

Arsenic and Boron Removal by Electrocoagulation with Aluminum Electrodes

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Received: 1 April 2015 / Accepted: 13 October 2015 / Published online: 7 November 2015
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Abstract Some boron deposits in Turkey contain considerable amounts of arsenic. Arsenic in the boron deposits can create a great risk due to its environmental effects on surface and underground waters. Water sources containing more than a certain concentration of boron and arsenic have negative effects on plants, animals and human beings. Thus, their removals are necessary. In this paper, the removal of arsenic (As) and boron (B) from aqueous solutions by electrocoagulation using aluminum (Al) electrode material was investigated. Specifically, the effects of initial pH, initial arsenic and boron concentrations and operating time on the performance of EC were investigated. Experiments were carried out with different pHs ranging from 2 to 8. Results showed that initial pH was highly effective on the efficiency and high removal efficiencies were observed at initial pH of 4.0 for both arsenic and boron. Initial arsenic and boron concentration affected the removal efficiencies. Arsenic removal efficiency decreased with increasing boron concentration, and boron removal efficiency decreased with

increasing arsenic concentration. The results also showed that boron ions prevented to arsenic removal and boron ions competed with arsenic ions. This situation led to the low arsenic and boron removal.

Keywords Aluminum electrode · Arsenic removal · Boron removal · Electrocoagulation

1 Introduction

In Turkey, which has the most abundant sources of boron in the World, commercial boron reserves are colemanite, tincal and ulexite. All of known borate reserves in Turkey are contained in Bigadiç in West Anatolia, and Sultancıyırı, Kestelek and Emet-Kırğa regions. Although boron minerals such as colemanite, uleksit and borax whose economical values are high and dominant, there are some other minerals accompanied with these boron minerals or not being boron. Borate minerals observed in Turkey's reserves are mainly Ca, Ca–Na and Na–Mg borates. It is known that there is rarely Sr borate in Kırka, and there are Ca–As and Sr borates in Emet region. The mineralogy of Emet borate beds has high of orpiment and celestite as well as realgar and sulfur due to rarity of Ca–As and Sr borates [1].

Kutahya-Emet region colemanites include approximately 0.1–5 % of arsenious compounds, mainly realgar (As₂S₂) and orpiment (As₂S₃) minerals [2]. Because of the fact that boric acid is being produced from the colemanite concentrates obtained from the Emet (Espey-Hisarçık) mines by means of sulfuric acid at the boric acid plant founded in the Espey region, the amount of the arsenic in the colemanite concentrates creates some problems related to both the marketability of the product and the damage of the tailings to the environment [3].

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In underground and surface waters, a lot of elements such as arsenic and boron reach at the values over normal standards depending on fast oxidization, high resonance and their mobility. They cause the changing of water quality, as regards agricultural irrigation and provision of freshwater. Therefore, rather objectable results have been occurred. In addition to arsenic in take via respiration in the media which is rich of arsenic, in case of prolonged consumption of freshwater with rich arsenic concentration, the fact that it impacts human life (health) in negative ways has been of global importance. Arsenic is a cause for skin, liver, lung and kidney or bladder cancer; it is a big headache to the nation [4]. According to the World Health Organization (WHO), the values more than 0.01 mg L^{-1} arsenic and 0.03 mg L^{-1} boron in drinkable and portable waters are very dangerous for human health [5].

When the ease of transfer among water, air and soil was considered, the fact that arsenic and boron whose mobility are high and contained in underground and surface water in a great amount is very dangerous. So, the control of arsenic and boron in water is vital. Nowadays, a number of research has been done about boron removal by electrocoagulation [6–9]. And electrocoagulation has been successfully used to treat arsenic waste waters, with removal efficiencies as high as 90–99% [10–13]. But the number of studies about both arsenic and boron removal with electrocoagulation is very limited [14]. In this study, the removal of arsenic and boron from aqueous solution containing arsenic and boron by the method of electrocoagulation, a process from which a high proportionate removal yield obtained and the use of field has been extended in recent times, will be studied. Electrocoagulation is fairly advantageous process, because it doesn't require chemical substance before and after purification and small space and costs of low investment,

The aim in electrocoagulation process is to provide the removal of arsenic and boron as much as possible from waters with arsenic and boron in optimum pH intervals under the light of the data which will be obtained from parameters such as initial arsenic and boron concentration.

1.1 EC Process Description

Treatment of wastewater by EC has been practiced for most of the 20th century with limited success and popularity [15, 16]. Using electricity to treat water was first proposed in UK in 1889, and the application of electrolysis in mineral beneficiation was patented by Elmore in 1904 [17]. Electrocoagulation is by now a well-known process and could be a good choice for water treatment because of the following reasons: (1) the amount of required chemicals is much lower, (2) a smaller amount of sludge is produced, (3) no mixing of chemicals is required, (4) coagulant dosing as well required over potentials can be easily calculated and controlled, and (5) operating

costs are much lower when compared with most of the conventional technologies [18].

