We are IntechOpen, the world's leading publisher of Open Access books
Built by scientists, for scientists

6,500
Open access books available

176,000
International authors and editors

190M
Downloads

154
Countries delivered to

Our authors are among the
TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Boron Removal by Donnan Dialysis According Doehlert Experimental Design

Ikhlass Marzouk Trifi, Lasâad Dammak, Lassaad Baklouti and Béchir Hamrouni

Abstract

Donnan dialysis is one of the membrane processes. It is based on the cross-exchange of ions having the same electric charge through an ion-exchange membrane. The removal of boron by Donnan dialysis was studied in this work. First, a preliminary study was conducted to determine the experimental field of operating parameters using two membranes (AFN and ACS). Then, a full factorial design was applied to investigate the influence of the operating parameters and their interactions on the boron removal. Response surface methodology using Doehlert design was adopted to predict the optimal conditions. This approach via experimental designs is more efficient than the conventional optimization approach (the "one-at-a-time" method) which is time-consuming and requires a large number of experiments.

Keywords: boron removal, Donnan dialysis, response surface methodology, experimental design, anionic exchange membranes

1. Introduction

Sources of boron in the environment are mainly natural or even anthropogenic. It can be found mainly in the form of boric acid or borate salts. The presence of boron compounds in water increases in a continuous and parallel way to industrial development. In fact, boron is used in a wide range of industrial applications such as glass and ceramic industry to produce borosilicate glass, insulation, fiberglass, and flame-retardant fiberglass [1]. Due to its high concentration of boron, natural water is often unsuitable for human consumption or agricultural use. Therefore, the harmful effects of boron on living organisms also increase, especially on plants, since boron manifests an important micronutrient-toxic boron duality [1]. Moreover, boron is a unique micronutrient in which overdose and underdose of boron supply cause toxicity and deficiency symptoms in plants, respectively. The level of boron in irrigation water exceeding 1 mg/L can affect the yield of sensitive crops (e.g., avocado and citrus fruits) [1]. Irrigation water with a very low boron content is required for certain metabolic activities, but when boron concentrations are increased to 4 mg/L [1], plants become poisoned, manifesting as yellow spots on leaves and fruits, and their decomposition speeds up and they die [2]. According to the World Health Organization (WHO), drinking water should have a boron content of less than 0.3 mg/L because humans may also be poisoned by excessive boron levels [3, 4]. Consequently, several studies have focused on boron removal such as adsorption [5, 6], electrocoagulation [7, 8], or membrane processes namely electrodialysis [9, 10], reverse osmosis [11, 12], nanofiltration [13, 14], microfiltration [15], ion-exchange [15, 16], membrane distillation [17], and Donnan dialysis which was the subject of this study [18, 19]. This membrane process referring to FG Donnan [20] uses ion-exchange membranes allowing cross-exchange of ions to separate or concentrate ionic species. Modern Donnan dialysis uses ion-exchange membranes to separate the two solutions that are involved in the transport process. With no external electric potential difference applied across the membrane, Donnan dialysis uses an ion-exchange membrane. Donnan dialysis uses the counterdiffusion of two or more ions through an ion-exchange membrane to achieve separation. Donnan dialysis is one of the easiest and most inexpensive membrane techniques. The chemical potential gradient between the constituents of two solutions separated by a membrane is what propels the process. When Donnan equilibrium is reached, the process of Donnan dialysis is complete. It involves the stoichiometric exchange of counterions, or ions with the same charge, over an ion-exchange membrane [21].

There is frequently no theoretical model or one that is quite sophisticated that links certain controllable variables (factors) to a response. In this situation, empirical data should be used to determine the link between the causes and the response. Box and Wilson first presented the Response Surface Methodology (RSM), a group of mathematical and statistical tools whose goal is to evaluate situations like the one given using an empirical model. The RSM was used to explore the removal of boron by Donnan dialysis. Herein, the removal of boron by Donnan dialysis was investigated using RSM approach. RSM is a useful method for process optimization when a number of independent factors and their interactions have an impact on the desired results. With RSM, multiple variables are tested concurrently with the least amount of trials possible in accordance with unique experimental designs built on factorial designs. This technology has the advantage over conventional approaches in that it requires less time and money. The goal of RSM is to characterize the behavior of a dataset in order to make statistical predictions. It is a set of statistical and mathematical tools enabling the adjustment of experimental data to a theoretical model expressed by a polynomial equation. The simultaneous variation of a large number of operating parameters at once, the reduced number of experiments, the detection of interactions between factors, and achieving the highest precision are all advantages of the RSM for optimization [22]. Recently, many statistical experimental design methods have been employed in optimization. Among them, Doehlert designs stand out, compared to other designs such as the central composite design or Box-Behnken design, by the reduced number of experiments and the possibility to assign a large or a small number of levels to the chosen variable. Indeed, this design presents variables with different numbers of levels. The variable with the stronger effect should be the variable with the highest levels if you want to learn as much as you can about the system.

Doehlert designs are also more efficient in mapping space: adjoining hexagons can fill a space completely and efficiently since the hexagons fill space without overlap. Moreover, Doehlert design is distinguished by a low ratio between the number of coefficients and the number of experiments. Thus, it can be considered as more efficient than the central composite design or Box-Behnken design [22]. Investigations of boron removal by Donnan dialysis were carried out considering four operating factors, i.e. the counterion concentration in the receiver compartment, the boron concentration, the pH of the feed compartment, and the type of the anionic-exchange membrane. The effect of these factors and their interactions were evaluated using the full factorial design. The Donnan dialysis was then optimized using the Response Surface Methodology based on the Doehlert design.

