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The technical and economical assessment of the different electrode materials for pH recovery in the anaerobic baffled reactor on a lab-scale

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ABSTRACT

This research focuses on the optimization of employed electrode material for pH recovery in a lab-scale anaerobic baffled reactor (ABR). Five types of material included iron, stainless steel, copper, aluminium, and brass were examined for pH revival with the least electricity consumption. The main characteristics including the distance and the contact surface of electrodes, current intensity, voltage, electrolysis time, and consumed electrical energy were investigated. The results showed that the iron electrode can recover a pH unit within a shorter time, and its consuming energy cost in proportion to stainless steel, copper, aluminium, and brass was 0.26, 0.56, 0.43 and 0.82, respectively. For the iron electrode, by augmenting the current density from 3.33 to 10 mA/cm^2, the electrolysis time was reduced from 51.6 to 20.6 min in constant current. While the time variation for stainless steel electrode was more pronounced and decreased from 215.3 to 69.3 min. From the perspective of by-products, copper and brass electrodes would have negative effects on reactor performance by releasing copper with the amounts of 34.6 and 58.3 mg/L, respectively. While the iron electrode will be beneficial for anaerobic bacteria growth with the release of 76.4 mg/L of iron by providing them soluble nutrients. In terms of initial investment and operating cost, the iron electrode is the most optimum option, because its procurement cost in proportion to stainless steel, copper, aluminium, and brass was 0.17, 0.05, 0.29 and 0.07, respectively. According to the obtained results, the application of an electrolysis system using iron electrodes in the clinging state to the baffles at the maximum distance would show the best performance in order to revive the pH in an anaerobic baffled reactor.

Keywords: Anaerobic baffled reactor; Electrolysis process; pH; Electrode material

1. Introduction

In the recent years, various anaerobic reactors have been employed for the wastewater treatment, due to the many advantages of anaerobic digestion [1,2], among which the anaerobic baffled reactor (ABR) has attracted a lot of attention [3]. Various changes have been applied to ABR reactor to improve its performance, including SFABR [4], PABR [5], CABR [6], MABR [7], HMABR [8], ABFR [9], EABR [10,11], IABRGAC [12].

Quick and sudden variation in pH value is one of the factors influencing ABR reactor efficiency. Most of the anaerobic bacteria have their best performance within the pH range of 6.8–7.2 [1,13]. Currently, chemicals are used to control pH value in anaerobic reactors [13], which require attention to a variety of things [14]; while the use of an electrolysis process to adjust the pH value has advantages like the ease of the design and the operation, the simplicity of the equipment needed for the treatment of wastewater, the potential for reducing contaminants, no need for auxiliary chemical [15], shorter retention time, less sludge production [16], and prevention of short-circuit current in up-flow reactors such as ABR and UASB [17,18]. To maintain the pH value, sufficient alkalinity in the wastewater is

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required. The alkalinity is initially in the form of bicarbonate and according to the reaction (1), it is in equilibrium with carbon dioxide in the biogas, at a certain pH value [19,20].

$$OH^- + CO_2 \leftrightarrow HCO_3^- \quad (1)$$

In the electrolysis process, by applying the electric field to the electrodes in aqueous solution, electrolysis of water occurs to maintain a load equilibrium that produces the oxygen gas and the proton (H^+) at the anode and the hydrogen gas and the hydroxide anion (OH^-) at the cathode. Consequently, the pH value near the cathode increases, while the pH reduces near the anode [21]. These reactions occur at the anode and the cathode as following (reactions 2–6) [21–23]:

At anode:

$$M \rightarrow M^{n+} + ne^- \quad (2)$$

$$2H_2O \rightarrow O_{2\,(g)} + 4H^+ + 4e^- \quad (3)$$

At cathode:

$$2H_2O + 2e^- \rightarrow H_{2\,(g)} + 2OH^- \quad (4)$$

$$2H_3O^+ + 2e^- \rightarrow 2H_2O + H_{2\,(g)} \quad (5)$$

$$M^{n+} + ne^- \rightarrow M \quad (6)$$

The reactions (3) and (4) produce proton and hydroxide ions, respectively and creating a pH gradient between the electrodes [21]. By reducing the pH value around the anode according to the reaction (3), the reaction (1) proceeds towards the production of the carbon dioxide and the hydroxide anion. Therefore, the foam formed around the anode during the electrolysis process is due to the production of carbon dioxide gas as a result of the displacement of the balance in the system. After the power outage and the reversal of hydrogen and hydroxide ions into wastewater, due to the low carbon dioxide solubility in accordance with Henry's law, the reaction (1) becomes irreversible. Consequently, the main reasons for increasing pH caused by the electrolysis are the displacement of the bicarbonate balance, hydroxide production and the release of carbon dioxide gas around the anode [19,20,22].