Electrocoagulation consists of an in situ generation of coagulants by an electrical dissolution of iron or aluminum electrodes. The metal ions generation takes place at the anode; hydrogen gas is released from the cathode. The hydrogen gas would also help to float the flocculated particles out of the water, and therefore, the process sometimes is named as electroflocculation [19]. Typically, aluminum, iron, carbon, mild steel, graphite and titanium plates are used as electrodes in the electrocoagulation process. Iron and aluminum have been reported to be very effective and successful in pollutant removal at favorable operating conditions. In the case of aluminum, main reactions are as follows:

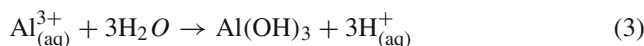
Anode:



Cathode:



In the solution:



Amorphous $\text{Al}(\text{OH})_{3(\text{s})}$ flocks having large surface areas formed in aluminum anode are active in rapid adsorption of soluble organic compounds and trapping of colloidal particles and are easily separated from aqueous medium by sedimentation or H_2 flotation [20]. However, depending on the pH of the aqueous medium, other ionic species such as $\text{Al}(\text{OH})_2^{2+}$, $\text{Al}_2(\text{OH})_2^{4+}$ and $\text{Al}(\text{OH})_4^{-}$ may also be present in the system [21].

2 Experimental

2.1 Materials

In this study, boron and arsenic concentrations were chosen high because boron and arsenic concentrations from boron industry wastewater were quite high. All chemicals were of analytical grade and supplied by Merck and Panreac. Wastewater samples used in the experiments were prepared synthetically using $\text{Na}_2\text{B}_4\text{O}_7$ and As_2O_3 . The solution with boron concentration of 1000 mg L^{-1} was prepared by dissolved 17.61 g borax dried at 105°C in distilled water and completed with distilled water to 2L. The same operations were repeated for the solutions with boron concentrations of 250, 500, 2000 and 1000 mg L^{-1} with different $\text{Na}_2\text{B}_4\text{O}_7$ weights. Stock arsenic solutions of 1.32 g L^{-1} were prepared

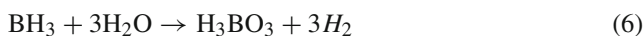
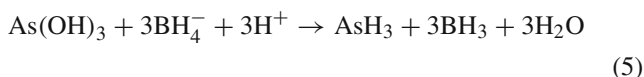


by dissolving arsenic oxide (As_2O_3) in 2N NaOH and then diluted the solution up to 1 L with deionized water. Solutions of lower concentrations were prepared by proper dilution. For the solution with boron concentration of 1000 mg L^{-1} and arsenic concentration of 50 mg L^{-1} , 17.61 g borax was dissolved in 100 mL of arsenic concentration of 1000 mg L^{-1} and completed with distilled water to 2 L. The pH of the solution was adjusted by adding either concentrated NaOH or H_2SO_4 .

2.2 Analytical Methods

The analytical determination of boron was done potentiometrically by means of mannitol, which forms a complex compound with boric acid. For this purpose, boron analysis was carried out as follows: (1) solution pH was adjusted to 7.60 after sample was filtered, (2) 5 g mannitol was added to solution, (3) the solution was titrated with 0.5 N KOH until solution pH became 7.60, and (4) boron amount was calculated from KOH consumption. One milliliter 0.5 N KOH is equivalent to $17.41 \text{ mg B}_2\text{O}_3$ [22].

The concentration of arsenic was determined by an Atomic Absorption Spectrophotometer model Shimadzu A–A 6800 equipped with a hydride generation. Hydride generation is, perhaps, the most popular sample derivation method used for inorganic arsenic detection, since Holak first reported it in 1969 [23]. Initially, it was developed as a method for AAS, whereby sodium or potassium tetrahydroborate (III) is used for arsine production (Eq. 5, 6). The reduction reagents NaBH_4 and KBH_4 have proved to be exceptionally reliable reagents for the conversion of the sample to volatile forms [24]. The hydride generation procedure can be also used for differential determination of As (III) and As (V), based on the fact that As (III) reacts with tetrahydroborate at a higher pH than As (V). Thus, tetrahydroborate is acting as a reductant for As (V) as well as a hydride source. The inclusion of online hydride generation generally increases the sensitivity of detection and reduces the possible interferences from the sample matrix. In this study, sodium tetrahydroborate (NaBH_4) was of analytical grade (Merck) and was dissolved in sodium hydroxide solution just before use.



The removal efficiency of As and B in solution treated by electrocoagulation is calculated as follows:

$$\eta_{\text{As}}(\%) = \frac{C(\text{As})_0 - C(\text{As})_t}{C(\text{As})_0} \times 100 \quad (7)$$

where η_{As} is arsenic removal efficiency and $C(\text{As})_0$ and $C(\text{As})_t$ are the initial arsenic concentration and concentration of arsenic at time t in solution (mg L^{-1}), respectively.

$$\eta_{\text{B}}(\%) = \frac{C(\text{B})_0 - C(\text{B})_t}{C(\text{B})_0} \times 100 \quad (8)$$

where η_{B} is boron removal efficiency and $C(\text{B})_0$ and $C(\text{B})_t$ are the initial boron concentration and concentration of boron at time t in solution (mg L^{-1}), respectively.

