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Innovative Adsorbent Materials for Efficient Silicon Extraction from Industrial Waters: A review

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ABSTRACT
Silica fouling reduces the effectiveness and durability of membrane-based treatment systems, and silicon contamination in industrial water streams poses ongoing operational issues. With an emphasis on their processes, drawbacks, and applicability for various silica species, this article provides a comparative examination of the main silica removal technologies: ion exchange, reverse osmosis (RO), ultrafiltration (UF), electrocoagulation (EC), adsorption, and lime softening. Although they need a significant amount of chemical input and pH control, lime softening and ion exchange are efficient for dissolved silica. RO requires thorough preparation and offers broad-spectrum separation, although it is susceptible to silica scaling. While UF works well with colloidal and particulate silica, it is unsuccessful with monomeric forms. EC achieves excellent removal rates with less sludge by combining electrochemical destabilisation and crystallisation. Adsorption provides variable selectivity, low energy consumption, and compatibility with membrane systems, especially when employing tailored materials like activated alumina, iron oxide-coated media, and functionalised hybrids. In addition to outlining important techno-economic considerations for scaling up silica extraction methods in intricate industrial water matrices, the paper highlights new developments in adsorbent design, such as surface modification, hierarchical porosity, and regeneration techniques.

Keywords: silica, industrial, wastewater, treatment, adsorption.

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Introduction

In industrial water systems, silicon is predominantly found as silica (SiO_2), which exists in granular, colloidal, and ionic forms. In industrial applications, silicon is predominantly present as reactive silica (monomeric and soluble), colloidal silica (non-ionic and suspended), and particulate silica (such as sand or silt). Silica removal is the main goal of extraction procedures to reduce the

possibility of scaling and equipment deterioration. The specific form of silica is determined by variables such as pH, temperature, and the characteristics of the water source. The most effective removal techniques include lime softening, ion exchange, reverse osmosis, and advanced ceramic media filtration [1]. Silicon-containing wastewater is primarily produced during steam throughput or steam drive extraction used for thick oil development. Injected steam causes hydrolysis of underground silicon rocks, forming silicates and resulting in significant amounts of silicon-laden wastewater [[1], [2]]. Large-scale pipeline clogs can arise from silicate scale buildup in oilfield wastewater collection systems. Compared to other water sources, well water includes more silica, which can damage equipment, particularly in deep wells where temperatures are greater. High silica levels also hinder well-water treatment methods, so concentrations must be lowered to protect equipment and membranes. There are many methods used to reoval silicon from industrial wastes. Among these, the most widely employed techniques include adsorption, electroddialysis, reverse osmosis, chemical precipitation, ion exchange, solvent extraction/liquid membrane separation and electrolysis [[3], [4], [5]]. Adsorption has become a critical process across numerous industrial applications, including natural gas storage, pollution control, catalyst support, and particularly in gas separation and purification, owing to its low energy requirements, operational flexibility, and the wide variety of available adsorbents [[6], [7], [8], [9], [10]]. Additionally, adsorption processes are widely recognized as a standard technique for determining the surface area and pore size distribution of solid materials. This process is characterised by its non-toxicity, cost-effectiveness, environmental sustainability, and renewability. As a result, it is seen as a practical substitute for conventional treatment procedures and an efficient way to remove heavy metals from wastewater. The process of adsorption can be accomplished via chemisorption, which involves the creation of a chemical connection between the sorbate molecule and the adsorbent surface, or physical adsorption, which is controlled by weak intermolecular interactions. Due to the remaining valence forces from surface molecules, chemical adsorption results in the formation of a monomolecular layer of adsorbate on the surface. On the other hand, physical adsorption results from molecule condensation inside the solid's capillaries [[11], [12]]. Consequently, a thorough understanding of adsorption mechanisms is essential not only for the design and optimization of industrial adsorption processes but also for accurately characterizing the structure of porous solids. Several methods have been documented for the treatment of industrial effluents. Ion exchange involves swapping ions between electrolytes, or between an electrolyte solution and a complex. Its primary purpose is to employ solid materials such as minerals, clays, membranes, and resins to purify, separate, and disinfect ion-containing fluids. This mechanism may facilitate adsorption and takes place at the solid's surface. However, ion exchange is costly in terms of capital and operating expenses [13]. A common technique for recovering materials or purifying solutions is chemical precipitation, which turns dissolved compounds into solid particles. There are several methods for improving chemical precipitation. Sodium decanoate, carbamates, carbonates, sulphides, and polymers are examples of reagents that generate insoluble metal compounds as alternatives to hydroxide precipitation. Large volumes of sludge and silt containing heavy metals are produced by flocculation and coagulation, and this method is typically ineffective in eliminating trace pollutants [14]. Desalination, water purification, and chemical recovery are three applications where electrodialysis, a membrane-based separation technique that uses an electric potential to selectively remove ions from solutions, is very beneficial. Electric fields are used in electrodialysis, a non-thermal separation technique, to move ions across ion-exchange membranes. Positively charged ions (cations) can pass through cation-exchange membranes, while negatively charged ions (anions) can pass through anion-exchange membranes. These membranes are systematically arranged in alternating order between two electrodes within a configuration known as an electrodialysis stack [[15], [16], [17]]. Research indicates that the potential of an electrodialysis cell is largely independent of ion type, instead depending on operational conditions and cell configuration. Despite various drawbacks, electrodialysis has significant advantages for treating heavy metal-containing wastewater, including the ability to efficiently remove unwanted particles from water and produce highly concentrated streams for recovery [18]. But because this technique produces hazardous waste, cooperation with businesses that can recover and recycle metals from the resultant sludge is required. While, reverse osmosis is a