The electrochemical reactions are affected by the electrode material and ions in the electrolyte environment [21]. Selection of the suitable material for the electrode depends on the chemical characteristics of the electrolyte and the target pollutants. So far, iron and aluminium electrodes have been abundantly used for wastewater treatment. In general, it seems that in cases where only treatment efficiency is considered, aluminium is superior to iron. However, the cost of aluminium is higher than iron. Also,titanium electrodes coated with metal oxides, called inert electrodes, are used when calcium and magnesium are high in the wastewater [24]. According to the results of the researches, it is concluded that the iron and aluminium electrodes are desirable to remove COD and turbidity, respectively. On the other hand, by employing the electrodes like stainless steel, the corrosion of the electrode is reduced. It also generates larger bubbles and can float more pollutants [25].

The oxidation of the anode material reduces the electrolysis efficiency. So far, researchers have conducted a variety of studies to select the optimal electrode material [10,23,26–28]. Metal anodes like stainless steel, particularly in rich halide context are prone to corrosion. While steels containing nickel have sufficient strengths, but their shelf life is short [29]. On the other hand,Electrode materials that are less soluble, such as lead dioxide, or metals like gold and platinum, which are not easily oxidized, are very expensive [21]. Although carbonate anodes are cheap, they are very fragile against mechanical and hydraulic stresses [29]. By using titanium coated with mixed metal oxides, the anode corrosion and electrochemical dissolution problems can be reduced [29,30]. However, they are not completely resistant to chemical attacks [21]. As a result of a previous study of the electrolysis process application to improve the anaerobic baffled reactor efficiency [10], it was determined that aluminium and steel electrodes could improve the reactor performance.

The purpose of this study is to optimize the electrode material used in the EABR, focusing on the pH value of the wastewater. To do this, various electrode materials were examined for their technical and economic evaluation to determine that which electrode material is more suitable for pH recovery on a lab scale. The best method for this examination is to use batch environment, like a beaker outside the ABR. The goal of the technical evaluation of each material is to study and compare the required electrolysis time, the electrical power and the consumed electrical energy to revitalize a pH unit by different materials and the constraints that each of them may produce. Also, the target of economic evaluation is to check and compare the supplying cost of each electrode material, the cost of the electricity and the providing cost of the equipment needed for the electrolysis process.