2.3 Electrocoagulation Test

The experiments carried out in a 1400-mL (1.4 L) laboratory-scale batch reactor made of Plexiglas. Two groups of alternating electrodes being cathodes and anodes (by six plates of each type) made of aluminum with total area of approximately 1400 cm^2 were arranged vertically. The net spacing between the aluminum electrodes was 0.5 cm. They were treated with the solution of HNO_3 for cleaning prior to use. At the end of run, the electrodes were washed thoroughly with water to remove any solid residues on the surfaces and dried. Electrodes were connected to a digital DC power supply characterized by the ranges 0.54 mA cm^{-2} for current and 0–30 V for voltage in monopolar mode. GW GPC -3060D was used as a power supply. Cell current was measured using Brymen BM–810 multimeter. During the experiments, the electrocoagulation unit was stirred at 150 rpm by a magnetic stirrer (Heidolph MR-3004). The pH and conductivity were measured by a multimeter (WTW, Multiline 340i), which was freshly calibrated by 2 points (4.01, 7.00) before each test. The reactor was fed with 1400 mL of arsenic- and boron-containing solution at the beginning of each run. After each run was timed starting with switching the DC power supply on, the residual arsenic and boron in the samples filtered and taken from the reactor were measured. The analytical determination of boron was done potentiometrically by means of mannitol, which forms a complex compound with boric acid. The analytical determination of arsenic was analyzed by atomic absorption spectroscopy with a hydride generation. In electrocoagulation studies, initial pH, electrolysis time, initial arsenic and boron concentration were used as parameters whose values are given in Table 1.

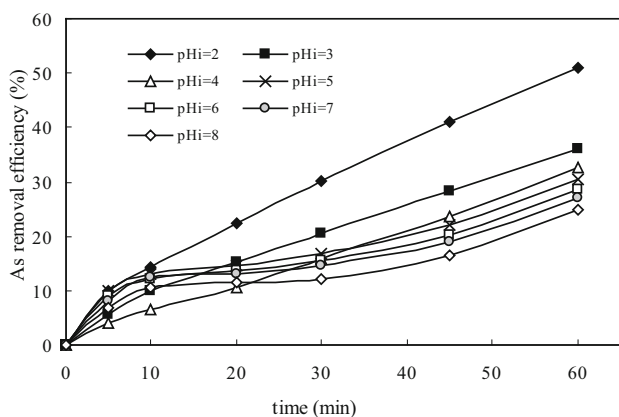
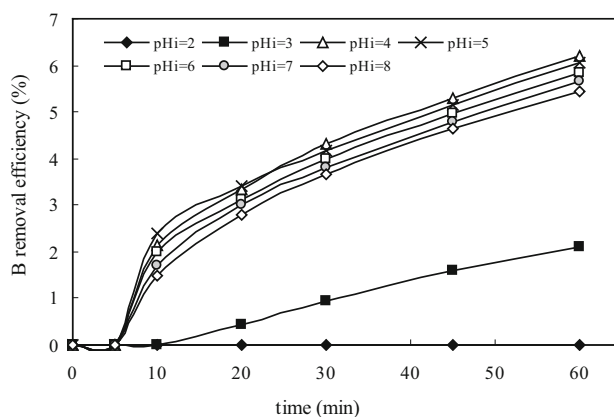
3 Results and Discussion

3.1 Effect of Initial pH

The initial pH is one of the important factors in affecting the performance of electrochemical process, so the pH is continuously observed during the study. To investigate this

Table 1 Experimental parameters

Parameters	Chosen parameter ranges	Constant variables
Initial pH	2.0, 3.0, 4.0, 5.0, 6.0, 7.0 and 8.0	Initial arsenic concentration: 50 mg L ⁻¹ , Initial boron concentration: 1000 mg L ⁻¹ , Current density: 0.54 mA cm ⁻² , Stirring speed: 150 rpm
Arsenic and Boron concentration, mg L ⁻¹	Boron concentration of 250, 500, 1000 and 2000 mg L ⁻¹ and Arsenic concentration of 50 mg L ⁻¹	Initial arsenic concentration: 50 mg L ⁻¹ , Current density: 0.54 mA cm ⁻² , Stirring speed: 150 rpm
	Boron concentration of 500 mg L ⁻¹ and Arsenic concentration of 10, 25, 50 and 100 mg L ⁻¹	Initial boron concentration: 1000 mg L ⁻¹ , Current density: 0.54 mA cm ⁻² , Stirring speed: 150 rpm Initial pH:4, Current density: 0.54 mA cm ⁻² , Stirring speed: 150 rpm

**Fig. 1** Effect of pH on the arsenic removal efficiency (initial arsenic concentration: 50 mg L⁻¹ and initial boron concentration: 1000 mg L⁻¹, current density: 0.54 mA cm⁻², stirring speed: 150 rpm)**Fig. 2** Effect of pH on the boron removal efficiency (initial arsenic concentration: 50 mg L⁻¹ and initial boron concentration: 1000 mg L⁻¹, current density: 0.54 mA cm⁻², stirring speed: 150 rpm)

effect, a series of experiments performed under conditions are given in Table 1.

