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Ion-exchange pilot test for the deboronation of previously treated mine drilling water in a reverse osmosis plant

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ABSTRACT

In this article, the boron removal efficiency of permeate water in a full-scale reverse osmosis system was examined using an AmberLite™ PWA-10 boron-selective resin (N-methylglucamine functional group). The reverse osmosis system was supplied with pre-treated water from the mine drilling process. This test was performed using an ion-exchange laboratory column; the results were not satisfactory when using first-pass reverse osmosis water, obtaining a lower operation cycle (0.45 h) at a higher boron inlet concentration (121.000 ppm). However, good results were achieved using second-pass reverse osmosis water at a lower boron inlet concentration (3.800 ppm). The results showed an average boron removal efficiency of 87.08% (0.491 ppm) lower than the Peruvian laws on drinking water quality (<1.500 ppm), and a higher operation cycle (41.35 h). Regarding the inorganic parameters analyzed in this test, the results showed concentration level below the limits established by Peruvian drinking water laws, making water suitable for human consumption. This finally confirms that the ion-exchange technology represents an important alternative as a polishing step for boron removal in water for reuse purposes.

Keywords: Boron-selective resin; N-methylglucamine; Operation cycle; Boron removal; Permeate water; Polishing step

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1. Introduction

The mining industry has enormously contributed to the world economy in recent years. However, the waste generated by this industrial activity poses many challenges. Among those challenges, water scarcity is a problem in many areas where exploitable natural resources abound. In this sense, mining industry is forced to research technologies for the recovery and reuse of water [1].

The use of water for mineral recovery causes the accumulation of some treatment chemicals and solids in the process water supply, resulting in water with high concentrations of suspended matter, sulfates, metals, boron, and other elements, depending on the mineral exploitation area and chemicals used in the metal recovery process [1].

Different treatment methods currently apply to these liquid effluents, such as cyanide destruction, chemical precipitation, neutralization, ion-exchange, electrochemical processes, and membrane separation processes [2,3]. The mining industry triggers intense environmental impacts during the mineral extraction and production process. Water can be contaminated by various toxic substances generated from the mining process, and it may suffer from acid mine drainage (AMD), one of the primary forms of water pollution resulting from mining activities. This process occurs due to the oxidative dissolution of sulfide minerals, lowering the pH of the water. AMD water may contain heavy metals, which generate a bioaccumulation effect for aquatic life in the environment. Therefore, human exposure to elements such as arsenic, iron, lead, zinc, silicon, titanium, manganese, lithium, chromium, copper, mercury, and boron represents a health risk [4].

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It is well known that boron is an essential element for organisms in many ways, and it becomes toxic when its concentration is slightly higher than required. Excessive boron concentrations can inhibit the photosynthesis process and the root cell division of the plants, so it can also prevent the deposition of lignin and chlorophyll, generating yellowish spots on the leaves, less fruit, as well as other adverse effects on crops. For humans and animals, the adverse effects cannot be ignored. The moderate concentration of boron is a beneficial nutrient; however, long-term chronic absorption may cause many harmful impacts, such as growth retardation, changes in blood composition, and problems with the nervous and reproductive systems [5]. Boron is widely distributed in the environment and naturally occurs in groundwater, mainly as a result of leaching from rocks and soils or from main anthropogenic sources such as agrochemicals like pesticides, fertilizers, and detergents [6]. This element is mainly found in the form of boric acid or borate salts [7]. The borate monovalent $B(OH)_4^-$ dominates at a higher pH, and conversely non-ionized boric acid $B(OH)_3$ at a lower pH. The dissociation of boric acid in water can be represented as follows: $B(OH)_3 + H_2O = B(OH)_4^-$ [8]. Regarding the level of boron concentration in water with high conductivity, it has been reported that at low boron concentration (≤216 mg/L) dissolved boron is mainly found as the mononuclear boron species, $B(OH)_3$ and $B(OH)_4^-$; however, higher concentrations with the increase in pH; polynuclear boron species such as $B_2O(OH)_6^{2-}$, or those incorporating B_3O_3 rings such as $B_3O_3\,(OH)_4^-$, $B_4O_5(OH)_4^{2-}$, and $B_5O_6(OH)_4^-$ are formed [9,10].

Boron is not only an essential micronutrient for living beings, but also an important raw material for several industries, such as the production of fiberglass, detergents, fertilizers, cleaning products, semiconductors, cosmetics, etc. The glass industry is the single largest user, which consumes more than half of the total world production of boron compounds. In the nuclear industry, it is very important to utilize the isotope boron-10, which can control the nuclear reaction rate and prevent a nuclear explosion [9]. However, excessive boron concentrations have recently been declared an unavoidable contaminant in various water supplies for the following reasons: Firstly, the leakage of boron compounds into water-receiving bodies can cause detrimental effects to some plants and crops, and secondly, the possible effects are adverse to human health [11].