pressure-driven membrane process designed to remove dissolved salts, contaminants, and microorganisms from water by passing it through a semi-permeable membrane that permits the passage of water molecules while restricting larger solutes such as salts, organic compounds, and microbes [[19], [20], [21]]. This technology is extensively employed for desalination, water purification, and industrial fluid separation. In reverse osmosis, the natural osmotic flow is counteracted by applying pressure exceeding the osmotic pressure, thereby enabling the selective removal of impurities. But solvent extraction transfers a solute from one liquid phase (typically aqueous) to another immiscible phase (usually organic) based on solubility differences. Because of operational and financial concerns, it is rarely utilised in wastewater treatment, even though it enables the recovery of important species. Because a liquid membrane permits targeted solute movement between two aqueous phases, combining solvent extraction and membrane separation with a membrane can increase selectivity [[18], [19], [20]]. The electrolysis process is a significant electrochemical technique that utilises electrical energy to drive non-spontaneous chemical reactions, commonly for the decomposition of compounds or extraction of elements. It plays an essential role in fields such as metallurgy, water splitting, and electroplating. Electrolysis operates by passing a direct electric current through an electrolyte a medium containing free ions which induces chemical changes at the electrodes and facilitates the extraction of heavy metals [[22], [23], [24], [25]].

Common methods for removal silica from industrial waste. Lime Softening

By introducing lime (calcium hydroxide), which increases the pH and causes magnesium to precipitate as magnesium hydroxide, the lime softening method eliminates silica from water. During water softening, silica may be removed via precipitation with calcium carbonate or by adsorbing onto solids [26] . This precipitate adsorbs dissolved silica, and both are then removed via sedimentation and filtration. The effects of MgO slaking on silica removal and the mechanisms by which MgO removes silica were investigated [26]. At different pH levels (8.0–11.3), doses (100–1000 ppm), and contact periods (15–120 min), experiments were conducted to assess the silica removal efficiency of slaked and nonslaked MgO under warm lime sodtening operating temperatures (65–85 °C). There are two competing methods for removing silica: adsorption onto process-formed $Mg(OH)_2$ or precipitation as magnesium silicate complexes. Slaked MgO showed a lower percentage of silica removal under WLS conditions than nonslaked MgO, which was explained by higher silica adsorption on $Mg(OH)_2$ after slaking. According to research, the amount of magnesium in the water affects how well silica is removed by precipitation processes [27]. Furthermore, silica solubility can be impacted by temperature, pH level, salt concentration, silica concentration, and pressure [28]. The hot lime process has been shown to effectively remove both water hardness and silica. Additionally, studies indicate that lime softening can reduce silica content even when performed at ambient temperatures. Three chemical treatments lime-soda softening, sodium aluminate addition, and magnesium oxide for reducing silica in water purification systems were examined. Jar-tester experiments measured the effect of varying doses on silica concentrations. Magnesium oxide was the most cost-effective option for treating 30,000 cubic meters of water, possibly saving around US$1.8 - 2.1 million annually [29].