The results are presented in Figs. 1, 2, 3 and 4. Initial pH of the solution affected the yield of arsenic and boron removal. As seen in Figs. 1 and 2, it was reached at the maximum arsenic removal efficiency at initial pH of 2.0, and it was reached at the maximum boron removal efficiency at initial pH of 4.0. But at initial pH of 2.0, there has been no change of boron removal. In order to understand this situation, arsenic

and boron removal studies were done with solutions containing only arsenic and only boron under the same conditions.

At initial pH values with the range 2.0–8.0, in 50 mg L⁻¹ of arsenic concentration and at current density of 0.54 mA cm⁻², it was reached at the maximum arsenic removal efficiency at initial pH of 4.0 (Fig. 3). In 1000 mg L⁻¹ of boron concentration and at current density of 0.54 mA cm⁻², it was reached at the maximum arsenic removal efficiency at initial pH of 4.0 (Fig. 4). It is thought



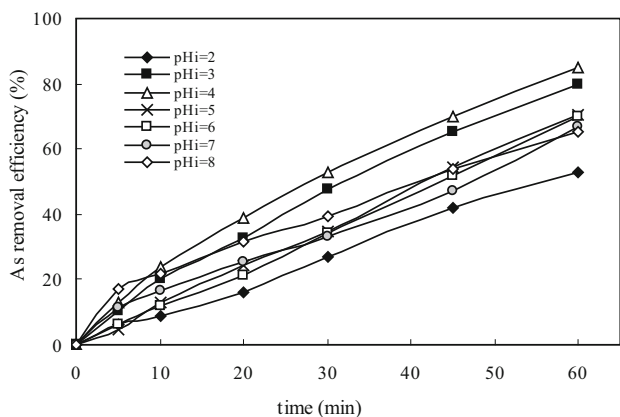


Fig. 3 Effect of pH on the arsenic removal efficiency (initial arsenic concentration: 50 mg L⁻¹, current density: 0.54 mA cm⁻², stirring speed: 150 rpm)

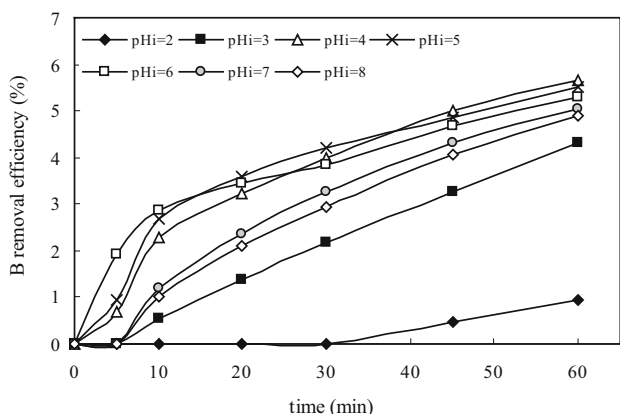


Fig. 4 Effect of pH on the boron removal efficiency (initial boron concentration: 1000 mg L⁻¹, current density: 0.54 mA cm⁻², stirring speed: 150 rpm)

that the reason why both arsenic and boron could not be removed with high efficiency from a solution was that boron ions went into the race with arsenic ions. When initial pH value was adjusted to 4 in solutions containing only arsenic, it was obtained the removal efficiency of 85 %, while in solutions containing both arsenic and boron. Although arsenic removal efficiency was too low, boron removal efficiency was reached at the maximum value. In the same way arsenic removal experiments from solutions containing only arsenic, the lowest arsenic removal efficiency was obtained at initial pH of 2. In the experiments done in solutions containing only boron, boron removal efficiency was not obtained. When arsenic and boron were together in the solution, in the experiment executed with the initial pH adjusted to 2, boron removal was not a change and the value of arsenic removal efficiency was obtained as 50 %, like in the experiment done with solution containing only arsenic. This shows that when boron cannot be removed in the solution, there is no change in the arsenic removal.