A guideline value of boron concentration in drinking water has been fixed at up to 2.4 and 1.0 mg/L by the World Health Organization (WHO) and the European Union (EU), respectively. Standard permissible values are difficult to achieve for several deboronation technologies [12]. The Drinking Water Quality Committee, at its meeting from November 9–13, 2009, recommended raising the boron guideline value to 2.4 mg/L per the data from the UK and USA on dietary intakes. This WHO guideline was formulated based on human health [13]. However, few countries follow it, and many of them have implemented their own standard. The recommended concentration of boron is 1.0 mg/L in the European Union, United Kingdom, South Korea, Singapore, and Japan, while according to the federal regulations in the United States, the boron concentration level depends on the state, and is in the range of 0.6 to 1.0 ppm. In New Zealand and Israel, the concentrations are 1.4 and 1.5 ppm, respectively. Canada and Australia have the maximum boron concentrations at 5.00 and 4.00 ppm, respectively, higher than WHO guidelines [5].

The current need for the use of water for drinking water and irrigation water in mining camps, as well as water scarcity and the increasing demand for this resource, have changed the alternatives for its use [11]. Although the metallurgical processes used in mining operations are similar, the wastewater composition varies widely, and there is not one single procedure for purification. There are different treatment technologies, such as neutralization, chemical precipitation, ion-exchange, electrochemical, and membrane separation processes. The traditional processes of neutralization and chemical precipitation use large amounts of alkaline reagents, and their main disadvantage is the generation of large volumes of sludge containing heavy metal compounds that must be disposed of. These processes have a certain limitation for complying with increasingly stringent environmental laws regarding treated effluents. As an alternative, membrane processes present many attractive advantages, such as the generation of high-quality permeate, metal concentrations, and low operation costs [14].

The stricter restrictions imposed by each country regarding the concentration of boron in water for human consumption have led to the evaluation and study of new water treatment alternatives with high performance in the removal of this element. [15].

Among the most widely applied technologies for boron removal, the following stand out: the use of multiple pass reverse osmosis membranes with pH adjustment and the use of ion-exchange with boron-selective resin are considered the most effective water treatment methods for the removal of this element. Hybrid processes, such as adsorption-membrane filtration (AMF), have also received special attention as emerging technologies, due to better performance, higher adsorption surface area, lower adsorbent cost, and lower pressure drop compared to conventional processes, such as a fixed-bed column for ion-exchange [5]. However, these processes are still in the research stage since they require boron-selective resins that have a small diameter, uniform size, and smooth edges to be resistant to abrasion and cracking. Therefore, the development of monodisperse boron-selective resins with average diameters of 50 um is still a challenge and one of the important issues of modern technology [16].

Because boron removal with reverse osmosis is sometimes insufficient under normal operating conditions, there is a strong need to improve the efficiency of the conventional treatment process for boron removal. Among these technologies, ion-exchange is a promising alternative because it requires simple operating conditions and can be applied to the treatment of water with low boron concentrations, such as boron removal from reverse osmosis permeate in the desalination process of mine water [17].

With the objective of reusing the water from the mine drilling process in the mining camp, this article presents the evaluation of the boron removal efficiency by ion-exchange using an AmberLite™ PWA-10 boron-selective resin as a polishing stage in the permeate water of a reverse osmosis plant.

2. Materials and methods

2.1. Study material

Comprised of the pre-treated mine drilling process wastewater from the chemical precipitation, sedimentation, microfiltration, ultrafiltration, and post-treated wastewater in a reverse osmosis process.

The characteristics of the mine drilling process wastewater and the post-treated effluent are shown in Tables 1 and 2, respectively.

2.2. Experimental equipment

The test was carried out in an ion-exchange column at a laboratory level. The ion-exchange unit was supplied with treated water at an industrial level through the following processes: chemical precipitation, sedimentation, microfiltration, ultrafiltration, and reverse osmosis. The flow diagram of the process is shown in Fig. 1.

For the experimental stage, the following materials were used: 1 burette of 50 mL capacity, with an internal diameter of 1.10 cm and a height of 51.50 cm. The column was filled with 25 mL of resin bed, and it was inserted with a small plug of glass wool in the restriction above the stopcock (Fig. 2). This test was carried out with mine drilling wastewater that had been pre-treated by chemical precipitation, sedimentation, microfiltration, and ultrafiltration, and then post-treated by reverse osmosis. The permeate water from reverse osmosis, with boron inlet concentrations of 121.000 and 3.800 ppm, was supplied to the ion-exchange system.

The test was carried out using the flow rate criterion established for the boron-selective resins (Laboratory Procedure for Testing Dupont Exchange Resins and Polymeric Adsorbents) [18], using a flow rate range of 15–30 BV/h and 25 mL of resin bed. This represented a working flow rate of 375.00–750.00 mL/h. The column mode test was performed considering a feed flow rate of 29.00 BV/h. This study sought to determine the boron removal efficiency by ion-exchange using an AmberLite™ PWA-10 boron-selective resin type in the permeate water of a reverse osmosis system. Fig. 2 shows the test schematic diagram.

Table 3 presents the technical specifications of the boron-selective resin, the subject of this article.