Ion exchange

By applying an anion exchange resin, which makes it easier for silica ions to be replaced with hydroxide ions and is regenerated using caustic agents like sodium hydroxide, ion exchange efficiently eliminates dissolved ionic silica from wastewater. Although this technique is quite effective at removing reactive silica, it needs to be treated first to transform the silica into its ionic form since ion exchange cannot deal with colloidal or particulate silicon. However, silica solubility is influenced by a range of factors, including temperature, pressure, pH, and ionic strength. For pH values below 9, solubility remains relatively constant; however, at higher pH levels, solubility increases as silicate ions form in addition to the monomer, which is in equilibrium with the solid phase. Salts lower silica solubility by increasing ionic strength [30]. Silica removal from hydrated lime was tested using ion exchange and UV spectrophotometry. By combining 10 mL of 2 M NaOH with 15 mL of 0.1 M HCl, the ideal technique reduced silica to 0.0054%. Sodium hydroxide reduces silica concentration and can limit silica accumulation on tube surfaces during water treatment [31]. The ideal conditions for silicon

removal from simulated wastewater were determined to be pH 6, a reaction time of 20 minutes, a current density of 27 mA/cm², and a temperature of 35 °C, based on single-factor and orthogonal experiments. Under the conditions of pH 8.0, reaction time of 20 minutes, current density of 27.2 mA/cm², and a temperature of 35 °C, the silicon concentration in Hongshan Oilfield wastewater decreased from 76.22 mg/L to 10.75 mg/L, achieving a silicon removal rate of 85.90% with an electrode mass loss of 0.0209 g. Calcium and magnesium ions greatly improve silica removal at pH 8. These findings inform industrial use of electrocoagulation to remove silicon from oilfield wastewater [1]. The removal of silica from water using the electro-Fenton (EF) advanced oxidation process was systematically evaluated. Experimental investigations varied several parameters, including pH, current density, reaction duration, monopolar versus bipolar system configurations, and inter-electrode distance. Results demonstrated that up to 95% silica removal was achieved after 40 minutes of operation at near-neutral pH utilizing a bipolar electrode arrangement. The extent of desilication increased proportionally with higher applied current densities. Optimal silica removal consistently occurred at near-neutral pH values [32]. The separate pretreatment of removing silica was explored using several methods. Testing was done on precipitation using $Fe(OH)_3$, $Al(OH)_3$, silica gel, and a strongly basic anion (SBA) exchange resin. While some aluminium remained and aluminosilicate colloids were not eliminated, $Al(OH)_3$ was the most successful, removing nearly all the dissolved silica. With a silica removal rate of up to 94%, the SBA resin also demonstrated good performance [33].