2. Material and methods

2.1. Lab-scale pilot preparation

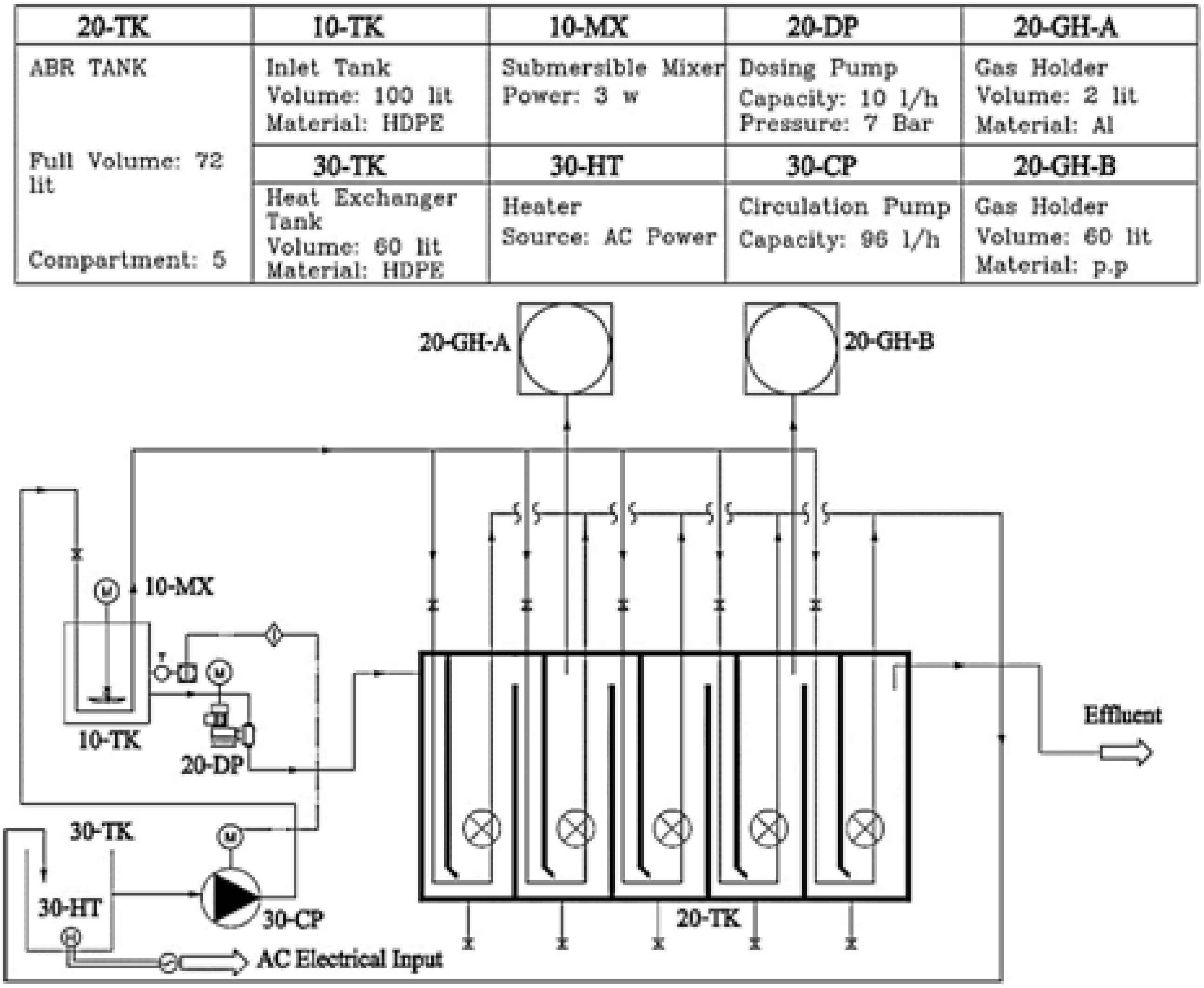
In order to conduct laboratory experiments about the electrolysis process effect on the pH recovery and achieve optimal design and operation conditions, the performance of a semi-industrial anaerobic baffled reactor with 5 chambers and dimensions of 90 cm (length), 20 cm (width) and 40 cm (depth) was investigated with the aim of studying the weaknesses of the reactor and the possibility of using the electrolysis process to improve its performance. For this purpose, samples were taken from different chambers with a volume of 500 cc in the laboratory beakers. Samples were electrolyzed using two identical electrodes with 12 cm length, 6 cm width at distances of 3, 5 and 7 cm, and different contact surfaces of 20, 40 and 60 cm^2 under the batch conditions. The existing materials and the reasons for choosing each one are as follows: copper (high conductivity), iron (a significant effect on coagulation and flocculation), aluminium (low volumetric mass), steel (high oxidation resistance) and brass (alloy). The mixing was carried out in a system with a manual stirrer. The semi-industrial pilot and the laboratory pilot described are shown in Fig. 1 and Fig. 2, respectively.

2.2. Analytical methods

At each part of the laboratory studies, the wastewater was transferred to beakers. In order to come close to real conditions during the organic shock, the initial pH value of samples was adjusted near 6.00 using sulphuric acid and the capability of each electrode material was examined by applying the electricity during the required time to reach a unit of pH increase. After passing a specific time period, the electricity was cut first, and then some samples were taken from the 3 cm depth of water surface for evaluation. At this point, the pH value, the concentration of each released metal in wastewater, the electrolysis duration, the current intensity and the required voltage were measured. In this regard, the pH value and the metal concentration were determined through direct reading using measuring device probe (Hanna, pH 211) and spectrophotometry (ICPS-7500, Shimadzu), respectively. The electrodes were connected to an analogue power supply 0.0–40.0 V and 0.00–1.80 A (TRIO: PR-653) to provide the electrical potential. All the experiments were conducted in accordance with the standard methods [31]. Using the extracted results, the amount of the consumed power and the energy and its cost for each case was computed. It should be mentioned that according to the price of unit mass, density and used dimensions, the final procurement cost of each electrode is calculated and considered as the cost of the initial investment. The results of the experiments were examined from the several perspectives:

The electrode purchase cost

1. The amount of the electricity consumed by each electrode
2. The power consumption of each electrode
3. The specific constraints for each electrode (as described earlier)



20-TK	10-TK	10-MX	20-DP	20-GH-A
ABR TANK Full Volume: 72 lit Compartment: 5	Inlet Tank Volume: 100 lit Material: HDPE	Submersible Mixer Power: 3 w	Dosing Pump Capacity: 10 l/h Pressure: 7 Bar	Gas Holder Volume: 2 lit Material: Al
	30-TK	30-HT	30-CP	20-GH-B
	Heat Exchanger Tank Volume: 60 lit Material: HDPE	Heater Source: AC Power	Circulation Pump Capacity: 96 l/h	Gas Holder Volume: 60 lit Material: p.p

Fig. 1. Piping and instruments diagram of semi-industrial anaerobic baffled reactor.

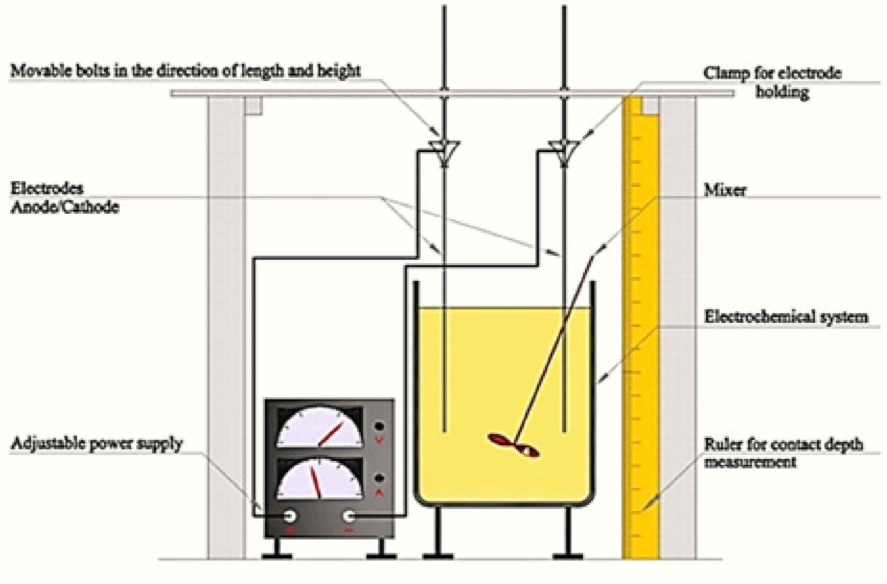


Fig. 2. Batch laboratory pilot of electrolysis system.

2.3. *Characteristics of the wastewater*

In the series of the experiments, synthetic wastewater was used in order to prevent fluctuations in the wastewater properties. The wastewater was prepared using molasses (2.197 g/gCOD), NH_4Cl (0.007 g/gCOD) and KH_2PO_4 (0.0006 g/gCOD). Other qualitative characteristics of the wastewater fed into the reactor are presented in Table 1.

Table 1
Qualitative characteristics of the synthetic wastewater

Characteristics (unit)	Amounts
Temperature (°C)	35±1
pH	7.77±0.04
COD (mg L^{-1})	700±40
TS (mg L^{-1})	1258±21
TDS (mg L^{-1})	633±4

3. Results and discussion

3.1. *The technical assessment*

In order to compare and evaluate the technical characteristics of each selected material, two different conditions have been investigated. The first is the investigation and comparison of each material effect by applying a constant voltage (10.0 V) at different distances (3, 5 and 7 cm) and distinct contact surfaces (20, 40 and 60 cm^2). The second is the study of the materials effect at a constant electrical current intensity (0.20 A). The result of this assessment is the determination of electrical power consumption, which indicates the type and the capacity of the required power supply. This factor is employed to define the cost of the facilities required for supplying electricity of the electrolysis system and, is a part of the initial investment cost, like the electrode purchase cost. In this regard, estimation of the electrolysis time, electrical energy and its cost for each electrolysis state at the constant voltage and the constant current intensity were carried out. The results are presented below.