2.3. Method

An ion-exchange laboratory test in column mode was established to evaluate the boron removal efficiency using a boron-selective resin with an N-methylglucamine functional group in the mining effluent of a company located in the south-central zone of the Peruvian Andes (Ayacucho Region). The test was carried out with the permeate water from the first and second-pass of the reverse osmosis unit. In both cases, the permeate water from each process was supplied independently to the ion-exchange unit. The experiments used a flow rate of 29.00 BV/h (725.00 mL/h, 25.00 mL of resin bed). The tests were carried out during the time that the operation cycle of the ion-exchange unit lasted. Samples were taken every hour for boron analysis in order to determine the operation cycle of the resin and the boron removal efficiency. For this experiment, a boron breakpoint value of 1.500 ppm was chosen, based on Peruvian drinking water laws. The samples collected during the development of the test were analyzed at the process plant laboratory.

Table 1
Characteristics of the mine drilling process wastewater

Parameter	Quantity
pH	8.20
Specific conductivity, us/cm	41,480.000
Total hardness (as mg/L $CaCO_3$), mg/L	941.000
Hydrogen carbonate (as mg/L $CaCO_3$), mg/L	2,581.000
Sulfates, mg/L	1,366.000
Chlorides, mg/L	12,773.400
Silver, mg/L	<0.002
Aluminum, mg/L	0.100
Arsenic, mg/L	46.020
Barium, mg/L	0.054
Beryllium, mg/L	0.014
Bismuth, mg/L	<0.020
Boron, mg/L	479.975
Calcium, mg/L	284.640
Cadmium, mg/L	0.004
Cerium, mg/L	0.030
Cobalt, mg/L	<0.002
Chromium, mg/L	<0.004
Copper, mg/L	<0.003
Iron, mg/L	0.830
Potassium, mg/L	487.800
Lithium, mg/L	53.191
Magnesium, mg/L	55.810
Manganese, mg/L	0.913
Molybdenum, mg/L	0.005
Sodium, mg/L	8,138.820
Nickel, mg/L	0.010
Phosphorus, mg/L	<0.060
Lead, mg/L	0.090
Antimony, mg/L	<0.008
Selenium, mg/L	<0.020
Silica, mg/L	17.960
Tin, mg/L	<0.007
Strontium, mg/L	5.186
Titanium, mg/L	<0.010
Zinc, mg/L	1.051

Source: Plant Process Laboratory – 2022.

2.4. Control and analysis

2.4.1. Parameters measured during the operation:

pH (Standard methods: Electrometric Method. Part – 4500 – H^+ B), sulfates (Standard methods: Turbidimetric Method. Part – 4500 – SO_4^{2-}), total hardness (Standard methods: EDTA Titrimetric Method. Part – 2340 C – Hardness), conductivity (Standard methods: Laboratory Method.

Table 2
Characteristics of the post-treated wastewater by reverse osmosis supplied to the ion-exchange system

Parameter	Quantity
pH	8.300
Specific conductivity, us/cm	41.500
Total hardness (as mg/L $CaCO_3$), mg/L	<1.000
Hydrogen carbonate (as mg/L $CaCO_3$), mg/L	8.000
Sulfates, mg/L	16.000
Chlorides, mg/L	<1.500
Silver, mg/L	<0.020
Aluminum, mg/L	<0.020
Arsenic, mg/L	<0.008
Barium, mg/L	0.003
Beryllium, mg/L	<0.0003
Bismuth, mg/L	<0.020
Boron, mg/L	3.800
Calcium, mg/L	0.310
Cadmium, mg/L	<0.001
Cerium, mg/L	<0.020
Cobalt, mg/L	<0.002
Chromium, mg/L	<0.004
Copper, mg/L	<0.003
Iron, mg/L	0.030
Potassium, mg/L	0.090
Lithium, mg/L	0.011
Magnesium, mg/L	0.030
Manganese, mg/L	0.002
Molybdenum, mg/L	<0.004
Sodium, mg/L	5.700
Nickel, mg/L	<0.002
Phosphorus, mg/L	<0.060
Lead, mg/L	<0.010
Antimony, mg/L	<0.008
Selenium, mg/L	<0.020
Silica, mg/L	0.160
Tin, mg/L	<0.007
Strontium, mg/L	0.002
Titanium, mg/L	<0.010
Zinc, mg/L	0.008

Source: Plant Process Laboratory – 2022.

Part – 2510 B – Conductivity), chlorides (Standard methods: Chloride Argentometric Method. Part – 4500 – Cl^- B), alkalinity HCO_3^- (Standard methods: Titration Method. Part – 2320 B – Alkalinity). Elements: silver, aluminum, arsenic, barium, beryllium, bismuth, boron, calcium, cadmium, cerium, cobalt, chromium, copper, iron, potassium, lithium, magnesium, manganese, molybdenum, sodium, nickel, phosphorus, lead, antimony, selenium, silica, tin, strontium, titanium, thallium, vanadium, and zinc. (Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-Atomic Emission Spectrometry, EPA Method 2007) [19,20].

The analysis of the results focused on evaluating the boron removal efficiency of the ion-exchange system, as well as other important inorganic parameters for the evaluation of the treated water for reuse purposes.

3. Results and discussion

The ion-exchange resin used in this research is a boron-selective resin. The boron adsorption mechanism is shown in Fig. 3.

