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Investigation of synchronous arsenic and salinity rejection via nanofiltration system and membrane cleaning

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ABSTRACT

The coexistence of arsenic (As) and other salts in high concentrations in groundwater in northwest China restricts its use as a drinking water supply source. The behavior of negatively charged membrane of nanofiltration (NF) at pilot-scale was investigated over the simultaneous removal of As and salinity from a synthetic solution. The parameters that affected the rejection of As(V) and salinity were studied; that include pH and temperature of the feed, applied pressure, natural organic matter (NOM), and the presence of different salts in the feed. Meanwhile, membrane fouling and cleaning while using this application were also investigated. The study shows the removal efficiency of the membranes increased in the sequence of NF-6 < NF-2A < NF-3A. Among those parameters, the pH of the feed greatly affected As(V) rejection; temperature and applied pressure influenced it slightly; and the existence of NOM was of great benefit to As and salinity removal. Meanwhile, with the concentration of background salts increasing, the effects were better and the efficiency of divalent ions was more obvious than monovalent ions. The cleaning efficiency depended on type of the pollutant and its ability to break down the integrity of the compact fouling layer.

Keywords: Drinking water; Arsenic removal; Salinity removal; Nanofiltration; Membrane cleaning

1. Introduction

Arsenic is a toxic and cancerogenic substance which is distributed widely in the natural world, especially in northwest China. The carcinogenic risk caused by arsenic ingesting is very serious and it is dangerous enough even if there is a little amount of it in the drinking water, declared by the World Health Organization (WHO) [1]. Thus, the level of arsenic allowed in drinking water is modified from 50 to 10 ppb [2–5].

Ingestion of potable water is an important source of arsenic exposure [6], and concentrations are generally high in groundwater, especially where the rock is rich in arsenic and geochemical conditions favor arsenic and mineral salts dissolution. So the brackish water is arsenic-rich. Arsenic compounds occur mostly in the form of As(V) and As(III). While in the present study only As(V) is considered, because this is a

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particular situation of northwest China. It is reported that the content of As(V) exceeds 0.7 ppm in certain areas, while in several individual regions it is as high as 3 ppm.

In recent years, the National Construction Ministry of China has proposed to improve the potable water quality. So far, some technologies such as coagulation, lime softening, and membrane treatment etc. are available for arsenic and salinity removing from drinking water [7]. Recent developments in membrane technology have expanded the application of NF membranes. By contrast with reverse osmosis, NF could be operated at lower applied pressure still with higher selectivity and permeate flux [8,9]. Numerous publications about arsenic removal with NF membranes had been reported. Most of them were likely to be concentrated on As removal singularly, while only a few investigated the salinity removal synchronously and no one had ever studied cleaning of the fouled membrane continuously [10–12].

An inherent problem associated with NF membrane is fouling and the requisite chemical cleaning process [13–15]. Membrane fouling occurs through the deposition of organic and inorganic matters on the membrane surface, resulting in a decline in the permeability over time. It restricts the membrane pores due to pore blocking or internal foulant adsorption, leading to a decrease in the convective solute transport through the membrane pores [16–18]. By contrast, the cake layer may hinder the back diffusion of solutes away from the membrane surface, leading to an enhanced concentration polarization phenomenon and reduced solute rejection [19–23]. So the foulants should be distinguished in order to choose the feasible cleaning agent in membrane regeneration process. In arsenic and salinity removal applications, prevalent forms of NF membrane fouling include both organic and inorganic [24,25].

One objective of this work is to evaluate the factors (the applied pressure, pH, temperature, natural organic matter (NOM), and background salts) which influence the rejections of arsenic and salinity to enhance the quality of drinking water. The other one concentrates on maintaining the performance of the membranes. So a feasible chemical agent should be chosen according to the type of the pollutants.

2. Materials and methods

2.1. Reagents and materials

NF experiments were performed with three types of commercial flat membranes which were provided by Zhejiang Mey Technology Co., Ltd. The support materials of all the membranes were polyester nonwoven fabrics. The effective membrane area of the NF unit was 12.6 cm^2, and some characteristics of the membranes are summarized in Table 1.

In this paper, synthetic water mixed with arsenic was prepared according to the ratio of each ion in groundwater in northwest China which was presented in Table 2. All salt solutions were prepared fresh, using chemically pure agents dissolved in deionized water (DIW). An arsenic stock solution, of concentration 1,000 ppm, was prepared from $Na_3AsO_4·7H_2O$. Arsenic standard solution was established by appropriate dilutions of it immediately before use. 0.6% (w/v) sodium borohydride solution was prepared in 0.5% (w/v) sodium hydroxide solution and was filtered through microfiltration membrane to remove undissolved solids. Commercial humic acid (CHA) was used as NOM in the synthetic water. Hydrochloric acid (HCl pH 2.0) and sodium hydroxide (NaOH pH 11.0) were chosen as the chemical cleaning agents. Moreover, certified grade EDTA as a metal chelating agent was also selected. They are all common cleaning agents and the pH was adjusted with 1.0 M NaOH as needed.

2.2. Apparatus

The NF membrane module is spiral-wound thin-film composite polyamide membrane. The unit used for carrying out the experiments is presented in Fig. 1. It was equipped with a feed tank, a pressure vessel containing the membrane module, a circulation and pressurization pump with a security valve, two pressure gauges, a thermometer for temperature measurement in the circulation reservoir [1], an automatic circulating cooling device for temperature control, and a flow meter on the feed water pipe.

2.3. Experimental procedure

Flat membrane coupons were soaked in a DIW bath for 24 h and at the beginning of all the experiments, the membrane pieces were pre-compacted by filtering with DIW under the applied pressure of 1.0 MPa until a steady-state flux was obtained. After that the synthetic solution was introduced into the feed tank, and the test was carried out. Full circulation mode was used during the experiments where the retentate and permeate were returned to the feed tank in order to maintain constant concentration of NF feed. As some feed solutes deposited onto the membrane surface or pipeline wall, there was a slight decrease in feed solute concentration during the

Table 1
Characteristics of nanofiltration membranes

Membrane	Material	Film thickness/(mm)	DIW permeability ($L\,m^{-2}\,h^{-1}$)[a]	Surface charge[b]	NaCl rejection (%)[b]
NF-6	Polyamide	0.145	117.71	Negative	16.0
NF-3A	Polyamide	0.158	57.84	Negative	38.0
NF-2A	Polyamide	0.151	77.16	Negative	30.0

[a] The values were measured in the study.