2. Methods and materials

2.1 Membranes

In the Donnan dialysis process, two membranes have been used, which are Neosepta® AFN and Neosepta® ACS (supplied by Alstom). Before any measurement, it is necessary to condition the samples to stabilize their physicochemical properties and to eliminate any impurities that could come from their manufacturing process. **Table 1** shows the properties of the used membranes determined according to the standard NF X 45-200 [23]. The water content was determined by the Mettler-Toledo moisture thermo balance device. The water content was calculated by Eq. (1):

$$WC(\%) = \frac{W_h - W_d}{W_h} \times 100 \tag{1}$$

where W_h is the mass of the hydrated membrane, Wd is the mass of the dried membrane, and WC(%) is the water content percentage. The water content is the difference in mass between the hydrated membrane (which has been immersed in the proper stabilization content and slightly compressed to remove the surplus liquid) and the dried membrane (which has been dried at 140°C until membrane mass stabilization indicates that all of the water has been removed).The mean value of 10 measurements at different locations using a 1−μm resolution Käfer Thickness Dial Gauge is the dry-state membrane thickness.

The ion-exchange capacity (in meq. of functional sites per gram of dry membrane or per cm^3 of wet membrane) was determined following the French standard NF X 45-200 [23].

In order to prepare the samples for the Donnan dialysis operations, the samples had to be conditioned before any measurement could be made. This was done primarily to eliminate contaminants from the production process and to stabilize their physical-chemical properties. French standard NF X 45-200 was followed in the conditioning process.

Membranes	ACS	AFN
Thickness (μm)	150	120
Water Content (%)	18.9	47.8
Ion-Exchange Capacity (meq/g)	1.85	3.00

Table 1.
Properties of the two membranes used.

2.2 Donnan dialysis (DD)

The Donnan dialysis is a method of membrane separation in which identically charged ions are exchanged between two solutions via an ion-exchange membrane [24–26]. The chemical potential gradient acts as the driving force in Donnan dialysis; anions are exchanged stoichiometrically through an anionic-exchange membrane, and the procedure is only complete if the Donnan equilibrium is attained. Since the electroneutrality is maintained, the feed should exchange the same number of anions with the receiver compartment in the opposite direction [19, 27, 28].

Figure 1 indicates the schematic flow of Donnan dialysis. The apparatus is used to study Donnan dialysis's removal of boron. It consists of a cell with feed and receiver compartments divided by an anion-exchange membrane inside a thermoregulated water bath. A peristaltic pump with two identical heads and a speed variator that allows for varied flow rates is used to pump the solutions through the cell. Through the use of two stirring rods with variable speeds, the hydrodynamic conditions on either side of the membrane can be changed. Two removable sections constructed of polymethylmetacrylate (plexiglass) make up the dialysis cell. It consists of four pieces that are connected by three threaded rods made of stainless steel. Supports provide the centering. The two tubes that make up the two compartments at the center are symmetrical. Each compartment has three threaded holes that provide support for inserting boxes. The membrane forms a seal by sandwiching itself between these two compartments. The feed and the receiver compartment were supplied, through a peristaltic pump, with NaCl and a containing boron solution, respectively. The used membranes were AFN and ACS. Boron concentrations were determined after 7 hours of treatment by Donnan dialysis for each experiment. By reacting the samples with azomethine-H and then measuring the absorbance at 420 nm with a UV-visible spectrophotometer, the samples' boron concentration was determined [29]. A linear concentration between 1 and 4 mg/L was found. Higher concentration samples were diluted to fit the previously mentioned linearity range.

Boron removal rate was determined by Eq. (2):

$$Y(\%) = \frac{C_0 - C_e}{C_0} \times 100 \tag{2}$$

With C_0 and C_e are the initial boron and equilibrium concentrations, respectively.

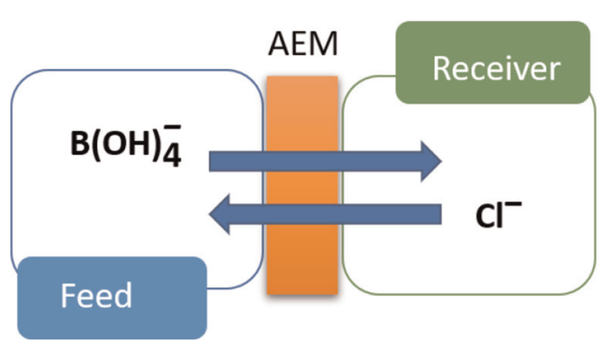

Figure 1.
Schematic flow of Donnan dialysis.

2.3 Optimization process

To identify the most significant and influencing parameter, a full factorial design was performed first, followed by an RSM design based on the Doehlert matrix. NemrodW® was the program employed in this study. The practical use of the Experimental Research Methodology (experimental designs) depends on the NemrodW® program.

3. The preliminary study

The definition of each factor's levels must be done with great care since if the domain is either too tiny or too large, the mathematical models might no longer work. Because of this, it is advised to do a preliminary study to help determine the appropriate high and low levels for each element. To establish the bounds of each parameter and better pinpoint the optimal value, a preliminary study was carried out as a phase in the parameters' pre-optimization process.

3.1 The pH effect in the feed compartment

The pH effect of the feed compartment is studied by varying the initial pH of the feed solution from 9.5 to 12.5. **Figure 2** shows the Boron removal rate under different initial pH values for a counterion concentration of 0.1 mol/L, an initial boron concentration of 50 mg/L, and a stirring speed of 500 rpm.