Reverse osmosis for silica removal

A semipermeable membrane is used in the popular water purification process known as reverse osmosis (RO) to eliminate impurities. Nevertheless, silica cannot be successfully removed by RO alone; pretreatment and scale control are required to avoid silica fouling. The many types of silica dissolved, colloidal, and particulate present difficulties for RO membranes. Although some particle silica is eliminated by RO, dissolved reactive silica frequently gets through and may subsequently result in chronic scaling. Pretreatment strategies for silica removal from reverse osmosis (RO) feed water encompass softening and coagulation, seed precipitation and aggregation, tight ultrafiltration, ion exchange, adsorptive media, and electrocoagulation. To mitigate RO membrane fouling under silica-rich conditions, common approaches include antiscalant dosing, pH optimization, and intermediate concentrate softening [[33], [30]]. Examined were the behaviour of silica scaling and its elimination in RO membrane processes, paying special emphasis to the gallic acid (GA)-based cleaning mechanism. Even at the lowest starting concentrations of silicic acid, silica scale accumulation caused a steady drop in membrane flow over time. Nonetheless, GA was quite successful in cleaning silica-fouled RO membranes; in the first half hour, it removed 81.87% of the silica scale, recovering 89.7% of the initial flow. GA's ability to clean is ascribed to its ability to adsorb onto silica scale particles, creating a surface complex that changes into a 1:3 complex that dissolves in water. Silica deposits on the membrane surface are gradually broken down by this contact.

These results enhance knowledge of the relationships between GA and silica scaling and provide important information for creating effective silica scale cleaning methods [34]. As feed water concentration rises, increasing osmotic pressure limits water recovery in reverse osmosis. However, this restriction has no effect on membrane distillation (MD), a thermally driven membrane desalination method. This study examined pH adjustment to reduce silica scaling in the MD process. When feed water pH was below 5 or above 10, negligible scaling occurred at silica concentrations up to 600 mg/L, whereas scaling peaked at neutral pH (6–8). The study also evaluated cleaning techniques; performance was momentarily restored by dissolving some silica scale with NaOH solutions that had a pH higher than 11. Re-exposed to supersaturated silica, however, caused quicker scaling than with fresh membranes because residual silica remained on membrane surfaces [35]. The electromagnetic field (EMF) influenced the performance of the RO system by reducing membrane scaling, altering the characteristics of the formed scales, and lowering the rate at which normalized water permeability declined. EMF treatment demonstrated efficacy in removing pre-existing scales and precipitates from water pipelines and storage tanks. It was only partially successful in getting rid of existing scaling on RO membranes, though. According to membrane autopsy, the scales that developed on the membrane surface when exposed to an electromagnetic field (EMF) had a

soft, powdery texture that made it easy to remove them with a simple water rinse. After examining the many ways that EMF impacted the RO membrane, the magnetohydrodynamic effect was shown to be the main one. This study presents EMF as a chemical-free method for controlling membrane scaling and maintaining RO performance during brackish groundwater desalination, providing detailed discussion on mechanisms and future perspectives [36].