[b] Information was provided by manufacturer. NF test condition: NaCl 2 g/L in water at 1.0 MPa.

Table 2
Quality of the groundwater in northwest China

Ions	Concentration	Unit
K^+	7.500	ppm
Na^+	882.9	ppm
Ca^{2+}	58.92	ppm
Fe^{3+}	0.375	ppm
Cl^-	653.2	ppm
SO_4^{2-}	1,271	ppm
NO_3^-	0.605	ppm
Mg^{2+}	61.00	ppm
HCO_3^-	108.8	ppm
As(V)	0.7/3[a]	ppm

[a] Concentration of As(V) was 0.7 or 3 ppm according to the quality of the groundwater.

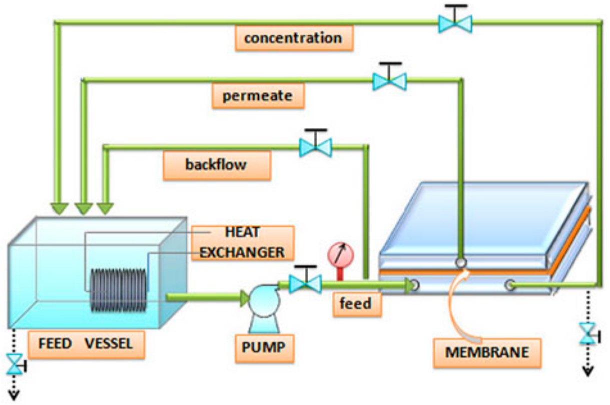

Fig. 1. Schematic experimental unit for NF.

process. Adding extra feed into the feed tank to minimize the change was performed [24].

The effects of applied pressure, pH, temperature etc. on the performance of the NF process were investigated in experimental trials. To ascertain the reproducibility of the results, a group of experiments were repeated and the results were found to vary within ± 3%. Rejections (R,%) of arsenic and salinity were calculated to Eq. (1):

$$R = \left(1 - \frac{C_p}{C_f}\right) \times 100\ \% \tag{1}$$

with C_f (μg/L) as the arsenic concentration and salinity of the feed; and with C_p (μg/L) as the arsenic concentration and salinity of the permeate water. Flux (J) is the volume of permeate (V) collected per unit membrane area (A) per unit time (t), which is calculated as:

$$J = V/At \tag{2}$$

Permeate samples were collected for arsenic concentration and salinity determination and the membrane permeate flux was measured at specified time intervals.

In order to investigate the cleaning efficiencies of different cleaning agents, chemical cleanings for membranes fouled by inorganic or organic pollutants were conducted, respectively. The cleaning process was operated with a flat-sheet laboratory-scale NF equipment detailed in Section 2.2. A feasible chemical agent was added to the feed tank instead of the synthetic solution according to different pollutant. During the entire test run, the membranes were cleaned under applied pressure of 0.1 MPa, cross-flow velocity of 2 L/min, and temperature of 20.0 ± 0.3℃. For each cleaning experiment with a cleaning agent, at least three repetitions were carried out. Flux recovery ratio (FRR) was calculated based on Eq. (3) to assess the cleaning efficiency [24,25].

$$\mathrm{FRR}(\%) = \frac{J_w - J_{fw}}{J_{iw} - J_{fw}} \times 100 \tag{3}$$

where J_{iw} is the pure water flux before fouling; J_{fw} is the pure water flux after fouling; and J_w is the pure water flux after cleaning. Pure water flux of membrane before and after fouling was measured. It was measured again after chemical cleaning and the residual cleaning agent removing. And all the pure water fluxes were measured under applied pressure of 1.0 MPa, cross-flow velocity of 1 L/min, and temperature of 20.0 ± 0.3℃.

2.4. Analytical methods

In the whole experiment, all samples were diluted to suitable levels for analysis. At the end of each filtration condition, permeate samples were analyzed using the AFS-230 dual-channel atomic fluorescence spectrophotometer. Each sample was measured for five times, so as to get more accurate results. The pH value was checked using a pH meter (DELTA 320) and the salinity was analyzed using a conductivity meter (DDS-307A).

2.5. Cleaning efficiency analysis

After chemical cleaning, scanning electron microscope (SEM), and atomic force microscopy (AFM) analysis methods was applied to evaluate the presence of foulants on the membrane surface and the cleaning efficiency.

Prior to SEM analysis, the membrane samples were cut into 3 × 5 mm size and coated with gold powder on the surface by a sputter coating machine before the observation of SEM. Images of fouled and chemically cleaned NF-3A membrane samples were taken at 10,000× magnification, 7 kv and the spot size of 55 nm with a scanning electron microscopy (SEM: S-4800, Hitachi High-Technologies Corporation, Japan).

The AFM measurements were carried out using a Nanoscope 3D multimode AFM controller (Veeco Metrology Group/ Digital instruments). Measurements were performed in tapping mode with etched silicon TESP probes (spring constant 42 N/m). Resolution of 512 × 512 data points at 1 Hz per image was used to collect the images. Membrane samples were cut into 10 × 10 mm size and then were put onto the substrate to be observed.