Table 1 presents the physical–chemical analysis of the mine drilling process wastewater supplied to the chemical precipitation– reverse osmosis system. This characterization showed a high-level concentration of polluting elements above the limit of Peruvian environmental standards for water reuse, both for discharge to receiving bodies and for use as water for human consumption. Total hardness: 941.000 ppm, sulfates: 1366.000 ppm, chlorides: 12773.400 ppm, sodium: 8138.820 ppm, arsenic: 46.020 ppm, lithium: 53.191 ppm, strontium: 5.186 ppm, and boron: 479.975 ppm. Those compounds are of interest for this evaluation since these concentration levels can cause adverse environmental impacts on aquatic ecosystems and soils, as well as affect the human health of exposed populations.

Table 2 presents the physical–chemical analysis of the mine drilling process wastewater pre-treated by chemical precipitation and post-treated by a double-pass reverse osmosis system. This characterization showed a low-level concentration in regards to the main compounds coming from the mine drilling process wastewater: arsenic: <0.008 ppm, mainly removed in the chemical precipitation stage, and other parameters, such as strontium: 0.020 ppm, total hardness: <1.000 ppm; sulfates: 16.000 ppm; chlorides: <1.500 ppm; lithium: 0.011 ppm; and boron: 3.800 ppm, removed in the reverse osmosis desalination stage. Despite the low-level boron concentration achieved in the permeate water of the second-pass reverse osmosis system (3.800 ppm), this value is above the maximum permissible limit of the Peruvian laws for its reuse for human consumption, which establishes a boron concentration limit of <1.500 ppm.

This test presents the results of the operation cycle of the AmberLite™ PWA-10 boron-selective resin in permeate water of the first pass and second-pass of the reverse osmosis system, as shown in Table 4 (Fig. 4) and Table 5 (Fig. 5).

Table 4 (Fig. 4) presents the operation cycle achieved by the ion-exchange system for a boron inlet concentration of 121.000 ppm. Under this condition, the ion-exchange system reached 0.45 h of operation, taking as a reference a boron breakpoint value of <1.500 ppm per the maximum permissible limit of the Peruvian laws for human consumption.

Table 5 presents the operation cycle achieved by the ion-exchange system for a boron inlet concentration of 3.800 ppm. Under this condition, the ion-exchange system reached 41.35 h of operation, using as a reference the first test a boron breakpoint value of <1.500 ppm per the maximum permissible limit of the Peruvian laws for human consumption.

Results from Table 5 show us that boron-selective resin has greater operational flexibility, fewer chemical

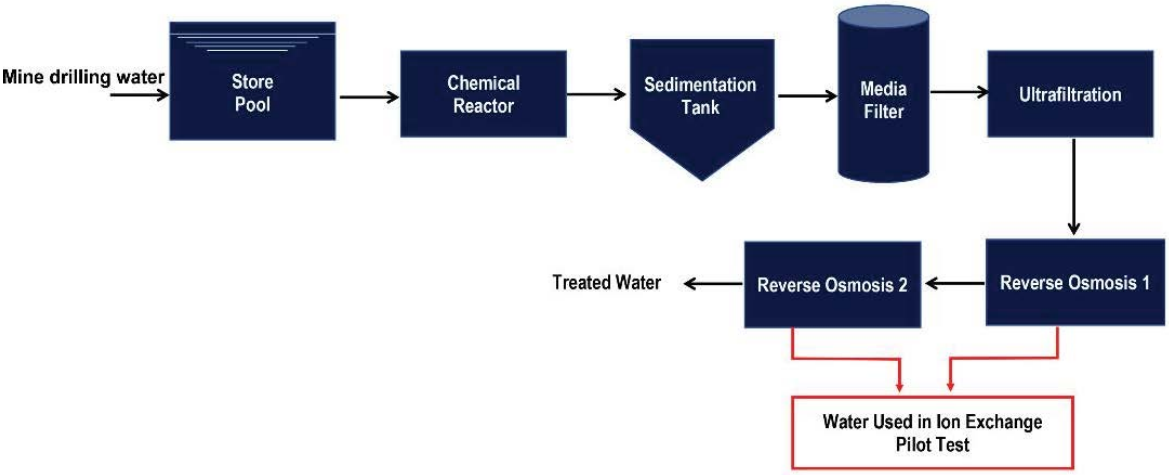

Fig. 1. Water treatment plant flow diagram.

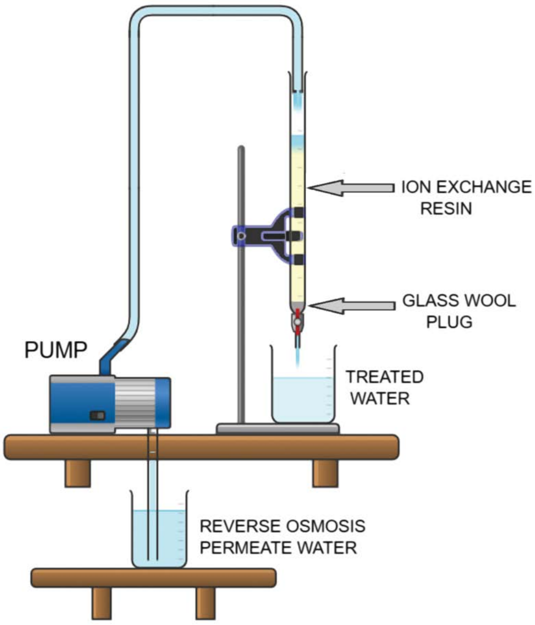

Fig. 2. Ion-exchange pilot test diagram.