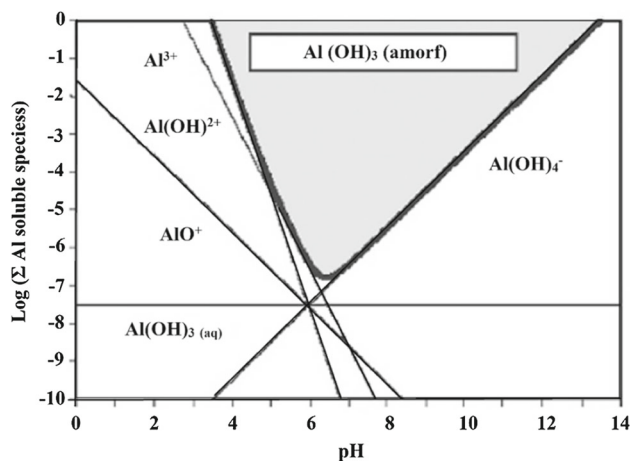


Fig. 5 Activity–pH diagram for Al(III) species in equilibrium with Al(OH)₃ (amorphous)

In experiments the reason why aluminum does not enter into chemical and physical interactions with arsenic and boron at the same time can be explained as the chemical structures of the two elements. Due to their size and charge, it is difficult to remove them from water [25]. Medium pH is an important parameter for boron removal, and as a result of reactions that occur throughout the system, pH is increasing constantly. As a result, aluminum, boron and arsenic change their forms depending on pH in aqueous solution, flock formation is insufficient, and it is prevented to achieve the desired treatment efficiency. Therefore, either the chemicals increased selectivity of boron and arsenic especially should be added to the aqueous medium or arsenic and boron can be removed especially.

Solubility of metal hydroxide species (arsenic, boron and aluminum hydroxides) strongly depends on the chemistry of the continuous media. Removal of arsenic and boron by EC is significantly affected by solution pH. Both initial pH and the elevation of pH during EC affect arsenic and boron solubility and hence their removal. For better understanding of this situation, changes in pH of the solution during the process in the all experiments are observed and presented in Tables 2 and 3. As shown in Tables 2 and 3, the pH value increases as the time of EC process is increased. This happened because of the OH⁻ ion accumulates in aqueous solution during the process.

Arsenic and boron removal depend on both the initial and final pH of solution. For better understanding of this situation, activity–pH diagram of Al(III) species, diagrams of speciation of arsenite and arsenate (As(III) and As(V)) as a function of pH and a diagram of changing of borate ions species depending pH are shown in Figs. 5, 6, 7 and 8, respectively [26].

Figure 5 is the solubility diagram for aluminum hydroxide, Al(OH)₃(s), assuming only mononuclear species. Al(OH)₃ formed at pH 5.0–8.5 interval. The solubility boundary

Table 2 Changes in system pH according to time at different initial pH (current density: 0.54 mA cm⁻², initial boron concentration: 1000 mg L⁻¹ and stirring speed: 150 rpm)

Time (min)	pHi 2.0	pHi 3.0	pHi 4.0	pHi 5.0	pHi 6.0	pHi 7.0	pHi 8.0
0	2.00	3.00	4.00	5.00	6.00	7.00	8.00
1	2.01	3.09	4.25	5.38	6.33	7.09	8.04
3	2.01	3.16	4.88	5.98	6.61	7.13	8.04
5	2.02	3.30	5.10	6.32	6.73	7.18	8.04
7	2.04	3.51	5.16	6.48	6.81	7.21	8.04
10	2.06	3.97	5.28	6.59	6.90	7.23	8.05
20	2.16	4.60	6.23	6.85	7.12	7.32	8.07
30	2.24	4.75	6.56	6.97	7.17	7.41	8.06
45	2.52	5.22	6.82	7.16	7.33	7.48	8.08
60	3.00	6.29	6.96	7.27	7.40	7.55	8.10

Table 3 Changes in system pH according to time at different initial pH (current density: 0.54 mA cm⁻², initial arsenic concentration: 50 mg L⁻¹, initial boron concentration: 1000 mg L⁻¹ and stirring speed: 150 rpm)

Time (min)	pHi 2.0	pHi 3.0	pHi 4.0	pHi 5.0	pHi 6.0	pHi 7.0	pHi 8.0
0	2.00	3.00	4.00	5.00	6.00	7.00	8.00
1	2.09	3.07	4.79	5.40	6.00	7.06	8.00
3	2.11	3.17	5.57	6.05	6.27	7.13	8.01
5	2.13	3.32	6.04	6.37	6.47	7.15	8.01
7	2.15	3.56	6.25	6.60	6.80	7.16	8.01
10	2.17	4.23	6.38	6.75	6.95	7.18	8.02
20	2.28	4.66	6.60	6.87	7.00	7.23	8.03
30	2.42	4.75	6.81	6.94	7.06	7.29	8.06
45	2.74	5.07	6.90	7.03	7.12	7.38	8.10
60	3.29	5.98	7.02	7.09	7.25	7.47	8.15

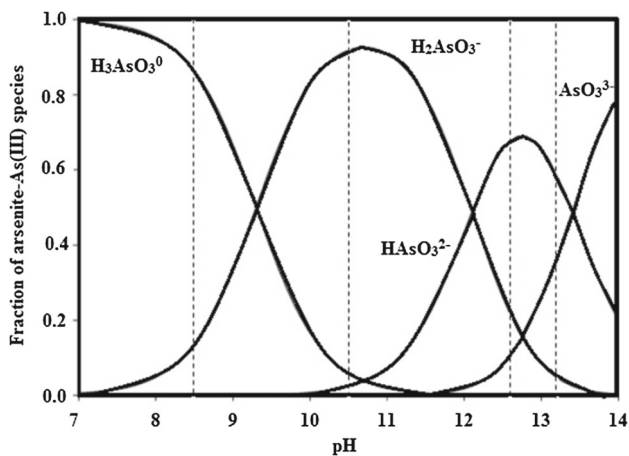


Fig. 6 Distribution of arsenite species as a function of pH

denotes the thermodynamic equilibrium that exists between the dominant aluminum species at a given pH and solid aluminum hydroxide. The minimum solubility occurs at approximately pH 6.5, with solubility increasing as the solution becomes more acidic or alkaline. However, as the aluminum concentration increases, polynuclear aluminum complexes are formed and aluminum hydroxide precipitates, as shown below [27].