3. Results and discussion

3.1. Removal of arsenic and salinity by NF system

3.1.1. Effect of temperature

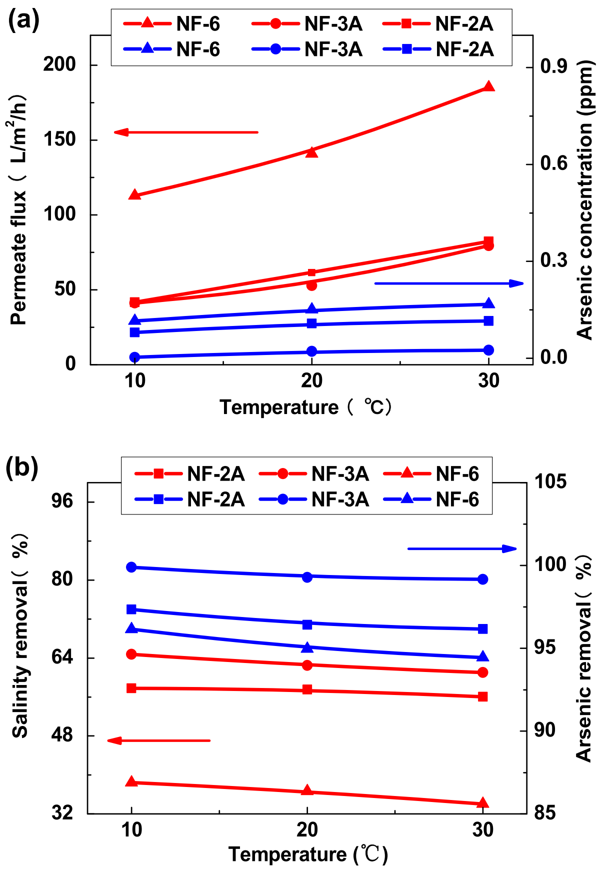

Fig. 2. Effect of temperature on the permeate flux, removal of As(V), and salinity of the three kinds of membranes under the constant conditions: pH was 7.42; the applied pressure was 1.0 MPa; feed flow was 4 L/min; the arsenic concentration was 3 ppm.

Fig. 2 showed the effect of temperature on permeation flux, arsenic and salinity retention of the three kinds of NF membranes. Also in the case, the flux linearly increased, the removal of arsenic decreased gradually with the temperature for all the NF membranes investigated. The range of water recovery was 5.6–15%. The formula used to calculate percentage water recovery was as follows:

$$\%\text{water recovery} = 100\ (Q_\text{p}/Q_\text{f}) \qquad (4)$$

where Q_f is feed water flow rate and Q_p is permeate flow rate. When arsenic concentration in the feed was 3 ppm, the correspondent total dissolved solids (TDS) were 3,000 ppm. The arsenic retentions of the NF membranes were more than 94%, and it increased in the sequence of NF-6 < NF-2A < NF-3A and temperature had a trivial effect on salinity removal. The membranes properties were reasonably good, but along with the decreased salt rejection; a decrease in growth rate of flux was also observed, indicating the possible concentration polarization of the synthetic solution, which made the osmotic pressure at the membrane surface higher, thereby causing a loss in the effective transmembrane pressure.

3.1.2. Effect of applied pressure

The permeation fluxes of these NF membranes were investigated as a function of applied pressure under steady-state after 1 h. The results were shown in Fig. 3(a). The experiment conditions were the same as Fig. 2 but the temperature was fixed at 20℃ here. Fig. 3(a) revealed that the permeation flux at steady-state increased with applied pressure increasing for all NF membranes, and the increasing efficiency of permeation flux through the NF-6 membrane was greater than the other ones.

Fig. 3(b) showed the As(V) and salinity rejection as a function of applied pressure. The efficiency of NF-3A membrane was higher than the values observed with NF-6 and NF-2A membranes over the pressure range investigated. In particular, the removal of As(V) with the NF-3A membrane was higher than 99.07%, while for the NF-6 membrane it was about 94.06%. The salinity removal of NF-3A membrane was close to 80%. This phenomenon could be accounted for assuming a lower molecular weight cut-off for the NF-3A membrane (~200 Da) in comparison with the NF-6 membrane (400 Da). The As(V) rejection was not sensitive to the change of applied pressure in the range of 1.0–2.5 MPa, in particular for the NF-3A membrane. It could be attributed that the As(V) content in the permeate water was increased with more water passing through the membrane. So the As(V) concentration of the permeate water (C_p) remained almost the same. Calculated with Eq. (1), then the rejection of arsenic (R) changed insensitively. Similarly, Sergio Perez-Sicairos, et al. [3] found that the arsenic removal was practically unrelated to the applied pressure in the NF system with synthetic water.

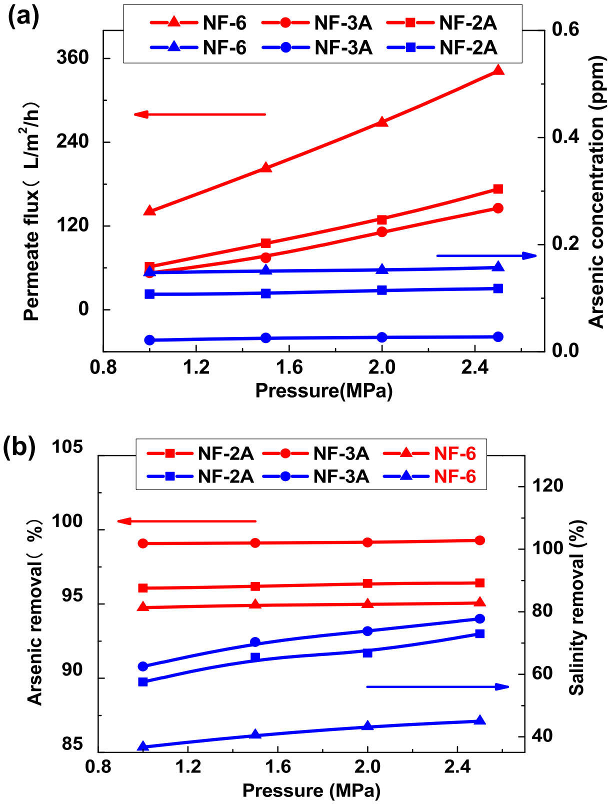

Fig. 3. Effect of applied pressure on the permeate flux, removal of As(V), and salinity of the three kinds of membranes under the constant conditions: pH was 7.42; the temperature was 20℃; feed flow was 4 L/min; the arsenic concentration was 3 ppm.

3.1.3. Effect of pH

Through the above researches, we could clearly see that the performance of the NF-3A membrane was the best. And bringing the arsenic concentration and salinity up to the standard of safe potable water could be achieved only with NF-3A membrane. While the other two kinds of membranes were not effective for drinking water production from arsenic-rich groundwater of northwest China. So the subsequent experiments were carried out with NF-3A membrane alone.