Due to its effect on the transfer of boron from the feed compartment to the receiver compartment, the effect of pH was first investigated. According to **Figure 2**, at a pH of 11.5 the AFN membrane removed the most boron (45%), while the ACS membrane removed 17%. This can be explained by the two species of boron that occur in aqueous solutions at various pH levels, which are the boric acid $B(OH)_3$ in diluted aqueous solutions below pH 7 and the metaborate anion $B(OH)_4^-$ at pH 10 [30, 31]. However, above a pH of 11.5, the presence and competition with OH are likely to have

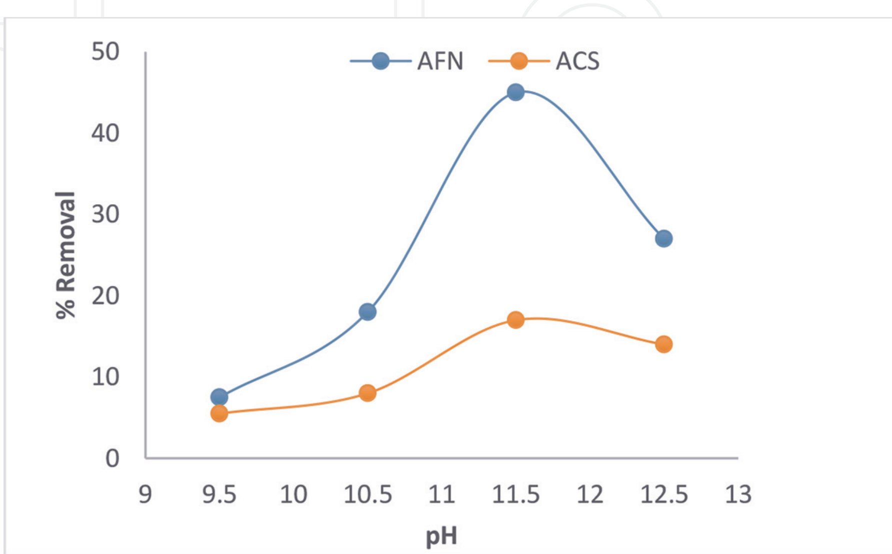

Figure 2.
Influence of pH on the removal rate of boron.

an impact on the transport of boron, which reduces boron removal because the hydroxyl ion transport is preferred because OH has much higher mobility than boron. In reality, the boron transfer process involves three steps. First, the boron in the feed solution is exchanged with ions or ionizable groups of the anion-exchange membrane. The second step involves the transport of boron across the membrane to the receiving solution side. In the third step, the boron is transported into the receiver solution following an exchange with the counterions to guarantee electroneutrality [32, 33]. Therefore, it can be said that for the two used membranes, the highest boron transport was attained at pH = 11.5 in this case.

3.2 Concentration of chloride in the receiver compartment effects performance

One of the factors influencing the elimination of boron through the anionic-exchange membrane during the Donnan dialysis procedure is the chloride concentration. To study the effect of this parameter, the concentration of the Cl counterion was varied from 0.01 mol/L to 0.05 mol/L in the receiver compartment for a boron concentration fixed at 50 mg/L. **Figure 3** displays the impacts of the two membranes' receiver compartment's chloride concentration.

According to **Figure 3**, the flux of boron ions through anion-exchange membranes increases with the increase of chloride concentration from 0.01 to 0.5 mol/L. At 0.01 mol/L of counterion, the boron removal rate reaches only 32% and 13% for AFN and ACS, respectively. At 0.5 mol/L of the concentration of Cl, the removal efficiency increases to 58% for AFN and 38% for ACS. The improvement in the cross-ion transfer between Cl and boron necessary to maintain electroneutrality is explained by the fact that the concentration gradient of the counterions grows.

For the two membranes, it appears that the improvement in the boron removal in the feed compartment, as shown by an improvement in the exchange's kinetics, is related to the increase in the concentration of counterions in the receiver compartment. In fact, it is known that ion exchange is faster when the concentration of counterions is higher in the receiver compartment [34–36].

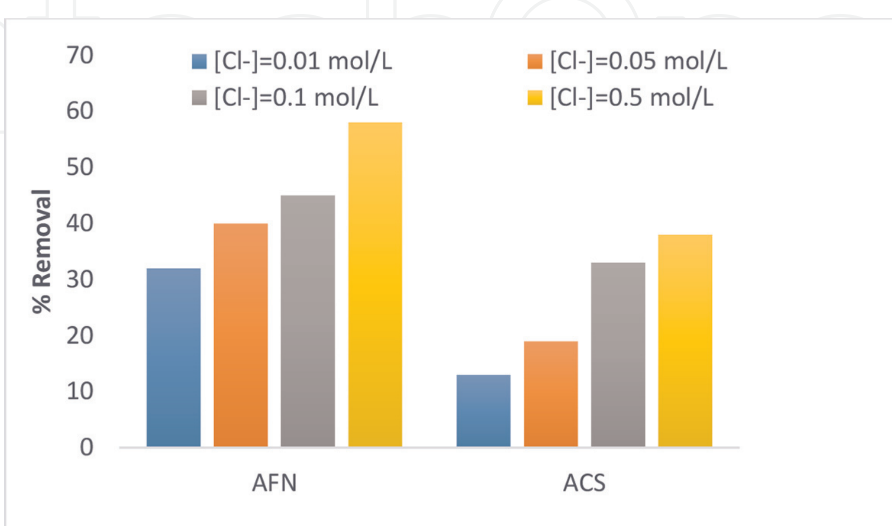

Figure 3.
Concentration of chloride in the receiver compartment effects performance.

3.3 Boron concentration effect

The elimination by Donnan dialysis is significantly influenced by the amount of boron in the feed compartment. Under these circumstances, the receiver compartment's Cl- concentration is 0.5 mol/L, the feed compartment's pH is 11.5, and the boron concentration rises from 5 mg/L to 100 mg/L. **Figure 4** presents the findings.

According to **Figure 4**, the improvement in cross-ion transfer between Cl^- and $B(OH)_4^-$ helps to maintain the gradient concentration of boron at a high level. The elimination was 40% for AFN and 17% for ACS at the feed compartment's lowest boron content (25 mg/L). When the boron content is raised to 100 mg/L, their elimination is improved to 75% with AFN and to 48% with ACS. A similar result was reported by Tor [37].