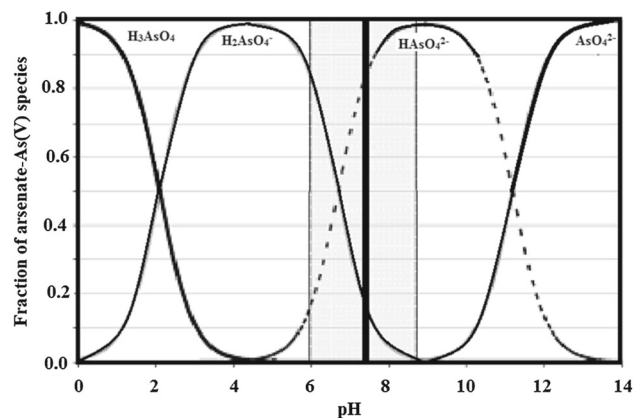
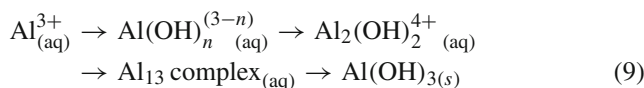


Fig. 7 Distribution of arsenate species as a function of pH



If activity–pH diagram for Al(III) species in equilibrium with Al(OH)_{3(s)} is investigated, it will be seen that dominant Al(III) species is in the form of Al(OH)_{3(s)} at pH 5.0–8.5 interval. Al(OH)_{4(aq)}⁻ forms at the higher pH and Al(OH)_{4(aq)}⁻ is a dissolving form and does not form flocks [28].

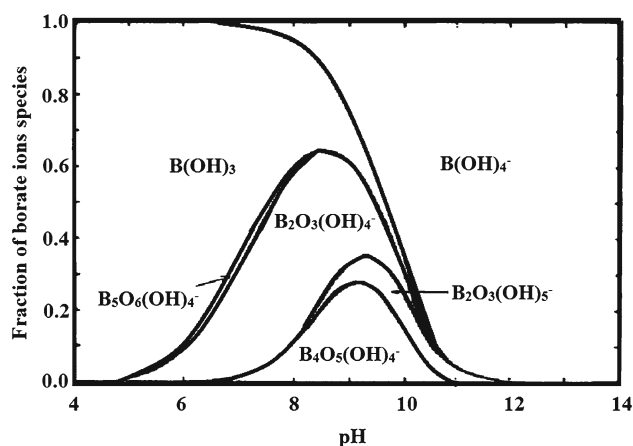


Fig. 8 Changing of borate ions species depending pH in aqueous media

When effect of pH on boron removal was investigated, borate ions species presented in solution must be known. For this purpose, diagram showing borate ions species at varied pH intervals is shown in Fig. 8. As seen in Fig. 8, when solution pH was higher than pH 9.0, borate ions in solution were dominantly $B(OH)_4^-$ form. When solution pH was lower than pH 9.0, borate ions in solution were dominantly $B(OH)_3$ form. The highest boron removal efficiency was obtained at initial pH of 4.0 because final pH reached at over 6.50 at the end of 60-min process and boron was at $B(OH)_3$ form and the formation $Al(OH)_{3(s)}$ was a quite high at this pH.

The chemistry of arsenic is quite complex and interesting, as it can be stable in four oxidation states, continue changing its states and its removal is dependent on pH of the medium, oxidation state and redox potential. In the aqueous environment, inorganic arsenic appears commonly in forms of arsenite (As(III)) and arsenate (As(V)). pH, redox potential and the presence of complexing ions such as ions of sulfur, iron and calcium determine the arsenic valence and speciation. Table 4 contains a summary of the forms of arsenic typically present in water.

In typical drinking water pH ranges of 6–9, the predominant arsenite species is neutral in charge (H_3AsO_3) while arsenate species are present as $H_2AsO_4^-$ and $HAsO_4^{2-}$. In oxygenated waters, As(V) is dominant, existing in an ionic forms either $H_2AsO_4^-$ or $HAsO_4^{2-}$ over the pH range typically encountered in water treatment. Under anoxic conditions, As(III) is stable with nonionic (H_3AsO_3) and anionic ($H_2AsO_3^-$) species dominant below and above pH 9.2 [29].