The effect of pH on arsenic and salinity removal for NF-3A membrane was depicted in Fig. 4. Arsenic rejection increased significantly by increasing pH. The salinity removal efficiency increased to almost 80% with respect to pH increasing to 9.66. Inorganic arsenic species that are stable in oxygenated waters include arsenic acid species viz., H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$ and AsO_4^{3-}. These results highlight the fact that arsenic in the commonly high oxidation state of (V) can be effectively removed. This can be accounted for assuming that the monovalent ion $H_2AsO_4^-$ is dominant in the range of pH 4–7 while the divalent ion $H_2AsO_4^{2-}$ is dominant above pH 7. Divalent ions are rejected at a higher rate compared to monovalent ions owing to larger radii of divalent ions compared to monovalent ions. So did the Donnan exclusion phenomena. Moreover, the NF-3A membrane was negatively charged at high pH and the effective charge density decreased at lower pH. Thus, it was beneficial to remove the arsenic and salinity from brackish water at neutral pH, and the rejection was almost more than 99%.

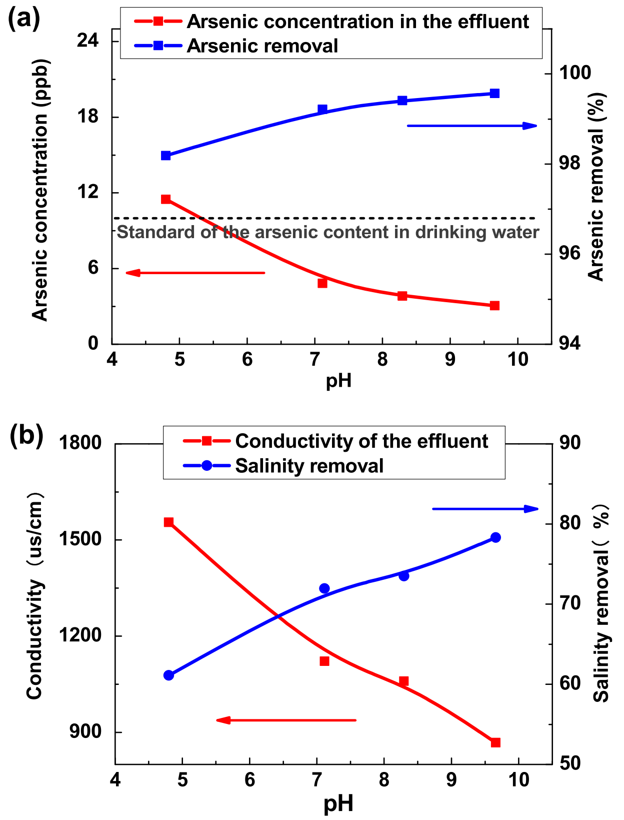

Fig. 4. Effect of pH on the permeate flux, removal of As (V), and salinity of the NF-3A membrane under the constant condition: The applied pressure was 1.0 MPa; the temperature was 20˚C; feed flow was 4 L/min; the arsenic concentration was 0.7 ppm.

3.1.4. Effect of NOM

To investigate the effect of NOM on arsenic rejection, CHA selected as the typical NOM was introduced into the feed water. Table 3 showed the effect of it on the permeation fluxes. The experiments were performed as follows. Initially, filtration was performed using the synthetic water without CHA for 1 h. And then the CHA (0.5 ppm) was added to the solution. After filtration for 2 h, sample was collected to analyze the arsenic concentration and more CHA was added to give a concentration of 12 ppm. The filtration was expected to continue for another 1 h. It was observed that the permeation flux decreased for all NF membranes. The NF-6 membrane, with higher permeability than others, showed the greatest decrease in flux with CHA concentration increasing. The CHA formed a fouling layer on the membrane surface in the filtration process and increased the permeation resistance.

Arsenic and salinity rejection of NF-3A membrane with different CHA concentrations in the synthetic water was shown in Fig. 5. With CHA changing from 0.5 to 12 ppm, arsenic was decreased from 0.043 to 0.026 ppm. And the salinity of the permeation water decreased greatly especially when the concentration of CHA greater than 6 ppm. However, the arsenic content was decreased strongly (below 10 ppb) with CHA of 40 ppm (the red dot in Fig. 5(a)). This is because the retention mechanism of the NF membrane was influenced by steric exclusion, the retention could potentially be improved to some extent by pore blocking caused by the attachment of organic molecules to the membrane surface. The presence of a fouling layer could affect the retention behavior by altering the membrane surface charge density. Meanwhile, complex formed by CHA and arsenic was easier to be removed because the size of it was bigger than the aperture of NF membrane. As the results demonstrated, CHA had a certain effect on arsenic and salinity removal. But it must decrease the permeation flux and cause membrane fouling with CHA increasing. So membrane should be chosen according to the quality of the feed water.

3.1.5. Effect of background salts

Experiments were carried out in a similar condition as described in Section 3.1.3. And quantity of salts added to the feed was at 3, 6, 15, and 30 mM.

Table 3
Effect of CHA on permeate flux for NF membranes

Membrane	Permeate flux (L m^{-2} h^{-1})					
	CHA concentration (ppm)					
	0.5	3	6	9	12	40
NF-6	117.71	117.13	116.28	115.11	113.69	102.37
NF-3A	58.41	58.22	57.85	57.66	56.77	52.16
NF-2A	77.16	76.81	76.33	75.86	75.27	70.91

Notes: Experimental conditions: Applied pressure 1.0 MPa, pH 7.44, feed As(V) concentration 0.7 ppm, feed flow 4 L/min.