3.4 Membranes choice

According to the results of **Figures 3** and **4**, the boron removal rate by Donnan dialysis depends significantly on the AEM properties. Therefore, the most effective membrane is AFN since it allows to reach 75% after 7 hours of treatment against 48% for ACS membrane. According to Akretche, (i) a high exchange capacity boosts the selectivity between monovalent and multivalent anions due to the higher repulsion charge, (ii) a high thickness reduces diffusion, resulting in a lower ions flux, and (iii) a high water content can reduce permselectivity and encourage the penetration of bulky ions [38]. In actuality, the AFN membrane exhibits the largest water content, the highest ion-exchange capacity, and a higher permeability to monovalent than bivalent anions. On the other hand, the ACS has the lowest permeability due to its large thickness and low water content. The works of Ayyildiz [31], who reported that the removal of boron by Donnan dialysis is more successful using the AFN membrane, support this conclusion. AFN membrane has been chosen as the subject of the following investigation.

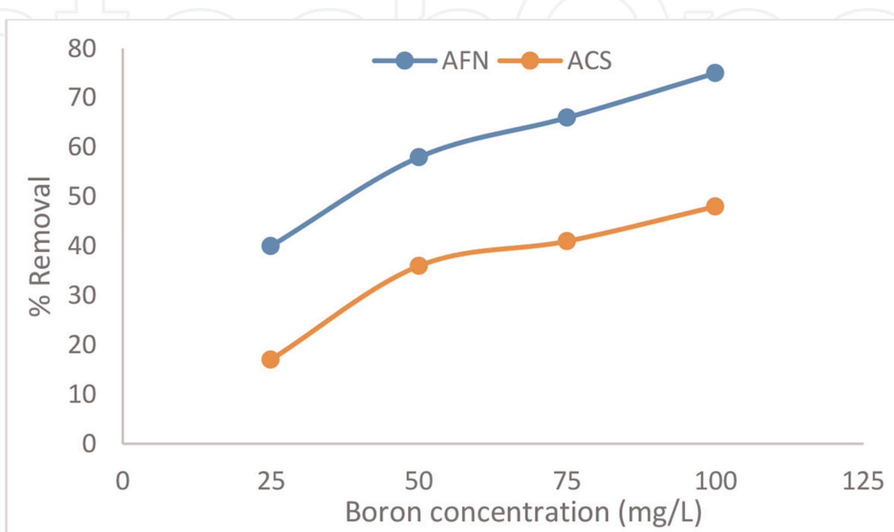

Figure 4.
Boron concentration effect.

4. Full factorial design

To ascertain the impact of these variables and how they interact with one another on the removal of boron by Donnan dialysis, the full factorial design was used. We were able to establish the experimental field and the level that had to account for every element thanks to the preliminary study. The starting boron concentration, counterion concentration, and feed compartment pH were the three variables that were selected. In order to more clearly define the examined response (boron removal efficiency), restrictions are imposed. The membrane AFN was used in the Donnan dialysis procedure.

A full factorial design was used to assess how operating parameters affected the removal of boron by Donnan dialysis. **Table 2** displays the experimental ranges and factors level. For each of the three component designs specified in the study, a full factorial matrix made up of eight distinct experiments was used. A linear polynomial model with interaction is used to model the experimental response related to a factorial design (see Eq. (3)):

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (3)$$

where Y is the experimental response, X_i denotes the coded variable, bi denotes the estimation of factor i's principal effect on the response Y, and b_{ij} denotes the estimation of factor i and factor j's interaction effect on the response Y.

The coefficients of the model were estimated in accordance with the findings in **Table 3**, and it was discovered that (see Eq. (4)):

Factors	Symbol	Range and levels	
Coded variable X_1	[B]	−1	1
Concentration of boron (mol/L)		25	100
Coded variable X_2	$[Cl^-]$	−1	1
Concentration of counter-ion (mg/L)		0.1	0.5
Coded variable X_3	pH	−1	1
pH of solution		10.5	12.5

Table 2.
Experimental range and factors level studied in the factorial design.

No	X_1	X_2	X_3	Y_B(%)exp	Y_B(%)cal
1	−1	−1	−1	19.9	20.2
2	+1	−1	−1	27.7	27.4
3	−1	+1	−1	30.7	30.4
4	+1	+1	−1	36.5	36.8
5	−1	−1	+1	36.9	36.6
6	+1	−1	+1	39.9	40.2
7	−1	+1	+1	41.9	42.2
8	+1	+1	+1	45.3	45.0

Table 3.
Full factorial design matrix.

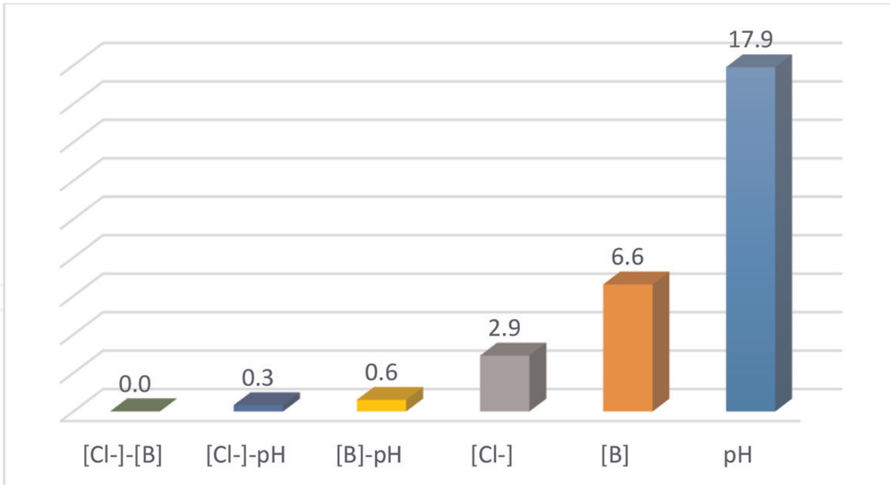

Figure 5.
Pareto analysis of the removal of boron.