In this study, the reason for the significant increase in the removal of arsenic ions is the flocks of $Al(OH)_{3(s)}$ consisted during electrolysis. As(V) species are negatively charged above pH 2.1, whereas negatively charged As(III) species do not predominate until pH levels exceed 9.2. Therefore for facilitating the arsenic removal, pre-oxidation is recommended. Inorganic As(III) (arsenite) should be converted to

Table 4 Forms of arsenic in water

Nature	Compound	pH ranges where compound is predominant
Inorganic As(V)	H_3AsO_4	<2
	$H_2AsO_4^-$	<7
	$HAsO_4^{2-}$	>7–12
	AsO_4^{3-}	>12
Inorganic As(III)	H_3AsO_3	<9.2
	$H_2AsO_3^-$	>9.2

As(V) (arsenate). When the As(III) oxidize to As(V), As(V) anions are captured by the $Al(OH)_3$ which are removed by sedimentation or by H_2 flotation. As(V) anions are adsorbed onto the aluminum hydroxide precipitates that are ultimately filtered out of solution. In our study (including both arsenic and boron), final pH reached at 3.00–8.15 at the end of 60-min process (initial pH of 2–8). Because arsenate species are present as $H_2AsO_4^-$ or $HAsO_4^{2-}$ and their molecular charges were negative, they pulled the positively charged metal hydroxides electrostatically, so that arsenic was removed from solution [30].

In all the EC experiments (including arsenic, boron and both arsenic and boron), final pH reached at over 5.98 at the end of 60-min process (initial pH of 3–8). Al^{3+} ions on hydrolysis may generate the aqueous complex $[Al(H_2O)_6]^{3+}$, which is predominant at pH < 4. As the pH (and/or temperature) increases, the hydrated trivalent aluminum ion undergoes hydrolysis, initially forming the $[Al(OH)(H_2O)_5]^{2+}$ ion and then hydroxyl aluminum species, such as $[Al(OH)_2]^+$, $Al(OH)_3$ (insoluble), $[Al(OH)_4]^-$, $[Al_2(OH)_2]^{4+}$ and $[Al(OH)_5]^{-2}$ and eventually hydroxyl polymers such as $[Al_{13}(OH)_{32}]^{7+}$ [31]. Between pH 5 and 6, the predominant hydrolysis products are $[Al(OH)]^{2+}$ and $[Al(OH)_2]^+$; between pH 5.2 and 8.8, the solid $Al(OH)_3$ is most prevalent; and above pH 9, the soluble species $[Al(OH)_4]^-$ is the predominant and the only species present above pH 10. Throughout the pH gradient (pH 4.7 and 10.5), the presence of polymeric aluminum hydroxides would provide significantly larger surface areas for arsenic species adsorption due to their amorphous nature [10].

3.2 Effect of Initial Arsenic and Boron Concentration

To investigate this effect, a series of experiments performed under certain conditions given in Table 1. The results are presented in Figs. 9, 10, 11 and 12. The obtained experimental data showed that increasing initial arsenic concentration decreased arsenic removal efficiency. Arsenic removal efficiency decreased with increasing boron concentration because increasing concentrations of boron blocked the coag-

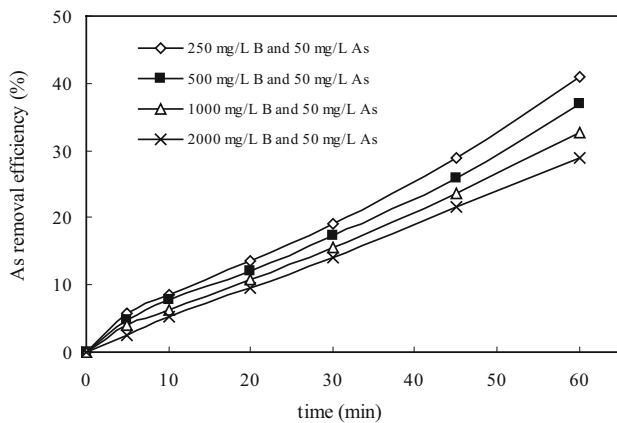


Fig. 9 Effect of initial arsenic and boron concentration on the arsenic removal efficiency (current density: 0.54 mA cm^{-2} , pH: 4.0 and stirring speed: 150 rpm)

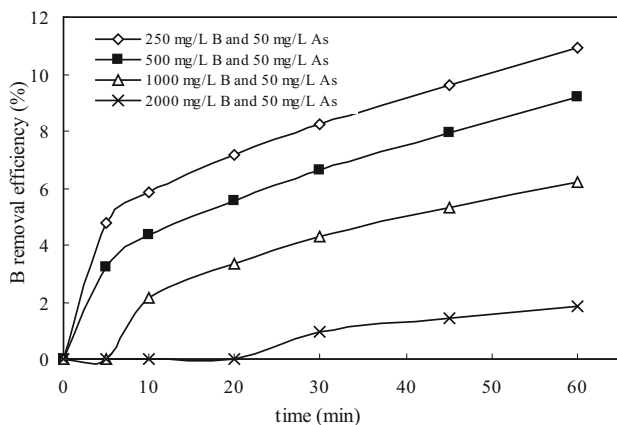


Fig. 10 Effect of initial arsenic and boron concentration on the boron removal efficiency (current density: 0.54 mA cm^{-2} , pH: 4.0 and stirring speed: 150 rpm)