3.1.1. *The constant voltage*

In this condition, each of the electrode materials generates a different electrical current intensity due to their nature. Therefore, the intensity of the metals separation from the electrodes surface, the rate of the metals dissolution in the wastewater, the amount of the electron transfer, and the required electrolysis time for reviving a pH unit will be different. The results of this state in the mentioned distances (3, 5 and 7 cm) and contact surfaces (20, 40 and 60 cm^2) are shown in Table 2 and Table 3 and illustrated in Fig. 3 and Fig. 4, as well the cost of the electricity was considered 0.02 $ per kWh in Iran.

In order to calculate the power in watts and the electrical energy in kWh/m^3, Eqs. (7) and (8) are used, respectively.

$$P = V \cdot I \tag{7}$$

$$E = \frac{V \cdot I \cdot t}{1000 \times v} \tag{8}$$

where V is the electrical voltage in volts (V), I is the electrical current intensity in amperes (A), t is the electrolysis time in hours (h), and v is the volume of the treated wastewater in cubic meters (m^3).

Changes in the electrical current density (i.e.: the electrical current distributed on the surface of the electrode) is an effective factor on the required time to revive the pH value.

Table 2
The required electrolysis time for a pH unit revival by any electrode materials at 10 V

Electrode material	Contact surface (cm^2)	Current density (mA·cm^{-2})			Current intensity (A)			Electrolysis time (min)		
		3	5	7	3	5	7	3	5	7
Iron	20	11.11	7.52	5.53	0.22	0.15	0.11	20.0	27.1	35.1
	40	11.12	7.51	5.53	0.44	0.30	0.22	20.0	27.2	35.2
	60	11.12	7.53	5.52	0.67	0.45	0.33	19.9	27.0	35.1
Stainless steel	20	7.26	4.69	4.00	0.15	0.09	0.08	120.9	177.5	200.0
	40	7.28	4.69	4.01	0.29	0.19	0.16	120.7	177.4	199.8
	60	7.28	4.70	4.02	0.44	0.28	0.24	120.5	177.2	199.6
Copper	20	7.60	5.91	4.57	0.15	0.12	0.09	36.7	46.7	60.0
	40	7.60	5.90	4.58	0.30	0.24	0.18	36.7	46.7	59.9
	60	7.61	5.90	4.57	0.46	0.35	0.27	36.6	46.6	59.9
Aluminium	20	7.41	4.87	3.69	0.15	0.10	0.07	50.3	71.3	90.5
	40	7.40	4.88	3.69	0.30	0.20	0.15	50.3	71.2	90.4
	60	7.42	4.88	3.69	0.45	0.29	0.22	50.1	71.0	90.3
Brass	20	8.25	6.06	4.38	0.17	0.12	0.09	29.4	38.2	51.0
	40	8.24	6.08	4.38	0.33	0.24	0.18	29.4	38.1	50.9
	60	8.25	6.08	4.40	0.50	0.36	0.26	29.2	38.0	50.7

Table 3
Electrical power, energy and electricity cost needed fora pH unitrevival by anyelectrode materials at 10 V

Electrode material	Contact surface (cm^2)	Electrical power (W)			Electrical energy (kWh·m^{-3})			Electricity cost (\$·m^{-3})		
		3	5	7	3	5	7	3	5	7
Iron	20	2.22	1.50	1.11	1.48	1.36	1.29	0.030	0.027	0.026
	40	4.45	3.00	2.21	2.97	2.72	2.60	0.059	0.054	0.052
	60	6.67	4.52	3.31	4.43	4.07	3.88	0.089	0.081	0.078
Stainless steel	20	1.45	0.94	0.80	5.85	5.55	5.33	0.117	0.111	0.107
	40	2.91	1.88	1.60	11.72	11.09	10.68	0.234	0.222	0.214
	60	4.37	2.82	2.41	17.54	16.66	16.05	0.351	0.333	0.321
Copper	20	1.52	1.18	0.91	1.86	1.84	1.83	0.037	0.037	0.037
	40	3.04	2.36	1.83	3.72	3.67	3.66	0.074	0.073	0.073
	60	4.57	3.54	2.74	5.57	5.50	5.47	0.111	0.110	0.109
Aluminium	20	1.48	0.97	0.74	2.48	2.31	2.23	0.050	0.046	0.045
	40	2.96	1.95	1.48	4.96	4.63	4.45	0.099	0.093	0.089
	60	4.45	2.93	2.21	7.43	6.93	6.66	0.149	0.139	0.133
Brass	20	1.65	1.21	0.88	1.62	1.54	1.49	0.032	0.031	0.030
	40	3.30	2.43	1.75	3.23	3.09	2.97	0.065	0.062	0.059
	60	4.95	3.65	2.64	4.82	4.62	4.46	0.096	0.092	0.089

As it can be seen, by increasing the current density, the required time for the revival of each unit of pH decreases. Since the recovery of the pH value occurs due to the electron transfer and facilitates and accelerates by increasing the current density; therefore, the electrolysis time needed to recover pH can be taken into account in the inverse relationship with the current density.