Ultrafiltration (UF)

Ultrafiltration (UF) is a membrane-based separation technology extensively utilised in industrial water treatment processes, particularly for silica removal. This technique uses semi-permeable membranes that function at low to moderate pressures (1–10 bar) and have pore diameters that are normally between 0.01 and 0.1 microns. UF may be used to remove particulate and colloidal silica, but it cannot extract dissolved (reactive) silica because it efficiently separates suspended solids, colloidal particles, and high-molecular-weight solutes from water. Several factors influence the efficacy of ultrafiltration, including pH which affects silica speciation and membrane charge; temperature which impacts viscosity and flux; transmembrane pressure where higher levels increase flux but may also promote fouling; and crossflow velocity which plays a crucial role in reducing concentration polarization and fouling [[37], [38]]. Feed solution pH significantly affects electrodialysis with ultrafiltration (EDUF) using polyethersulfone (PES) membranes by altering membrane selectivity through electrostatic interactions with peptides. These effects can cause high molecular weight peptides to accumulate softly. EDUF at pH 9 efficiently isolates cationic peptides (<400 Da) in KCl and restricts anionic peptide variety in KCl 1. A two-step UF–EDUF method using UF permeate as feed is being tested to better understand the influence of high molecular weight peptides [39]. The role of solution chemistry in PES ultrafiltration membrane fouling by silica nanoparticles and natural organic matter was assessed under controlled pH, ionic strength, and calcium conditions. The Lifshitz–van der Waals, electrostatic, and acid–base interactions were measured using the Extended Derjaguin–Landau–Verwey–Overbeek (xDLVO) theory. The main force behind adhesion and cohesion was found to be acid–base attraction, and fouling rose with decreasing pH, increasing ionic strength, and increasing calcium. In complicated colloidal systems, the inverse relationship between estimated interaction energy and fouling potential highlights the usefulness of xDLVO theory in forecasting membrane behaviour [[40], [41]]. To investigate how adding and then removing silica (SiO_2) nanoparticles affected the membrane's shape, hydrophilicity, and separation performance, an ultrafiltration membrane based on polysulfone (PSf) was designed. Three types of membranes were prepared pristine PSf, PSf/SiO_2 composite, and acid-washed PSf/$WSiO_2$ and characterized systematically. Pure water flux tests showed that the PSf/$WSiO_2$ membrane had higher permeability compared to the other samples, while the PSf/SiO_2 membrane had lower fouling during bovine serum albumin filtration. These findings indicate that introducing and subsequently removing sacrificial fillers can influence transport properties and performance in PSf-based ultrafiltration membranes [42]. Silica was eliminated using a semi-batch adsorption method that included hollow fibre ultrafiltration membranes and iron oxy/hydroxide agglomerates (IOAs). Adsorbent dose, residence period, and silica content were the main factors investigated. Maximum adsorption occurred within 15 minutes, matching batch results. Higher silica concentrations increased, while greater adsorbent dosages decreased, adsorption capacity. The ultrafiltration membrane separated loaded adsorbent without significant fouling before breakthrough. A simple model accurately predicted breakthrough curves [43].