Table 3
Technical specifications of the AmberLite^{TM} PWA-10 boron-selective resin

Specification	Description
1. Physical properties	
Copolymer	Styrene – divinylbenzene
Matrix	Macroporous
Type	Weak base anion
Functional group	N-methylglucamine
Physical form	Cream, opaque, spherical beads
2. Chemical properties	
Ionic form	Freebase
Total exchange capacity	≥0.7 eq/L
Water retention capacity	48%–54%
3. Particle size	
Particle diameter	525 ± 75 um
Uniformity coefficient	≤1.2
<300 um	≤0.1%
>1,180 um	≤5.0%

Source: Product Data Sheet – DUPONT.

regeneration cycles, and therefore lower chemical costs when the ion-exchange unit is supplied with water at a lower boron inlet concentration (3.800 ppm). During this test, an average boron removal efficiency of 87.080% was achieved in the effluent of the ion-exchange unit supplied with permeate water of the second-pass reverse osmosis. In regards to the second-pass reverse osmosis system with pH adjustment, a boron removal efficiency of 99.210% was reached. Kabay et al. [7] showed a comparative study of boron removal processes that must be applied to keep boron at <0.500 ppm. In this study, the technology second-pass reverse osmosis with pH adjustment was able to achieve a boron removal efficiency of 40%–100%, while with boron chelation technology using N-methyl-D-glucamine it was able to achieve a boron removal efficiency of >80%.

Table 6 presents the physical–chemical analysis of the ion-exchange unit effluent. The results show that the concentrations of the inorganic chemical compounds analyzed in this experiment were satisfactory, as was the boron concentration level—an important parameter of this study—which was below the maximum boron permissible limit according to Peruvian laws (discharge in receiving bodies <1.000 ppm and for drinking water <1.500 ppm.)

Results from Table 6 show us a reduction in the concentration of the parameters such as hydrogen carbonate, sulfates, and other ions, which could give indications of ion-exchange competition on the active sites of the amine group of the resin N-methyl-D-glucamine regarding the boron. This type of resin belongs to the weak base anion resin