$$Y(\%) = 34.85 + 2.50\ X_1 + 3.75\ X_2 + 6.15\ X_3 - 0.20\ X_1X_2 - 0.90\ X_1X_3 - 1.15\ X_2X_3 \quad (4)$$

The different coefficients of the polynomial model (Eq. (4); R^2 = 0.999) were determined, which represented the effects and interactions of the various investigated factors. The Pareto analysis (**Figure 5**) allows to evaluate the contribution of each parameter on the response according to the equation (Eq. (5)):

$$P_i = \left(\frac{b_i^2}{\sum b_i^2}\right)^2 \times 100 \quad (5)$$

The three investigated factors have a favorable impact on the observed behavior, i.e., increasing them improved boron removal. In contrast to the 17.9% they contributed to pH, and their contributions to the examined response were just 6.6% for boron concentration and 2.9% for chloride concentration. Thus, two factors—pH and boron concentration—can have a significant impact on the elimination. The solution pH coefficient's positive value indicates that boron removal was enhanced. This is brought on by the existence of, which, high pH levels, becomes the dominant species. The elimination of boron by Donnan dialysis is moderately affected by both the counterion concentration and the boron concentration. Therefore, the feed compartment's pH is the most crucial variable.

5. Doehlert design

In this investigation, the optimum condition was found using the Response Surface Methodology (RSM) in accordance with the Doehlert design. By evenly dispersing the experimental points within the space-filling of the variables, Doehlert's method is created. N = k^2 + k + 1 is the total number of experiments for k factors. Fifteen tests were in total, three of which were replicated in the central field [39, 40]. The initial boron concentration, feed compartment pH, and receiver compartment counterion

Factors	Coded symbol	Range and levels		
		−1	0	+1
Concentration of counter-ion (mol/L)	X_1	0.1	0.3	0.5
pH of the solution	X_2	10.5	11.5	12.5
Initial concentration of boron (mg/L)	X_3	25	62	100

Table 4.
Experimental range and levels of the factors.

concentration were all factors that were examined. According to the preliminary study, these parameters' upper and lower limits were established. To get the most information out of the system, it is typically preferable to use the variable with the significant effect as the variable with the highest levels. The experimental field of the factors under investigation is shown in **Table 4**.

An experiment conducted in the Doehlert domain is able to predict, at any point in the experimental domain, the value of an answer by estimating the coefficients of a second-order function [40]. The selected model uses a polynomial equation (see Eq. (6)) to describe the predicted values of the responses Y:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (6)$$

The estimated principal effect of factor i is denoted by the letters b_i, the estimated second-order effects by the letters b_{ii}, the estimated interactions between factors i and j by the letters b_{ij}, and the coded variable by the letters X_i.

The regression coefficients (R^2) and the percentage absolute errors of deviations (AED) between experimental and calculated results must be considered for model validation. The AED was calculated from Eq. (7):

$$AED\ (\%) = \frac{100}{N}.\left|\frac{Y_{exp} - Y_{theo}}{Y_{exp}}\right| \quad (7)$$

where Y_{exp} and Y_{theo} are the responses obtained from experiments and from the model, respectively. N is the number of points at which measurements were carried out. A model was considered valid if $R^2 > 0.7$ and AED $< 10\%$ [41].

For boron removal optimization, Response Surface Methodology via Doehlert design was used with membrane AFN. To optimize the factors, 15 experiments involving three variables were evaluated using a Doehlert experimental design (**Table 5**).

No	X_1	X_2	X_3	$Y(\%)_{Exp}$	$Y(\%)_{Cal}$
1	1.0	0.000	0.000	87.3	87.4
2	−1.0	0.000	0.000	81.5	81.4
3	0.5	0.866	0.000	51.4	51.6
4	−0.5	−0.866	0.000	16.1	15.9
5	0.5	−0.866	0.000	21.1	20.7

No	X_1	X_2	X_3	$Y(\%)_{Exp}$	$Y(\%)_{Cal}$
6	−0.5	0.866	0.000	50.7	50.6
7	0.5	0.287	0.816	65.2	64.9
8	−0.5	−0.287	−0.816	35.9	36.2
9	0.5	−0.287	−0.816	40.1	39.9
10	0.0	0.577	−0.816	46.6	46.5
11	−0.5	0.287	0.816	62.6	62.7
12	0.0	−0.577	0.816	39.5	39.6
13	0.0	0.000	0.000	84.2	84.2
14	0.0	0.000	0.000	84.2	84.2
15	0.0	0.000	0.000	84.2	84.2

Table 5.
Doehlert Matrix and obtained results.

Using the experimental results from **Table 5**, the second-order polynomial equation was fitted to the data appropriately and the coefficients were presented in Eq. (8):

$$Y = 84.2 + 3.01X_1 + 18.81X_2 + 9.12X_3 + 0.20X_1^2 - 65.90X_2^2 - 37.40X_3^2 - 2.38b_{12}X_1X_2 - 010\ X_1X_3 - 12.20X_2X_3 \quad (8)$$

Based on the obtained results, the coefficients show that pH of the feed compartment had a significant effect on boron removal (b_2 = 18.81). As a second influencing factor, boron concentration (b_3 = 9.12) was taken into consideration. However, chloride concentration had a less significant effect on boron removal (b_1 = 3.11). The feed compartment's pH and boron concentration (b23 = −12.20) had the most significant interaction and had an adverse impact on Donnan dialysis's ability to remove boron.

Although they had a small impact on the removal of boron by Donnan dialysis, the interactions between the chloride concentration and the feed compartment's pH (b_{12} = −2.38) and the concentration and boron concentration (b_{13} = −0.10) were not.