Electrocoagulation for Silica Removal

Electrocoagulation (EC) uses a direct electric current to dissolve metal electrodes usually aluminum or iron which release ions that bind with and remove silica from water. This chemical-free procedure minimises sludge and eliminates the need for additional chemicals by forming solid floc that is easy to remove, making it an effective substitute for conventional industrial and geothermal water treatment techniques [[44], [45]]. An electrochemical reaction serves as the foundation for the electrocoagulation (EC) process. The anode, such as aluminium, oxidises and dissolves when a direct current is supplied, releasing metal ions into the water. Water reduction results in the production of hydroxide ions at the cathode, which causes hydroxide creation. The metal ions released from the anode subsequently react with these hydroxide ions to form metal hydroxides, such as aluminum hydroxide. These metal hydroxides function as coagulants, aggregating with dissolved silica to produce stable hydroxy-aluminosilicate polymers

and other flocs. Because of their size, these flocs can be eliminated by filtering or sedimentation procedures [[44], [45], [46]]. The following elements affect the EC process: iron is good for both silica and sulphide, whilst aluminium is good for silica; Results are influenced by electrical factors, including voltage, time, and current density; Flow rate reducing power consumption and increasing efficiency by optimising flow rate and electrode spacing; and Conductivity and pH in water chemistry affect treatment efficacy and cost. [47], [44], [48], and [49]. Electrocoagulation is an effective and energy-efficient approach for removing silica and hardness from oil-sands produced water. Key operating parameters including charge loading, current density, flow rate, and polarity reversal period significantly influence removal efficiency and system performance. Over 80% silica removal was made possible under ideal circumstances (8 mA cm^{-2} current density and 1000–1500 C L^{-1} charge loading), with aluminium electrodes surpassing iron in terms of pollutant reduction and operating costs. Extended polarity reversal intervals further enhanced removal efficiency while reducing energy consumption and cell voltage. These findings highlight the potential of EC, particularly Al-based systems, as a scalable and cost-effective solution for silica-rich industrial wastewater treatment [48]. Meanwhile, the aluminium electrode is frequently used in electrocoagulation (EC) to remediate wastewater that contains SiO_2. The effectiveness of SiO2 removal using iron was increased by methodically optimising the current density, plate spacing, plate-to-water ratio, and electrode passivation control. A multiphysical field linked simulation model was also used to examine the temperature field, velocity, concentration, and electricity distributions inside the silica removal system. An optimal silica removal rate of 97.4% was achieved with a theoretical iron consumption of 0.251 g Fe/L, an adsorption capacity of 660 mg SiO2/(g Fe L), and electricity usage of 0.312 Wh/L. Simulation results demonstrated that EC promotes mass and heat transfer within the cell, and anodes featuring square holes are more effective in enhancing the iron corrosion rate [49]. Fouling and scaling from silica are major challenges in membrane desalination. Studies of pretreatment and SDI tests found silicate salts stay insoluble in brackish and seawater, and fouling does not relate to silica levels between 15–200 mg/L. Electrocoagulation using Al^{3+} is more effective than Fe^{3+}, reaching 90.2% silica removal efficiency for brackish water containing roughly 28 mg/L silica [50]. The use of hybrid coagulants composed of polyaluminum nitrate sulfate (PANS) and three polyamines (PAs) with different molecular weights for silica removal was investigated. For each polymer, four hybrids with varying PANS-to-polyamine ratios (5–20%) were examined at five doses (500–2,500 mg/L) and two beginning pHs (8.4 and 10.5). In terms of silica removal, all hybrids performed better than PANS at pH 8.4; they needed lower doses (500 vs. 2,500 mg/L) and were best at 5% polyamine (over 50% vs. PANS's 30%). At pH 10.5, all products removed up to 90% of the material with no variation in efficiency. Generally speaking, hybrids eliminated more COD than PANS, particularly at higher pH values. While PA molecular weight did not affect silica removal, higher weights improved COD removal. Mechanism analysis indicated that PANS promoted sweep flocculation, whereas hybrids combined sweep flocculation with patch formation [51]. The influence water quality affects dissolved silica removal using electrocoagulation with aluminum electrodes was studied. Experiments were performed on replacement water (RW) and cooling tower blowdown water (CTBW), both assessed at a small pilot scale with a continuous flow system including electrocoagulation, flocculation, sedimentation, and sand filtration. Key variables evaluated included silica removal efficiency, aluminum usage, head loss, and voltage. Treatment costs for all water types were considered. The Al^{3+}/silica removal ratio ranged from 1.09 to 1.33 for RW and was 0.85 for CTBW [52].

Adsorption for removal silica

An effective method for removing silica from water is adsorption, which makes use of substances like silica-based adsorbents, activated alumina, and iron-based compounds. Activated alumina's remarkable selectivity and regeneration capabilities make it particularly beneficial. Additionally, composite materials, including magnetic iron–aluminum hydroxide nanoparticles, provide the benefit of magnetic separation, facilitating straightforward recovery processes [[53], [54], [55], [56]]. Absorbent materials include activated alumina, which is a commonly used and well-researched adsorbent, particularly for complex industrial wastewaters, due to its selectivity for silica and capacity for regeneration. Although they are also used, iron-based absorbents such iron (III) hydroxide and similar substances have the potential to create deposits that make regeneration procedures more difficult. To improve stability and