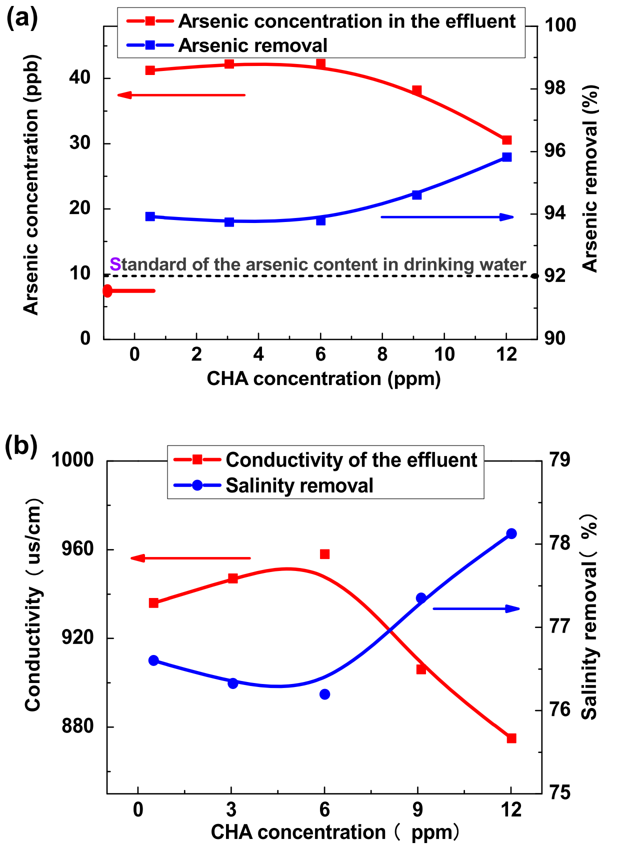

Fig. 5. Effect of NOM in the feed water on the permeate flux, removal of As(V), and salinity of the NF-3A membrane. Conditions for this experiment were similar to those in Fig. 4 except for the concentration of CHA.

The influence exerted by the presence of background salts was summarized in Fig. 6. Several studies showed that increasing the concentration of monovalent or divalent ions decreased the passage of As(V). As shown, the results revealed that arsenic rejection was insensitive to the variation of background salts concentration; arsenic removal was in the range of 96–99% and salinity removal was changed from 66.3 to 78.5%. Arsenic and salinity rejection with the presence of $MgSO_4$ was greater than NaCl by about 0.8 and 2.5%, respectively. With salts concentration increasing, the rejection was improved and arsenic content and TDS (<10 ppb, <1,000 ppm) in the permeation water almost satisfied the standard of safe drinking water.

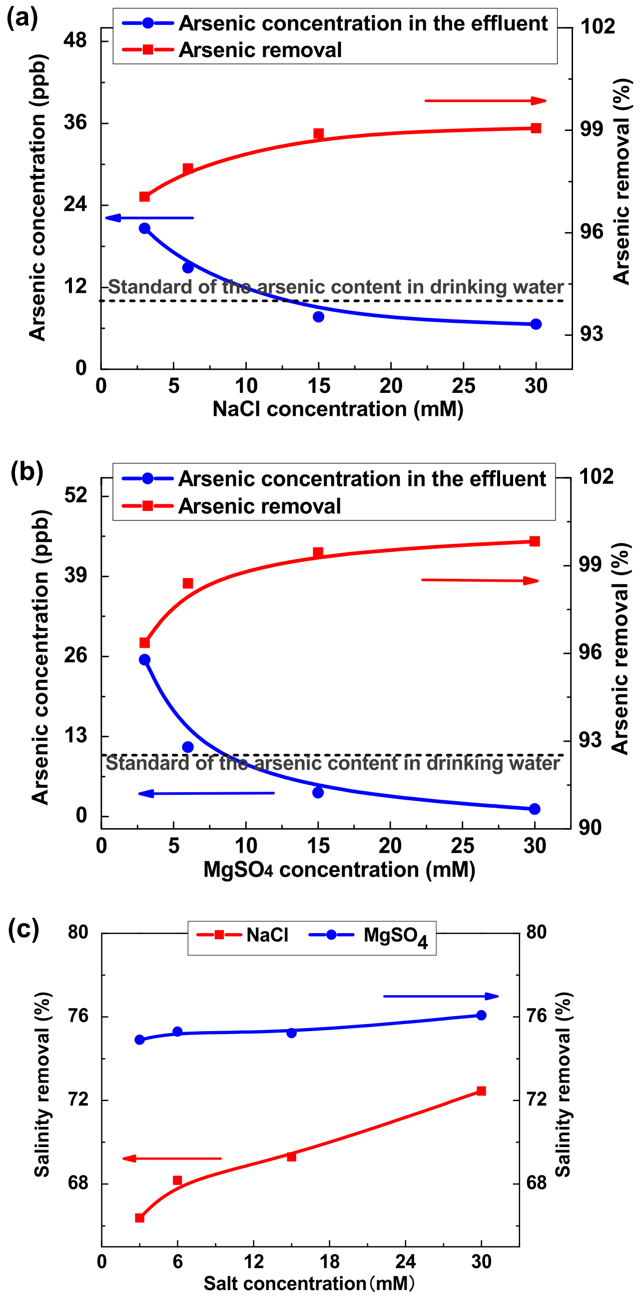

Fig. 6. Effect of background salt on the permeate flux, removal of As(V) and salinity of the NF-3A membrane. Conditions for this experiment were similar to those in Fig. 4 except for the ion concentration and pH (pH was 7.42 in this experiment).

3.2. Membrane chemical cleaning and regeneration

3.2.1. Inorganic pollutant cleaning

For inorganic fouled membrane, chemical cleanings with HCl, NaOH, and DIW were performed to remove fouling from membrane surfaces. The chemical cleaning was carried out for a time within the range of 10 to 100 min. Chemical cleaning efficiencies of HCl (pH 2, 365 ppm), NaOH (pH 12, 400 ppm), and DIW were shown in Fig. 7. The virgin-membrane surface was smooth, by contrast, many salt particles were placed on the fouled one. As shown in SEM images, the cleaning efficiency was increased in the sequence of DIW < NaOH < HCl. Membrane cleaned with HCl was quite similar to that of the virgin one. This confirmed that HCl was the best cleaning agent for inorganic pollutants.

The cleaning efficiency with respect to membrane FRRs was presented in Fig. 8. DIW was utilized to serve as a baseline for the comparison. It was noted that with cleaning time increasing, FRR increased more obviously for membranes cleaned by HCl or NaOH than that by DIW. Owing to the efficiency of HCl in dissolving the organic salts especially those that closest to membrane surface to lessen foulant-membrane interaction.