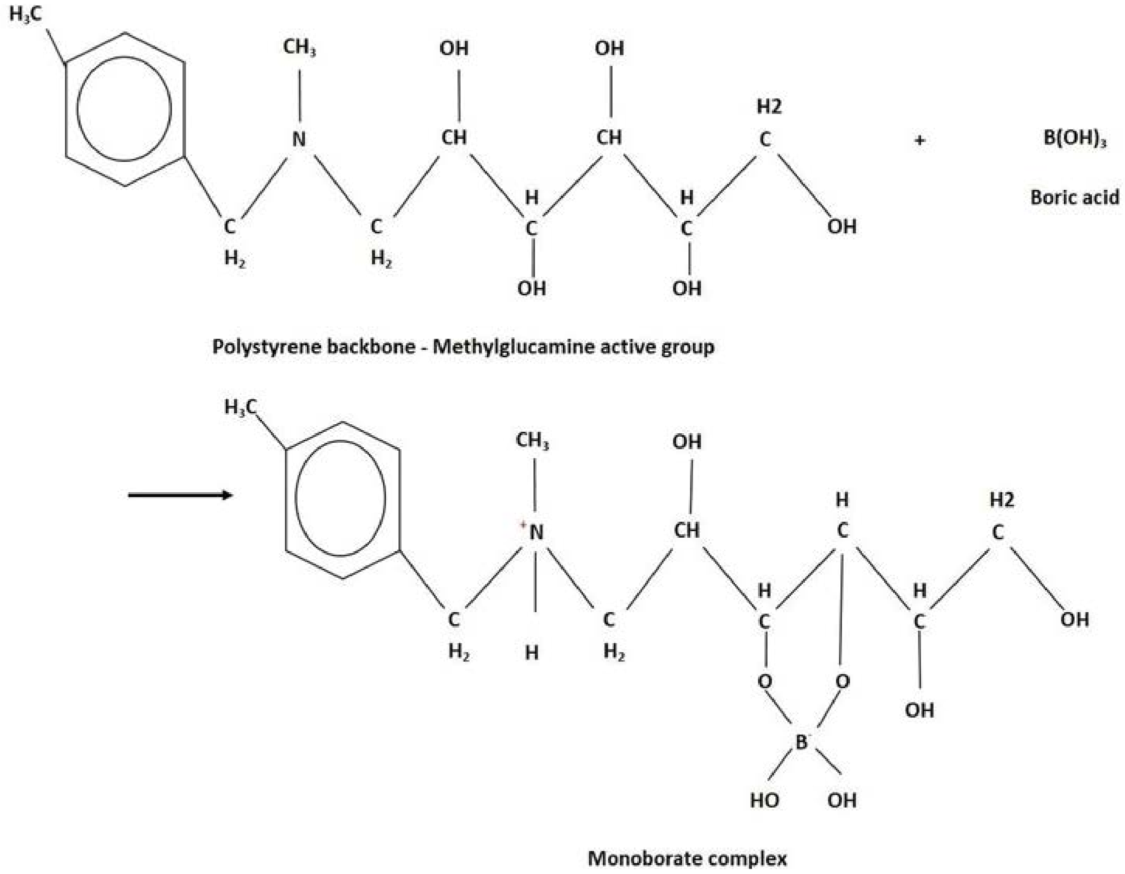

Fig. 3. Mechanism of boron removal.

Table 4
Operation cycle of the boron-selective resin in permeate water of the first pass reverse osmosis at a boron inlet concentration of 121.000 ppm

Date	Time (h)	Time elapsed (h)	Boron (mg/L)
08-24-2022	09:15	0:00	121.000
08-24-2022	09:30	0:15	0.521
08-24-2022	10:00	0:45	1.510
08-24-2022	10:30	1:15	56.714
08-24-2022	11:30	2:15	105.523
08-24-2022	12:30	3:15	121.010

Source: Plant Process Laboratory – 2022.

group, and it could show certain anion exchange capacity due to the presence of tertiary amine groups. This is why it is important to conduct further research as the next step of this study, so as to verify the interference of these ions on the boron adsorption process, removal efficiency, and resin operation cycle [21].

Table 7 shows the results of the specific inorganic parameters analyzed in the ion-exchange unit effluent, which show concentration levels below the maximum permissible limit for human consumption water according to Peruvian laws. This study focused mainly on the evaluation of the boron removal efficiency, as well as the evaluation of the important inorganic parameters present in the source water. Due to the low conductivity reached in the ion-exchange unit effluent, it is important to consider the inclusion of a post-treatment stage for water remineralization in order to make it more suitable for human consumption. The final step of this study is to verify the compliance of other important parameters stipulated in Peruvian and international standards regarding the concentration of organic, microbiological, and parasitological compounds, which from a technical point of view should already have been removed in the reverse osmosis unit.

Boron removal studies carried out in water for human consumption [7] showed high boron removal efficiencies in waters with low ionic strength. These tests were carried out with the addition of 5.00 ppm $B(OH)_3$, as shown in Table 8.

A recent study carried out in Spain about the use of ion-exchange resins to reduce boron concentration in desalinated seawater for irrigation has shown good results as a polishing stage of the reverse osmosis system. According to this study, during the first 38–45 h of operation, the resin was able to maintain the boron concentration of the effluent at 0 mg/L, achieving the woody crop boron threshold/boron concentration of 0.50 mg/L after the 84–92 h of operation, with boron rejections of up to 99.00% during the first 41 h [22].

Table 5
Operation cycle of the boron-selective resin in permeate water of the second-pass reverse osmosis at a boron inlet concentration of 3.800 ppm

Date	Time (h)	Time elapsed (h)	Boron (mg/L)
08-26-2022	09:55	0:00	3.800
08-26-2022	10:30	0:35	0.404
08-26-2022	13:30	3:35	0.312
08-26-2022	15:30	5:35	0.205
08-26-2022	17:30	7:35	0.207
08-26-2022	19:30	9:35	0.415
08-26-2022	21:30	11:35	0.408
08-26-2022	21:40	11:45	0.321
08-27-2022	22:10	12:15	0.412
08-27-2022	00:00	14:05	0.510
08-27-2022	03:00	17:05	0.409
08-27-2022	05:00	19:05	0.607
08-27-2022	07:00	21:05	0.230
08-27-2022	08:30	22:35	0.215
08-27-2022	09:30	23:35	0.512
08-27-2022	10:30	24:35	0.405
08-27-2022	11:30	25:35	0.415
08-27-2022	12:30	26:35	0.500
08-27-2022	14:30	28:35	0.710
08-27-2022	15:30	29:35	0.504
08-27-2022	16:30	30:35	0.703
08-27-2022	17:30	31:35	0.809
08-27-2022	19:30	33:35	1.210
08-28-2022	21:30	35:35	1.104
08-28-2022	23:30	37:35	1.312
08-28-2022	01:30	39:35	1.309
08-28-2022	03:30	41:35	1.506
08-28-2022	05:30	43:35	1.702
08-28-2022	07:30	45:35	2.213
08-28-2022	09:30	47:35	2.101

Source: Plant Process Laboratory – 2022.