The regression coefficient (R^2) and the percentage of absolute errors of deviation (AED) were used to evaluate the model's validity. The regression coefficient (R^2) is better than 0.7, and the percentage of absolute errors of deviation (AED) (%) = 0.425% was less than 10%.

The contour plots (curve of constant response) are used to describe how boron is removed by Donnan dialysis. The response surface is represented in a contour plot as a two-dimensional plane where all points with the same response are joined to form contour lines with constant responses. Typically, a surface plot shows a three-dimensional image that could give a clearer idea of the response. To show the relationship between two factors and a response, use contour plots. The graph shows values of the pH for combinations of the $[Cl^-]$ and $B(OH)_4^-$. The $[Cl^-]$ and $B(OH)_4^-$ values are displayed along the X- and Y-axes, while contour lines and bands represent the response value Y. The obtained plots are illustrated in **Figure 6**.

At a constant boron content of 62 mg/L, the first plot displays the combined fluctuation of chloride concentration and pH. The contour plots' form demonstrates that, only at pH 11.5 when chloride concentration increases from 0.1 mg/L to 0.3 mg/L,

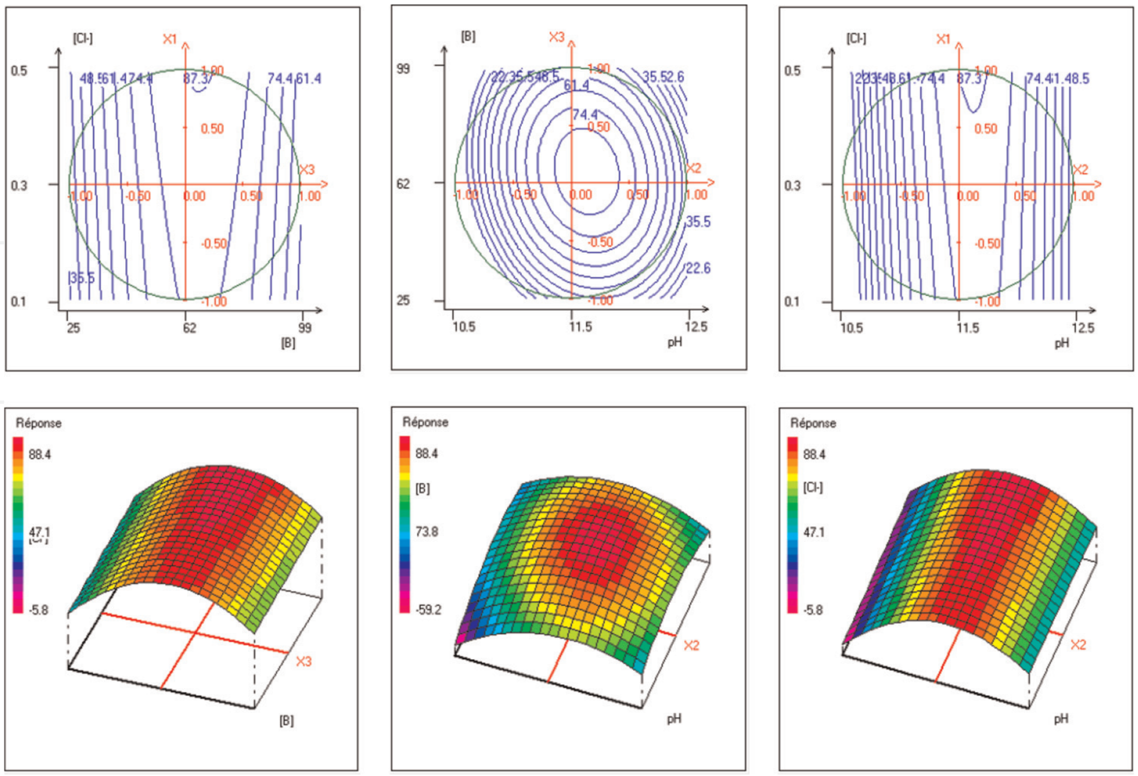

Figure 6.
Contour plots and three dimensions plots.

boron removal improves. This was attributable to the many boron forms that can exist in aqueous solutions at various pH levels. At higher pH levels, the $B(OH)_4^-$ is the dominating species. However, beyond pH 11.5, the presence and competition with OH-, which reduces the removal of boron, are likely to have an impact on the transport of boron. Therefore, it can be said that pH 11.5 produced the largest boron transfer.

The variation in boron concentration and pH at a fixed chloride concentration of 0.3 mol/L is shown in the second plot. The shape of these iso-response curves, which are concentrated in the center of the domain, demonstrates that the pH has a significant impact on the elimination of boron. This was anticipated because boron removal was positively influenced by the pH and chloride content. The variation of chloride and boron concentrations with a constant pH of 11.5 is depicted in the third plot. According to the contour plots, the rate of boron removal improves only when the chloride concentration is increased from 0.1 mg/L to 0.3 mg/L around the boron concentration of 62 mg/L.

The optimum values are 66 mg/L for the concentration of boron, 0.5 mol/L for the concentration of chloride, and 11.6 for the pH of the feed compartment. These conditions led to a maximum removal of boron of 88.8%. A replicate three times of experiment was conducted in the optimum conditions in order to verify the efficiency of predicting values. The coefficient of repeatability is less than 1%, so it can be concluded that the removal of boron by Donnan dialysis is reproducible.