adsorption performance, a variety of silica-based materials are used, such as mesoporous silica and silica aerogels, occasionally with additional metal oxides. To make separation and reuse easier, composite materials like magnetic iron-aluminum hydroxide nanoparticles combine silica adsorption capabilities with magnetic qualities [[57], [58], [59], [60], [61]]. Surface contacts, pH, and the chemical affinity of silica species for the adsorbent are all factors that affect adsorption. Strong pH dependence characterises the adsorption process; for example, adsorption onto activated alumina is pH-dependent, whereas iron-based adsorbents work best at pH 9. As shown with gallic acid-modified resins, chemisorption—the formation of chemical bonds between silica and the adsorbent occurs sometimes [[53], [57], [62], [63]]. Adsorption and chemical precipitation were used to study the removal of reactive silica from synthetic solutions and industrial anodising waste streams. Seven precipitants and twelve commercial adsorbents were evaluated. Ferrolox (based on iron (III) hydroxide) was the most effective adsorbent, particularly at pH 9, producing 16.22 mg/g for synthetic solutions and 11.25 mg/g for wastewater. According to molecular modelling, Ferrolox and silica species formed a hydroxo-complex during the silica removal process. Magnesium chloride was removed up to 87% in precipitation, and the most important factor was found to be pH (variance value 81.42) [57]. The effectiveness of boehmite (γ-AlOOH) as an adsorbent for silica removal was assessed. Both chemical and physical adsorption processes were shown by kinetic analysis, and the pseudo-second-order model suggested the existence of chemisorption. At concentrations more than 50 mg/L, the silica adsorption isotherm complied with the Freundlich model, and mesoporous structures facilitated silica adsorption in tap water. According to this study, γ-AlOOH can be used as an adsorbent to alleviate silica-related issues in a variety of sectors [56]. At a SiO_2 concentration of 200 mg/L, with a dosage of 0.10 g/L, pH 10.5, and temperature of 303 K, integrated chemical precipitation using Fennofix type FF40 and evaporation achieved 96% silicon removal. This result is marginally higher than reported silicon removal rates for precipitation using CaO (93%) and electro-coagulation (95%) at initial SiO_2 concentrations of 954 mg/L and 250 mg/L, respectively. Both chemical precipitation and evaporation were able to treat thermo-mechanical pulping (TMP) whitewater of varying strengths, as the treated effluents complied with the regulatory silicon limit of less than 50 mg/L [63]. Magnesium oxide effectively removes soluble silica from water via adsorption, especially when combined with hot-process lime-soda softening, without increasing lime or soda ash usage. The process aligns with Langmuir and Freundlich isotherms and reduces the solids content of treated water, unlike chemical reagents such as ferric sulphate. While final traces of silica are hardest to eliminate, practical applications have shown reductions from 6.3 ppm to 0.6 ppm and from 56 ppm to 1 ppm in full-scale and natural water treatments, respectively [64]. Core-shell composite magnetic $Al(OH)_3@Fe_3O_4$ nanoparticles were created as adsorbents to extract silica from brackish water. Silica adsorption is made possible by the $Al(OH)_3$ shell, while magnetic separation is made simple by the Fe_3O_4 core.

At 2 g L^{-1}, these nanomaterials removed approximately 95% and 80% of silica from solutions with initial concentrations of 0.5 and 2 mM, respectively. After four cycles, regeneration with 0.05 M NaOH retained reusability and removal effectiveness of around 40%. The presence of silica polymerisation on the $Al(OH)_3$ shell during adsorption was verified by spectroscopic investigations. Utilising these nanoparticles in reverse osmosis showed decreased silica scaling and enhanced water recovery, suggesting that they might be used for effective brackish water treatment and inland desalination [[65], [66]]. Ferric hydroxide ($Fe(OH)_3$) and ferric chloride ($FeCl_3$) were investigated for the removal of silica from integrated circuit (IC) effluent. $Fe(OH)_3$ absorbed 94.6% of reactive silica in less than 60 minutes, whereas optimised $FeCl_3$ decreased turbidity by 97.2%. Adsorption was modelled using PHREEQC and suited the Langmuir isotherm, showing silica polymerisation on iron surfaces. Silica may be effectively removed from industrial effluent by using both $FeCl_3$ and $Fe(OH)_3$ [67].

Conclusions

Removing silica from industrial water is vital for preventing membrane fouling and maintaining efficiency. In addition to their advantages, traditional techniques including electrocoagulation, ion exchange, reverse osmosis, ultrafiltration, and

lime softening have disadvantaged such high chemical usage, high energy costs, and restricted compatibility. The selective removal of reactive and colloidal silica using adsorption, particularly with improved materials, requires less energy and produces less sludge. Research on enhanced adsorbents via regeneration, porous architectures, and surface modification is essential to creating scalable and cost-effective solutions. The development of efficient and sustainable water treatment systems for silicon management can be facilitated by incorporating these developments.

Conflicts of interest. Authors declare no conflict of interest.