Table 6
Characteristics of the ion-exchange unit effluent

Parameter	Quantity
pH	6.700
Specific conductivity, us/cm	18.700
Total hardness (as mg/L $CaCO_3$), mg/L	1.000
Hydrogen carbonate (as mg/L $CaCO_3$), mg/L	2.000
Sulfates, mg/L	<1.000
Chlorides, mg/L	<1.500
Silver, mg/L	<0.002
Aluminum, mg/L	<0.020
Arsenic, mg/L	<0.008
Barium, mg/L	<0.001
Beryllium, mg/L	<0.0003
Bismuth, mg/L	<0.020
Boron, mg/L	0.491
Calcium, mg/L	0.400
Cadmium, mg/L	<0.001
Cerium, mg/L	<0.020
Cobalt, mg/L	<0.002
Chromium, mg/L	<0.004
Copper, mg/L	<0.003
Iron, mg/L	0.030
Potassium, mg/L	0.140
Lithium, mg/L	0.013
Magnesium, mg/L	0.030
Manganese, mg/L	0.007
Molybdenum, mg/L	<0.004
Sodium, mg/L	2.690
Nickel, mg/L	<0.002
Phosphorus, mg/L	<0.060
Lead, mg/L	<0.010
Antimony, mg/L	<0.008
Selenium, mg/L	<0.020
Silica, mg/L	0.180
Tin, mg/L	<0.007
Strontium, mg/L	0.002
Titanium, mg/L	<0.010
Zinc, mg/L	0.009

Source: Plant Process Laboratory – 2022.

Table 7
Comparative table of the physical–chemical parameters from the ion-exchange unit effluent and Peruvian laws on water quality for human consumption

Parameter	Ionic exchange unit effluent	Peruvian drinking water law
pH	6.700	6.50–8.50
Specific conductivity, us/cm	18.700	1,500.000
Total hardness (as mg/L $CaCO_3$), mg/L	1.000	500.000
Sulfates, mg/L	<1.000	250.000
Chlorides, mg/L	<1.50	250.000
Aluminum, mg/L	<0.020	0.200
Arsenic, mg/L	<0.008	0.010
Barium, mg/L	<0.001	0.700
Boron, mg/L	0.491	1.50
Cadmium, mg/L	<0.001	0.003
Chromium, mg/L	<0.004	0.050
Copper, mg/L	<0.003	2.000
Iron, mg/L	0.030	0.300
Manganese, mg/L	0.007	0.400
Molybdenum, mg/L	<0.004	0.070
Sodium, mg/L	2.690	200.000
Nickel, mg/L	<0.002	0.020

Parameter	Ionic exchange unit effluent	Peruvian drinking water law
Lead, mg/L	<0.010	0.010
Antimony, mg/L	<0.008	0.020
Selenium, mg/L	<0.020	0.010
Zinc, mg/L	0.009	3.000

Source: Plant Process Laboratory 2022 – Peruvian Drinking Water Laws.

Table 8
Composition of the treated waters (tap water) with the addition of 5.00 ppm $B(OH)_3$. Columns previously regenerated by HCl and NaOH and rinsed with water (Case 1), rinsed with $NaHCO_3$ and water (Case 2) [7]

Parameter	Case 1 5.00 ppm $B(OH)_3$	Case 2 5.00 ppm $B(OH)_3$
Calcium, meq/L	0.760	2.000
Sulfates, meq/L	0.550	0.470
Chlorides, meq/L	0.610	0.610
Potassium, meq/L	0.080	0.080
Magnesium, meq/L	0.840	0.820
Nitrates, meq/L	0.010	0.010
Sodium, meq/L	0.900	0.910
Hydrogen carbonate, meq/L	0.770	1.250
Fluo, meq/L	0.005	0.005
Total phosphate, meq/L	0.000	0.000
Boron, mg/L	0.010	0.010

Source: Adapted from the article "Boron Removal from Drinking Water with a Boron-Selective Resin: Is the Treatment Really Selective?" Water Research, 2000, Elsevier Science Ltd.

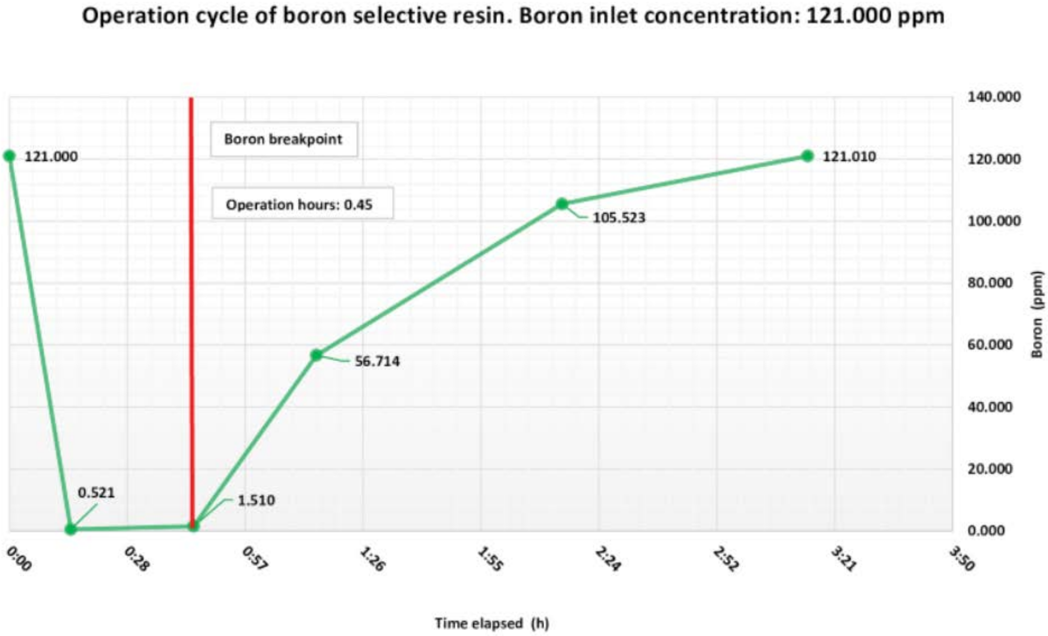

Fig. 4. Graph depicting the operation cycle of boron-selective resin – permeate water of the first pass reverse osmosis.