Increasing the distance and the contact surface of the electrodes with the wastewater, reduces and increases the electrical current intensity, respectively. This is related to the direct association between the electrical resistance of the solution and the distance between the electrodes, its inverse relationship with the electrode's contact surface, and Ohm's law for the electrolyte solutions. Given that, these two effects are divergent, they can neutralize each other, which is important from the perspective of the economics and the energy consumption. By increasing the distance and the contact surface of the electrodes, more control volume of wastewater (i.e.: a volume of wastewater that is affected by the electrolysis between the two cross-sections of the electrode) is exposed to the electrolysis and improves the process efficiency from the operation point of view.

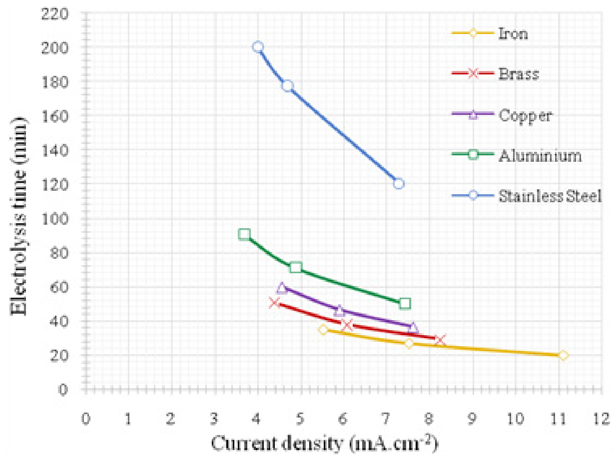


Fig. 3. Test results curve for electrolysis time as a function of current density for all materials at 10 V.

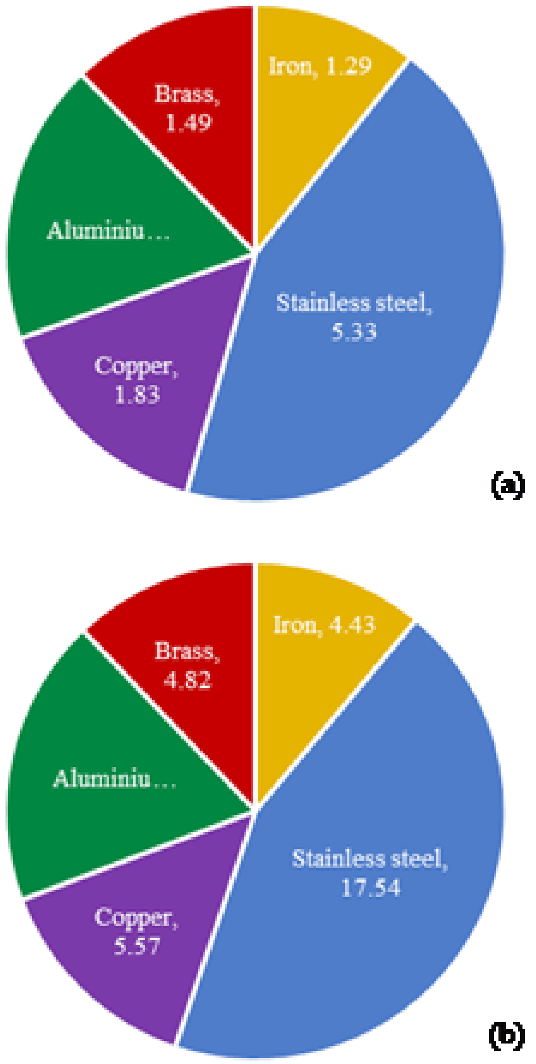


Fig. 4. Minimum (a) and maximum (b) amount of electrical energy consumption for a pH unit revival by all materials at 10 V.

The results are presented in Tables 2 and 3 and Fig. 4 indicate that the iron electrode has the ability to revive a pH unit with a higher electrical power and less electrical energy in a shorter time in comparison to the other materials. After the iron electrode, brass, copper, aluminium and stainless steel electrodes are appropriate, respectively, regards to the electrolysis time and the electrical energy. Thus, it can be seen that the superiority of the aluminium electrode to the stainless steel electrode was correct in the study of Aqaneg had and Moussavi [10], but iron electrode advantages were not mentioned.