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ТҮЙІНДЕМЕ

Кремнеземмен ластану мембраналық тазарту жүйелерінің тиімділігі мен ұзақ мерзімді беріктігін төмендетеді, ал өнеркәсіптік су ағындарында кремнийдің болуы тұрақты пайдалану кезінде елеулі қиындықтар тудырады. Бұл мақалада кремнийді кетірудің - ион алмасу, кері осмос (КО), ультрафильтрация (УФ), электрокоагуляция (ЭК), адсорбция және әкпен жұмсарту сияқты негізгі технологияларына олардың жұмыс істеу процестері, кемшіліктері мен әртүрлі кремнезем түрлеріне қолданылу ерекшеліктері тұрғысынан салыстырмалы талдау жүргізіледі. Олар айтарлықтай мөлшерде химиялық заттарды және pH бақылауын қажет етсе де, әкпен жұмсарту және ион алмасу әдістері еріген кремнеземді кетіруде тиімді. Кері осмос кең ауқымды бөлу қабілетіне ие болғанымен, алдын ала дайындықты қажет етеді және кремнезем тұнбасының түзілуіне бейім. Ультрафильтрация коллоидты және дисперсті кремнеземді тиімді жояды, дегенмен, ол мономерлі түрлерге қатысты тиімсіз. Электрокоагуляция электрохимиялық тұрақсыздандыру мен кристалдану процестерінің үйлесуі нәтижесінде аз көлемді шлам түзе отырып, жоғары жою тиімділігін қамтамасыз етеді. Адсорбция әдісі әсіресе белсендірілген глиноземді, темір оксиді негізіндегі қаптамаларды және функционалдандырылған гибридтер сияқты арнайы материалдарды пайдаланған жағдайда айнымалы селективтілікке, төмен энергия тұтынуға және мембраналық жүйелермен жақсы үйлесімділікке ие. Сонымен қатар, күрделі өнеркәсіптік су матрицаларынан кремнеземді кетіру әдістерін кеңейтудің негізгі техникалық және экономикалық аспектілерін талдаумен қатар, мақалада адсорбентті жобалаудағы соңғы жетістіктер, мысалы, беттік модификация, иерархиялық кеуектілік және регенерация әдістері талқыланады.

Түйін сөздер: кремний диоксиді, өнеркәсіптік, ағынды сулар, тазарту, адсорбция.

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Инновационные адсорбирующие материалы для эффективного извлечения кремния из промышленных вод: Обзор

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АННОТАЦИЯ

Загрязнение кремнеземом снижает эффективность и долговечность мембранных систем очистки, а присутствие кремния в промышленных водных потоках создаёт постоянные эксплуатационные проблемы. В данной статье проводится сравнительный анализ основных технологий удаления кремнезема - ионного обмена, обратного осмоса (ОО), ультрафильтрации (УФ), электрокоагуляции (ЭК), адсорбции и умягчения известью - с акцентом на их механизмы, недостатки и применимость к различным формам кремнезема. Несмотря на необходимость использования значительного количества химических реагентов и контроля pH, известковое умягчение и ионный обмен эффективны для удаления растворённого кремнезема. ОО требует тщательной предварительной подготовки, но обеспечивает широкий диапазон разделения, хотя и подвержен образованию осадков кремнезема. УФ эффективно удаляет коллоидный и частично дисперсный кремнезем, однако не справляется с мономерными формами. ЭК демонстрирует высокие показатели удаления при меньшем объёме осадка благодаря сочетанию электрохимической дестабилизации и кристаллизации. Адсорбция характеризуется переменной селективностью, низким энергопотреблением и совместимостью с мембранными системами, особенно при использовании специально разработанных материалов - активированного оксида алюминия, покрытий на основе оксида железа и функционализированных гибридов. Помимо анализа ключевых технико-экономических аспектов масштабирования методов удаления кремнезема из сложных промышленных водных матриц, в статье также рассматриваются последние достижения в области проектирования адсорбентов, такие как модификация поверхности, иерархическая пористость и методы регенерации.

Ключевые слова: диоксид кремния, промышленные, сточные воды, очистка, адсорбция.

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