6. Conclusion

The influence of operating parameters on boron removal by Donnan dialysis was investigated using two different membranes, AFN and ACS. For an initial boron concentration of 100 mg/L, a pH of 11.5 in the feed compartment and 0.5 mol/L of Cl-, the counterion, in the receiver compartment, 75% of boron removal rates for AFN and 48% for ACS were recorded. The influence and interactions of these parameters were then evaluated using a full factorial design. It was concluded that pH is the most influent in the elimination of boron. The Response Surface Methodology by Doehlert enabled the identification of the ideal working conditions for the removal of boron, which reached an efficiency of 88.8% using an AFN membrane, which were [B] = 66 mg/L, pH = 11.6 and [Cl-] = 0.5 mol/L. Compared to the conventional "one-at-a-time" approach, using the Response Surface Methodology to identify the optimal conditions for 13.8% can be seen of as a good option.

Acknowledgements

The researchers would like to thank the ICMPE/University Paris Créteil Est for funding the publication of this project.

Author details

Ikhlass Marzouk Trifi[1]*, Lasâad Dammak[2], Lassaad Baklouti[3] and Béchir Hamrouni[1]

1 Desalination and Water Treatment Research Laboratory, Faculty of Sciences of Tunis, University of Tunis El Manar, Tunis, Tunisia

2 Institute of Chemistry and Materials Paris-Est (ICMPE), Paris-Est University, Thiais, France

3 Department of Chemistry, College of Sciences and Arts at Al Rass, Qassim University, Saudi Arabia

*Address all correspondence to: ikhlassmarzouk@gmail.com

IntechOpen

© 2023 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

[1] Brdar-Jokanovic M. Boron toxicity and deficiency in agricultural plants. International Journal of Molecular Sciences. 2020;**21**:1424-1444. DOI: 10.3390/ijms21041424

[2] Pandey A, Khan MK, Hakki EE, Gezgin S, Hamurcu M. Combined boron toxicity and salinity stress—An insight into its interaction in plants. Plants. 2019;**8**:364-386. DOI: 10.3390/plants8100364

[3] Guler E, Kaya C, Kabay N, Arda M. Boron removal from seawater: State of the art review. Desalination. 2015;**356**:85-93. DOI: 10.1016/j.desal.2014.10.009

[4] Chruszcz-Lipska K, Winid B, Madalska GA, Macuda J, Lukanko L. High content of boron in curative water: From the Spa to industrial recovery of borates? (Poland as a case study). Minerals. 2021;**11**:8-26. DOI: 10.3390/min11010008

[5] Lyu J, Zhang N, Liu H, Zeng Z, Zhang J, Bai P, et al. Adsorptive removal of boron by zeolitic imidazolate framework: Kinetics, isotherms, thermodynamics, mechanism and recycling. Separation and Purification Technology. 2017;**187**:67-75. DOI: 10.1016/j.seppur.2017.05.059

[6] Ting TM, Nasef MM, Aravindan D, Rosslan IFN, Ruslan N. Selective removal of boron from industrial wastewater containing high concentration of ammonia by radiation grafted fibrous adsorbent in fixed bed column. Journal of Environmental Chemical Engineering. 2021;**9**:104993. DOI: 10.1016/j.jece.2020.104993

[7] Yilmaz A, Boncukcuoğlu R, Kocakerim M. A quantitative comparison between electrocoagulation and chemical coagulation for boron removal from boron-containing solution. Journal of Hazardous Materials. 2007;**149**:475-481. DOI: 10.1016/j.jhazmat.2007.04.018

[8] Chen M, Dollar O, Shafer-Peltier K, Randtke S, Waseem S, Peltier E. Boron removal by electrocoagulation: Removal mechanism, adsorption models and factors influencing removal. Water Research. 2020;**170**:115362. DOI: 10.1016/j.watres.2019.115362

[9] Turek M, Dydo P, Bandura-Zalska B. Boron removal from dual-staged seawater nanofiltration permeate by electrodialysis. Desalination Water Treatment. 2009;**10**:60-63. DOI: 10.5004/dwt.2009.782

[10] Guesmi F, Louati I, Hannachi C, Hamrouni B. Optimization of boron removal from water by electrodialysis using response surface methodology. Water Science and Technology. 2020;**81**:293-300. DOI: 10.2166/wst.2020.105

[11] Ali Z, Al Sunbul Y, Pacheco F, Ogieglo W, Wang Y, Genduso G, et al. Defect-free highly selective polyamide thin-film composite membranes for desalination and boron removal. Journal of Membrane Science. 2019;**578**:85-94. DOI: 10.1016/j.memsci.2019.02.032

[12] Li Y, Wang S, Song X, Zhou Y, Shen H, Cao X, et al. High boron removal polyamide reverse osmosis membranes by swelling induced embedding of a sulfonyl molecular plug. Journal of Membrane Science. 2020;**597**:117716. DOI: 10.1016/j.memsci.2019.117716

[13] Kumar R, Ahmed M, Ok S, Garudachari B, Thomas JP. Boron selective thin film composite

nanofiltration membrane fabricated via a self-assembled trimesic acid layer at a liquid–liquid interface on an ultrafiltration support. New Journal of Chemistry. 2019;**43**:3874-3883. DOI: 10.1039/C8NJ05670F

[14] Lan N, Wang KY, Weber M, Maletzko C, Chung TS. Investigation of novel molecularly tunable thin-film nanocomposite nanofiltration hollow fiber membranes for boron removal. Journal of Membrane Science. 2021; **620**:118887. DOI: 10.1016/j. memsci.2020.118887

[15] Alharati A, Swesi Y, Fiaty K, Charcosset C. Boron removal in water using a hybrid membrane process of ion exchange resin and microfiltration without continuous resin addition. Journal of Water Process Engineering. 2017;**17**:32-39. DOI: 10.1016/j. jwpe.2017.03.002

[16] Hussain A, Sharma R, Minier-Matar J, Hirani Z, Adhama S. Application of emerging ion exchange resin for boron removal from saline groundwater. Journal of Water Process Engineering. 2019;**32**:100906-100915. DOI: 10.1016/j. jwpe.2019.100906