3.1.2. The constant current intensity

In this case, for the same contact surface of the electrode materials with the wastewater, the severity of materials separation from electrode surface is equal because of the equivalent current density. Therefore, the study and the comparison of the required time for the pH recovery, the electrical energy and the cost of electricity consumption due to the same conditions for all electrodes is more accurate. At each test stage, the required voltage to generate the desired current intensity (0.20A) was achieved. The results of this state in the mentioned distances (3, 5 and 7 cm) and contact surfaces (20, 40 and 60 cm^2) are presented in Table 4 and Table 5 and shown in Fig. 5 and Fig. 6.

According to the Ohm's law about the electrolyte solutions [32], the voltage and the electrical resistance variations to maintain a constant current intensity are consistent. Thus, in the case of a single electrode material at the same contact surface, by increasing the distance of the electrodes, the required voltage enhances, which is associated with the rising electrical resistance of the solution. Moreover, at the same distance, by augmenting the contact surface of the electrodes with the wastewater, the produced current density and the required voltage are both reduced. The reason for this result is that by increasing the contact surface, the electrical resistance of the solution decreases, and due to the constant current intensity, the voltage reduces equally.

Another important point is that the electrolysis time is shortened by increasing the distance of the electrodes in the constant current densities since more control volume of the wastewater is affected by the electrolysis process. Therefore, at a constant current intensity, with the increase in the contact surface of the electrodes with the wastewater, the electrolysis time will be longer to recover a pH unit, while the electricity consumption will be less.

The results obtained from Fig. 6 indicate that the iron electrode has the ability to increase a unit of pH in a shorter time than other electrodes with the less power and the electrical energy. Regarding the electrolysis time and the electrical power and the energy, brass, copper, aluminium and stainless steel electrodes are placed after iron, respectively. Accordingly, in constant intensity, the iron electrode has the best performance among different electrodes, similar to the constant voltage.

Based on the above tables and figures, it can be found that in both states of the constant voltage and the constant current, the electrical energy consumption for the iron electrode is the lowest compared to other materials. Therefore, it

Table 4
The required electrolysis time for a pH unit revival by any electrode materials at 0.20 A

Electrode material	Contact surface (cm^2)	Current density (mA·cm^{-2})			Voltage (V)			Electrolysis time (min)		
		3	5	7	3	5	7	3	5	7
Iron	20	10.00	10.00	10.00	9.0	13.3	18.1	20.7	20.7	20.5
	40	5.00	5.00	5.00	4.5	6.7	9.1	39.6	39.6	39.6
	60	3.33	3.33	3.33	3.0	4.5	6.0	51.7	51.6	51.5
Stainless steel	20	10.00	10.00	10.00	13.8	21.4	24.9	70.0	69.9	69.7
	40	5.00	5.00	5.00	6.9	10.7	12.5	150.1	150.1	150.0
	60	3.33	3.33	3.33	4.6	7.1	8.3	215.4	215.3	215.1
Copper	20	10.00	10.00	10.00	13.2	16.9	21.9	31.6	31.5	31.3
	40	5.00	5.00	5.00	6.5	8.5	11.0	61.2	61.1	61.0
	60	3.33	3.33	3.33	4.3	5.6	7.2	72.7	72.7	72.5
Aluminium	20	10.00	10.00	10.00	13.5	20.6	27.1	45.3	45.2	45.0
	40	5.00	5.00	5.00	6.7	10.2	13.6	65.5	65.4	65.2
	60	3.33	3.33	3.33	4.5	6.9	9.0	95.6	95.5	95.3
Brass	20	10.00	10.00	10.00	12.1	16.5	22.9	25.1	25.0	25.0
	40	5.00	5.00	5.00	6.0	8.2	11.3	46.2	46.0	46.0
	60	3.33	3.33	3.33	4.1	5.5	7.6	79.3	79.2	79.0

Table 5
Electrical power, energy and electricity cost needed for a pH unit revival by any electrode materials at 0.20 A