3.2.2. Organic pollutant cleaning

3.2.2.1. Characterization by membrane flux. The organic pollutant was mainly caused by CHA. Chemical

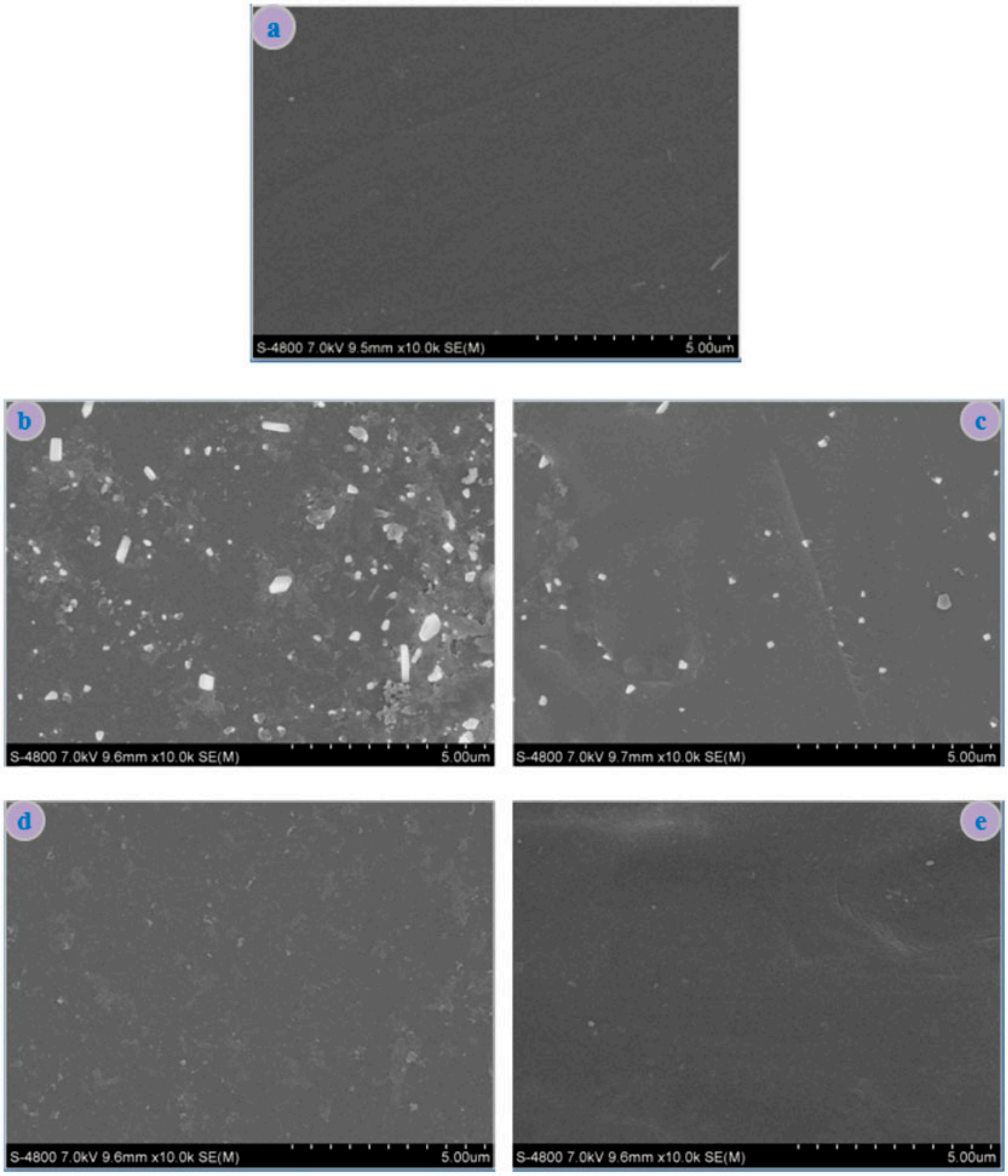

Fig. 7. SEM images of surface morphologies of (a) virgin membrane, (b) fouled membrane and membranes after chemical cleaning using: (c) DIW, (d) NaOH, (e) HCl.

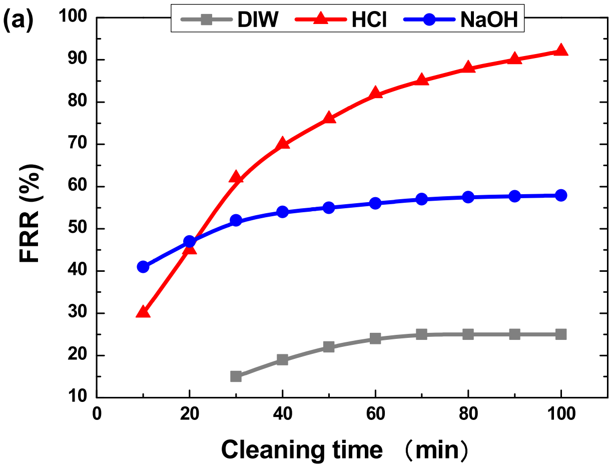

Fig. 8. Variation of membrane FRR with respect to cleaning time.

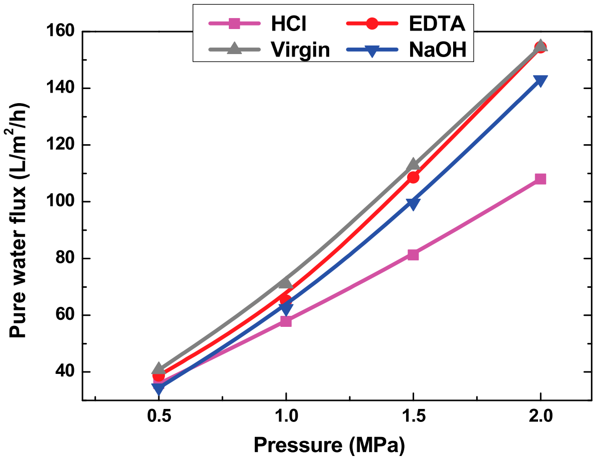

Fig. 9. Pure water flux of membranes cleaned with chemical agents with respect to pressure.