[17] Eryildiz B, Yuksekdag A, Korkut S, Koyuncu İ. Performance evaluation of boron removal from wastewater containing high boron content according to operating parameters by air gap membrane distillation. Environmental Technology & Innovation. 2021;**22**: 101493. DOI: 10.1016/j.eti.2021.101493

[18] Turek M, Bandura-Zalska B, Dydo P. Boron removal by Donnan dialysis. Desalination and Water Treatment. 2009;**10**:53-59. DOI: 10.5004/ dwt.2009.711

[19] Bryjak M, Duraj I. Anion-exchange membranes for separation of borates by Donnan dialysis. Desalination. 2013;**310**: 39-42. DOI: 10.1016/j.desal.2012.07.025

[20] Freeth FA. Frederick George Donnan, 1870-1956. Biographical Memoirs of Fellows of the Royal Society. 1957;**3**. DOI: 10.1098/rsbm.1957.0003

[21] Marzouk I, Dammak L, Chaabane L, Hamrouni B. Optimization of chromium (VI) removal by Donnan dialysis. American Journal of Analytical Chemistry. 2013;**4**:306-313. DOI: 10.4236/ajac.2013.46039

[22] Marzouk Trifi I, Trifi B, Djamel A, Hamrouni B. Simultaneous removal of nitrate and nitrite by Donnan Dialysis. Environmental Engineering and Management Journal. 2020;**20**(6): 973-983

[23] French Standard NF X 45-200. Membranes Polymers Échangeuse d'Ions. Paris, France: AFNOR; 1995

[24] Strathmann H. Ion-Exchange Membrane Separation Processes. 1st ed. Amsterdam: Elsevier Science; 2004

[25] Nouri S, Dammak L, Bulvestre G, Auclair B. Studies of the crossed ionic fluxes through a cation-exchange membrane in the case of Donnan dialysis. Desalination. 2002;**148**:383-388. DOI: 10.1016/S0011-9164(02)00734-8

[26] Mokrani S, Dammak L, Bulvestre G, Auclair B. Experimental and theoretical studies of the crossed ionic fluxes through a cation-exchange membrane. Journal of Membrane Science. 2002;**199**: 147-160. DOI: 10.1016/S0376-7388(01) 00692-5

[27] Wisniewski J, Rozanska A. Donnan dialysis with anion exchange membranes as a pretreatment step before electrodialytic desalination.

Desalination. 2006;**191**:210-218. DOI: 10.1016/j.desal.2005.06.038

[28] Rozanska A, Wiśniewski J, Winnicki T. Donnan dialysis with anion-exchange membranes in a water desalination system. Desalination. 2006;**198**:236-246. DOI: 10.1016/j.desal.2006.02.006

[29] Rodier J. L'analyse de l'eau. 9th ed. Paris: Edition Dunod; 2009

[30] Zohdi N, Mahdavi F, Abdullah LC, Choong TSY. Removal of boron from aqueous solution using magnetic carbon nanotube improved with tartaric acid. Journal of Environmental Health Science and Engineering. 2014;**12**:3-15. DOI: 10.1186/2052-336X-12-3

[31] Ayyildiz HF, Kara H. Boron removal by ion exchange membranes. Desalination. 2005;**180**:99-108. DOI: 10.1016/j.desal.2004.12.031

[32] Sato K. Effects of the feed solution concentration on the separation degree in Donnan dialysis for binary systems of amino acids. Journal of Membrane Science. 2002;**196**:211-220. DOI: 10.1016/S0376-7388(01)00598-1

[33] Hichour M, Persin F, Sandeaux J, Gavach C. Fluoride removal from waters by Donnan dialysis. Separation and Purification Technology. 2000;**18**:1-11. DOI: 10.1016/S1383-5866(99)00042-8

[34] Veerman J. The effect of the NaCl bulk concentration on the resistance of ion exchange membranes—Measuring and modeling. Energies. 2020;**13**:1946-1972. DOI: 10.3390/en13081946

[35] Amang DN, Alexandrova S, Schaetzel P. Mass transfer characterization of Donnan dialysis in a bi-ionic chloride–nitrate system. Chemical Engineering Journal. 2004;**99**: 69-76. DOI: 10.1016/j.cej.2003.11.030

[36] Wisniewski J, Rozanska A, Winnicki T. Removal of troublesome anions from water by means of Donnan dialysis. Desalination. 2005;**182**:339-346. DOI: 10.1016/j.desal.2005.02.032

[37] Tor A, Çengeloğlu Y, Ersöz M, Arslan G. Transport of chromium through cation-exchange membranes by Donnan dialysis in the presence of some metals of different valences. Desalination. 2004;**170**:151-159. DOI: 10.1016/j.desal.2004.04.002

[38] Akretche D, Kerdjoudj H. Donnan dialysis of copper, gold and silver cyanides with various anion exchange membranes. Talanta. 2000;**51**:281-289. DOI: 10.1016/S0039-9140(99)00261-1

[39] Hosni N, Zehani K, Djebali K, Mazaleyrat F, Bessais L, Maghraoui-Meherzi H. Experimental design approach for the synthesis of 3D-CoFe2O4 nanoflowers thin films by low-cost process. Materials Chemistry and Physics. 2020;**255**:123493-123503. DOI: 10.1016/j.matchemphys.2020.123493

[40] Trifi B, Marzouk Trifi I, Kouass S, Zahraa O, Alatrache A. Gliding arc plasma treatment of levofloxacin using experimental design approach. Clean - Soil, Air, Water. 2023;**00**:1-13. DOI: 10.1002/clen.202200364

[41] Nde Bup D, Abi CF, Tenin D, Kapseu C, Tchiegang C. Optimisation of the cooking process of sheanut kernels (vitellaria paradoxa gaertn.) using the Doehlert experimental design. Food and Bioprocess Technology. 2012;**5**:108-117. DOI: 10.1007/s11947-009-0274-z