Hu, in their work they used coagulants to separate silica which concluded that the concentration of silica and the pH of solution had an effect on the separation of silica ion from water.

It was observed that fouling formed very fast at low TMP values and high concentration of SiCl_4 solution, thus cleaning the membrane was needed. It was noticed that the membrane retained to its original condition after the cleaning stage. The importance of cleaning the membrane is supported by Bin Lin et. al. [15]. Where in their work they used ceramic membrane and performed a cleaning stage and a coating stage.

Distilled water was used to observe if complete fouling occurred. Before and after SiCl_4 solution experiments, an experiment using distilled water was run. Thus, it was found that the volumetric flux for distilled water increased as the TMP increased [8]. In addition, distilled water volumetric flux was higher than the volumetric flux of SiCl_4 solution. It can be concluded that; complete fouling did not occur and the membrane returned to its original condition after cleaning the membrane.

In summary, it was demonstrated that the use of Nanofiltration membranes offers a viable means of eliminating silica and chloride ions from water, allowing for its subsequent reuse in industrial settings. If this research is carried out successfully, it may ensure a sustainable water supply, which will benefit the local community and the businesses in the long run [17]. A mining company might use the study's findings to enhance their water treatment procedures and lower the expenses related to water treatment performance.

Applying nanofiltration membranes can guarantee regulatory compliance while offering substantial environmental benefits. It directly addresses the elevated pollutant levels, silica in particular, that make JPMC's wastewater difficult to manage (So, et al. 2023), and the approach isn't limited to phosphate mining: other silica-affected sectors, geothermal energy and desalination among them, face the same issue. A cleaner effluent for reuse is the payoff, supporting circular water management, cutting pollution reaching local water bodies, and helping operators stay within regulatory limits.

Earlier work by He et al. (2019) and Kuan and Hu (2009) noted the same influence of solution chemistry on silica rejection seen here. Overall, the results support nanofiltration as a viable, sustainable

treatment option for JPMC, one that reduces scaling, fouling, environmental pollution, and freshwater demand, while helping the operation manage its water more efficiently, stay within regulatory limits, and remain economically sustainable over the long term.

Put simply, this work moves nanofiltration from a laboratory-scale possibility toward a demonstrated industrial option, and a ceramic NF system at JPMC could reshape the site's wastewater management in three ways:

1. Producing an effluent with far lower scaling and corrosive-ion content (Si and Cl), suitable for recycling back into mining or processing operations and reducing freshwater demand.
2. Cutting the volume of untreated, pollutant-laden wastewater reaching local water bodies, which supports regulatory compliance and protects the surrounding ecosystem.
3. Reducing scaling and fouling in downstream equipment, lowering both maintenance frequency and energy costs, an outcome the membrane's demonstrated cleanability over repeated cycles makes realistic.

A long-term pilot study at the JPMC site itself is the logical next step, one that would confirm these findings under continuous, real-world operating conditions and add the economic and lifecycle analysis this scale of decision requires. It would also be worth testing whether integrated pre-treatment steps can cut fouling further and improve the system's overall cost-effectiveness.

Stepping back, these results suggest nanofiltration is not just another option among existing treatment technologies for the phosphate mining sector, but a technology capable of anchoring a genuinely more sustainable, circular approach to water management, one that could extend to other water-intensive industries facing similar silica and chloride challenges [18-33].

5. Nomenclature

R is the ion rejection.

R_m is membrane resistance.

R_{cp} is concentration polarization resistance.

R_f is fouling resistance.

C_p is the permeate ion concentration (M).

C_f is the feed ion concentration (M).

TMP is transmembrane pressure (bar).

NF is nanofiltration membrane.

JPMC is Jordan phosphate mines company.

η is viscosity.

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