Table 9
Values of physical and chemical properties of the desalinated seawater supplied by the Escombreras Desalination Plant, as well as values of boron concentration levels in treated effluent after 84–92 h of operation

Date	pH (–)	Conductivity (us/cm)	Calcium (mg/L)	Magnesium (mg/L)	Chloride (mg/L)	Sodium (mg/L)	Boron (mg/L)
August 2021	8.35	760.000	23.270	1.480	170.950	102.170	0.912
January 2022	8.45	615.000	17.600	1.620	150.010	92.950	1.013
Average	8.40	665.000	20.440	1.550	160.480	97.560	0.963
Treated effluent							0.500

Source: Adapted from the article "Ion-Exchange Resins to Reduce Boron in Desalinated Seawater for Irrigation in Southeastern Spain", Agronomy, June 2022, MDPI.

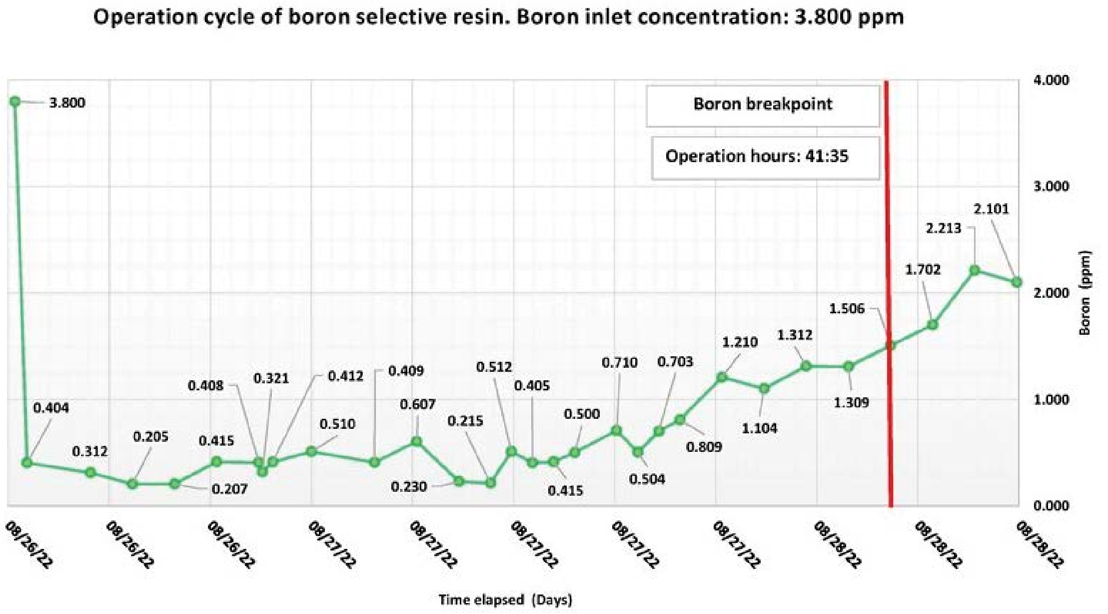

Fig. 5. Graph depicting the operation cycle of boron-selective resin – permeate water of the second-pass reverse osmosis.

Laboratory and pilot-scale research (Tables 8 and 9) has shown that boron removal technology by ion-exchange is a promising technology as a polishing stage in the water treatment for reuse purposes, both for human consumption and the irrigation of boron-sensitive crops.

4. Conclusion

- It is concluded that the ion-exchange process for boron removal using a boron-selective resin (N-methylglucamine functional group) represents an important technical alternative as a polishing stage for boron reduction in water for reuse purposes.
- At a boron inlet concentration of 3.800 ppm, an average boron removal efficiency of 87.080% was achieved.
- A higher operating cycle (41.35 h) was achieved at a lower boron inlet concentration (3.800 ppm) than at a higher boron inlet concentration (121.00 ppm), obtaining in this case a lower operating cycle (0.45 h).
- The results showed a reduction of 75.00% and 93.75% in the concentration of hydrogen carbonate and sulfates, respectively, in the ion-exchange-treated effluent, which is presumed to be due to the occurrence of ion-exchange competition on the active site of the amine group of the N-methylglucamine resin regarding the boron. More studies are required to validate this behavior.
- The results of the physical–chemical parameters analyzed in the treated effluent of the ion-exchange unit are below the Peruvian drinking water law limits. Therefore, the water could be used for human consumption after a remineralization process.

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