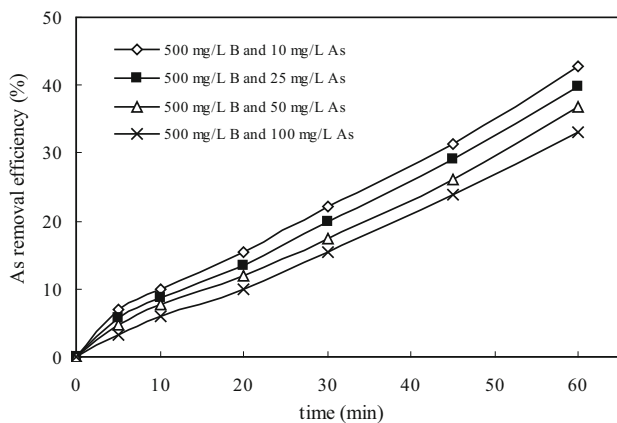


Fig. 11 Effect of initial arsenic and boron concentration on the arsenic removal efficiency (current density: 0.54 mA cm^{-2} , pH: 4.0 and stirring speed: 150 rpm)

ulant to remove the arsenic. More boron concentration means competitive race. Hence, boron prevented arsenic removal. Boron removal efficiency decreased with increasing boron

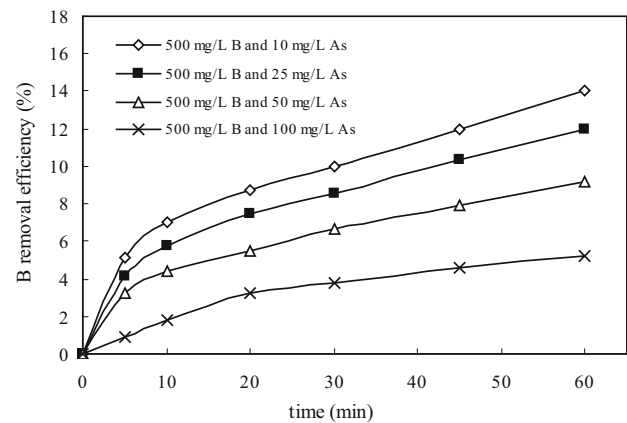


Fig. 12 Effect of initial arsenic and boron concentration on the boron removal efficiency (current density: 0.54 mA cm^{-2} , pH: 4.0 and stirring speed: 150 rpm)

concentration. This can be explained as following; although the same amount Al^{3+} passed to solution at the same current density for all boron concentration, Al^{3+} was insufficient for solutions including higher boron concentration. Arsenic removal efficiency decreased with increasing arsenic concentration. This can be explained as following; although the same amount Al^{3+} passed to solution at the same current density for all arsenic concentration, Al^{3+} was insufficient for solutions including higher arsenic concentration. Boron removal efficiency decreased with increasing arsenic concentration. Increasing the concentration of arsenic caused arsenic to be the winner of the race because arsenic removal for aluminum is easier than boron removal. On account of it can be said that coagulant preferred arsenic to boron.

4 Conclusions

The removal efficiencies of arsenic and boron from aqueous solutions were experimentally done by electrocoagulation technique. The effects of initial pH, initial arsenic and boron concentration and operating time on the extent of arsenic and boron removal were studied in detail and explained. In solutions containing boron concentration of 1000 mg L^{-1} and arsenic concentration of 50 mg L^{-1} at initial pH of 4, current density of 1.54 mA cm^{-2} , stirring speed of 150 rpm, the arsenic removal efficiency was obtained as 32.78% and boron removal efficiency was obtained as 6.20%, whereas, in solutions containing arsenic concentration of 50 mg L^{-1} at initial pH of 4, current density of 1.54 mA cm^{-2} , stirring speed of 150 rpm, the arsenic removal efficiency was obtained as 85.00%. The results showed that boron prevented to arsenic removal and boron ions competed with arsenic ions because in solutions containing boron concentration of 1000 mg L^{-1} at initial pH of 4, current density of

1.54 mA cm⁻², stirring speed of 150 rpm, the boron removal efficiency was obtained as 5.66%. Arsenic removal efficiency decreased with increasing boron concentration, and boron removal efficiency decreased with increasing arsenic concentration. Increasing the concentration of arsenic caused arsenic to be the winner of the race. It can be said that coagulant (Al(OH)₃) preferred arsenic to boron. Aluminum, boron and arsenic change their forms depending on pH in aqueous, flock formation is insufficient, and it is prevented to achieve the desired treatment efficiency. Therefore, either the chemicals increased selectivity of boron and arsenic especially should be added to the aqueous medium or arsenic and boron can be removed especially.

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