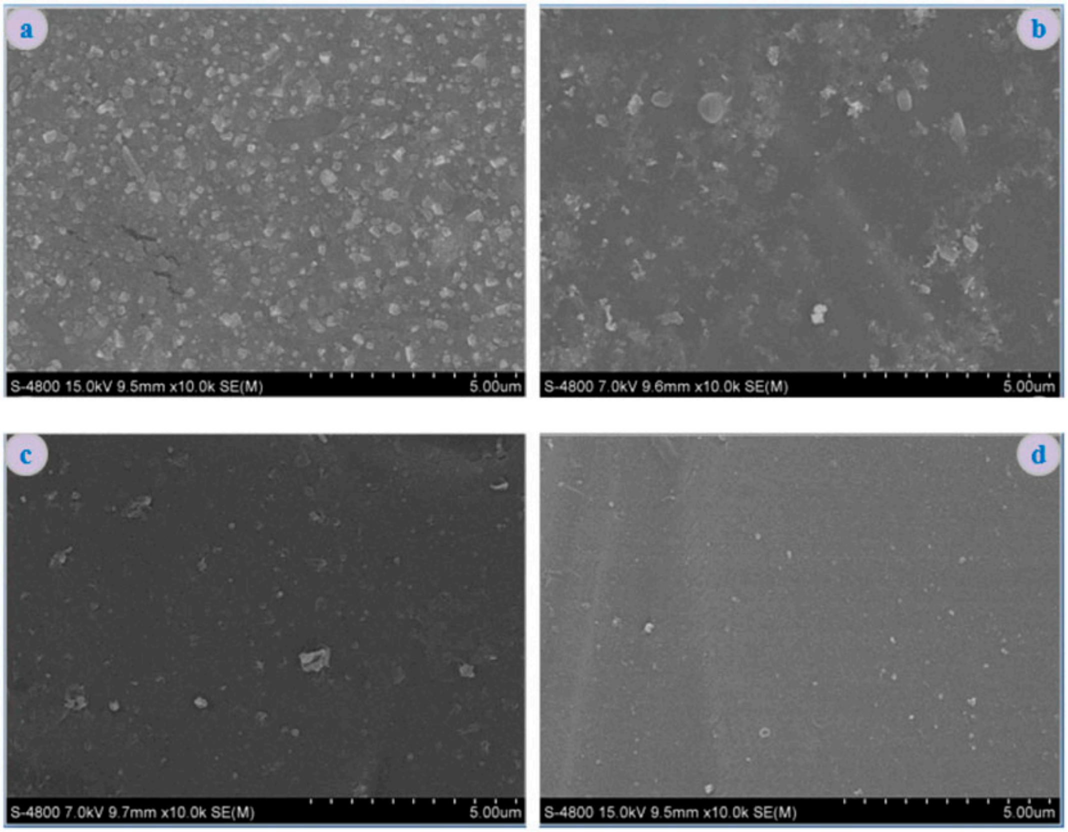

Fig. 10. SEM images of (a) organic fouled membrane and membranes after chemical cleaning using: (b) HCl, (c) NaOH, and (d) EDTA.

cleaning was carried out according to the operation in Section 3.2.1, but cleaning time was controlled in 40 min. The cleaning efficiency of agents with respect to pure water flux recovery was presented in Fig. 9. It was determined, respectively, and then compared with the virgin one. As shown, pure water flux of the

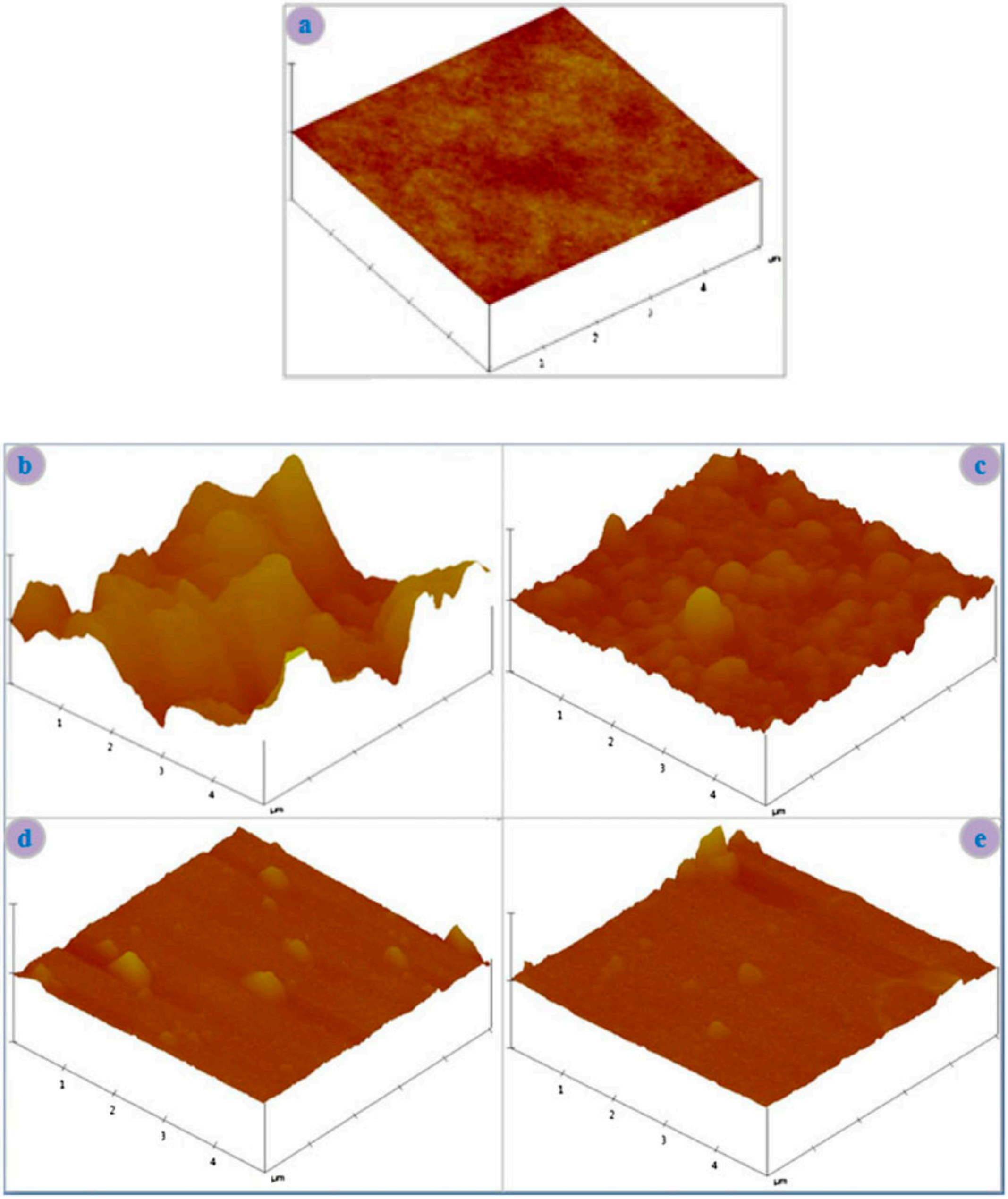

Fig. 11. AFM images of (a) virgin membrane, (b) organic fouled membrane and membranes after chemical cleaning using: (c) HCl, (d) NaOH, and (e) EDTA.

virgin membrane was obviously the best. After cleaning, fouled ones had a certain degree of recovery. And EDTA (3.5 ppm) was the most favorable cleaning agent for organic pollutant, as compared with extra-investigated agents. EDTA was a strong metal chelating agent. It could react through ligand exchange with calcium ions in organic matter-calcium complexes. The reaction between EDTA and foulants across the whole fouling layer to form soluble complexes cause the total breakdown of the densely packed fouling layer, which could be the reason for the best efficiency of the EDTA cleaning.

3.2.2.2. Characterization by SEM. The cleaning efficiency was also characterized by SEM image which was illustrated in Fig. 10. And it was increasing in the sequence of HCl < NaOH < EDTA. The results were in line with the pure water flux recovery.

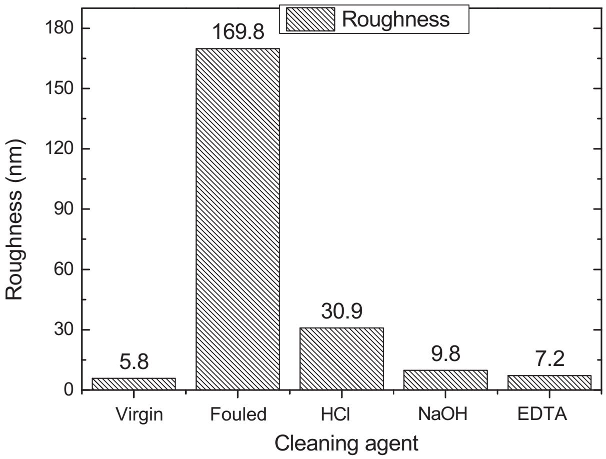

Fig. 12. The roughness of membranes with different cleaning agents.

3.2.2.3. Characterization by AFM. The cleaned efficiencies were examined by AFM, which was more visual to describe the cleaning efficiencies. A high accuracy morphology diagram of the membrane surface could be achieved and it reflected the ion repulsion between the membrane surface and the probe. Then the roughness of the membrane surface and the degree of pollution could be reached. The three-dimensional stereograms were presented in Fig. 11. The area was 5 × 5 μm and the *X* axis of each scale on behalf of 1 μm, which was 500 nm for the *Z* axis. As showed, there were many peak valley structures on polluted membrane surface which indicated that there were many pollutants. After cleaning, it became cleaner.

The roughness of the membrane surface was displayed in Fig. 12. The polluted membrane without cleaning was about 169.8 nm and others cleaned with HCl, NaOH, and EDTA were 30.9, 9.6, and 9.3 nm, respectively. AFM images revealed the results.

4. Conclusion

The present investigation demonstrated the effective use of a NF process for arsenic and salinity removal from groundwater in northwest China. The negatively charged NF membranes used in this study could almost decrease arsenic and salinity to the safe potable water standard set by WHO, and the efficiency of the membranes increased in the sequence of NF-6 < NF-2A < NF-3A.

For all membranes, the removal efficiencies for As (V) and salinity were influenced by the operation conditions such as applied pressure, the presence of NOM, pH, and background salts concentration in different degrees. As(V) rejection was not very sensitive to the change of temperature and applied pressure (decreased slightly with temperature and increased slightly with applied pressure); while for salinity rejection, the effect of applied pressure was stronger than that of temperature. pH of the solution was a major factor. When pH < 7, the main form of arsenic was $H_2AsO_4^-$, while it transformed into $H_2AsO_4^{2-}$ with pH increasing. There were complexation between arsenic and NOM and the formed complex is bigger than the pore size of membrane. So NOM benefited arsenic removal and then affected salinity removal. While contamination maybe formed in the membrane surface, so the concentration of NOM should be monitored properly. The rejection of As(V) and salinity was enhanced because the existence of background salts and the effects of divalent ions were more obvious than monovalent ions. So we should consider these factors comprehensively in practical applications.

The chemical cleaning for membrane was studied after arsenic removal treatment. Repetitive membrane fouling and chemical cleaning resulted in notable changes in NF membranes surface properties and solute separation efficiency. The efficiency of a cleaning agent depended on the type of pollutants and its ability to break down the integrity of the compact fouling layer. For inorganic pollutant, HCl (pH 2) agent was selected and EDTA (3.5 ppm) was for organic pollutant.

Acknowledgments

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List of symbols

R — rejection of arsenic and salinity
C_p — arsenic concentration and salinity of the permeate
C_f — arsenic concentration and salinity of the feed
J — water flux
V — volume of permeate
A — effective membrane area
t — time
FRR — flux recovery ratio
J_w — pure water flux after cleaning
J_{fw} — pure water flux after fouling
J_{iw} — pure water flux before fouling
Q_p — permeate flow rate
Q_f — feed water flow rate

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