Electrode material	Contact surface (cm^2)	Electrical power (W)			Electrical energy (kWh·m^{-3})			Electricity cost ($·m^{-3})		
		3	5	7	3	5	7	3	5	7
Iron	20	1.80	2.66	3.62	1.24	1.84	2.47	0.025	0.037	0.049
	40	0.90	1.34	1.82	1.19	1.77	2.40	0.024	0.035	0.048
	60	0.60	0.90	1.20	1.03	1.55	2.06	0.021	0.031	0.041
Stainless steel	20	2.76	4.28	4.98	6.44	9.97	11.57	0.129	0.199	0.231
	40	1.38	2.14	2.50	6.90	10.71	12.50	0.138	0.214	0.250
	60	0.92	1.42	1.66	6.61	10.19	11.90	0.132	0.204	0.238
Copper	20	2.64	3.38	4.38	2.78	3.55	4.57	0.056	0.071	0.091
	40	1.30	1.70	2.20	2.65	3.46	4.47	0.053	0.069	0.089
	60	0.86	1.12	1.44	2.08	2.71	3.48	0.042	0.054	0.070
Aluminium	20	2.70	4.12	5.42	4.08	6.21	8.13	0.082	0.124	0.163
	40	1.34	2.04	2.72	2.93	4.45	5.91	0.059	0.089	0.118
	60	0.90	1.38	1.80	2.87	4.39	5.72	0.057	0.088	0.114
Brass	20	2.42	3.30	4.58	2.02	2.75	3.82	0.040	0.055	0.076
	40	1.20	1.64	2.26	1.85	2.51	3.47	0.037	0.050	0.069
	60	0.82	1.10	1.52	2.17	2.90	4.00	0.043	0.058	0.080

can be demonstrated that the cost of providing the facilities such as the power supply and the electricity consuming cost for the iron electrode is as minimum amount as possible.

3.1.3. The specific constraints

Regarding the aspect that electrolysis process is supposed to be used for improving the ABR reactor performance, it is important to know the effect of electrolysis by-products on the bacterial population in the biological reactor. Therefore, the spectrophotometric tests were performed on the samples right before and after electrolysis in order to determine the concentration of the released metals in the wastewater, under the identical conditions to revive a pH unit. The results of these experiments are presented in Table 6. Based on the type of the presented compounds in the examined electrodes,the metals studied in these tests are included iron, nickel, copper and aluminium.

According to the obtained results of the spectrophotometric tests and the inhibitory concentration of each metal, it can be seen that the copper and brass electrodes released the copper more than the permitted limits (0.5 mg L^{-1} (solution) and 50–70 mg L^{-1} (total)) [1] in the wastewater and they can have a strong inhibitory effect on the growth of the anaerobic microorganisms. Therefore, they are not suitable for the use in the anaerobic reactors. Meanwhile, up to 120 mg L^{-1} of iron is considered as a micronutrient component for the growth of the microorganisms [33]. On the other hand, the stainless steel electrode is not suitable for the application in the anaerobic reactors due to the long required electrolysis time and high electrical energy consumption to revive a pH unit. Also, the aluminium electrode uses a higher energy compared to the iron electrode to recover a pH unit.

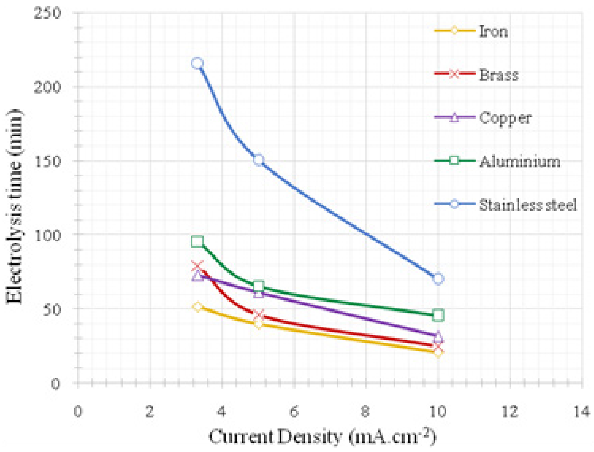


Fig. 5. Test results curve for electrolysis time as a function of current density for all materials at 0.20 A.

3.2. The economic assessment

Due to the nature of the batch mode, which is in line with the simulation of one of the smaller ABR chambers, the economic assessments must be made to maximize macro-level performance. For this purpose, a form of the electrode should be used that has the highest efficiency/cost ratio. A plate electrode having a contact surface greater than that a cylindrical electrode can provide the required efficiency with the minimum electrode mass and the electrical energy consumption. So all used electrodes in experiments

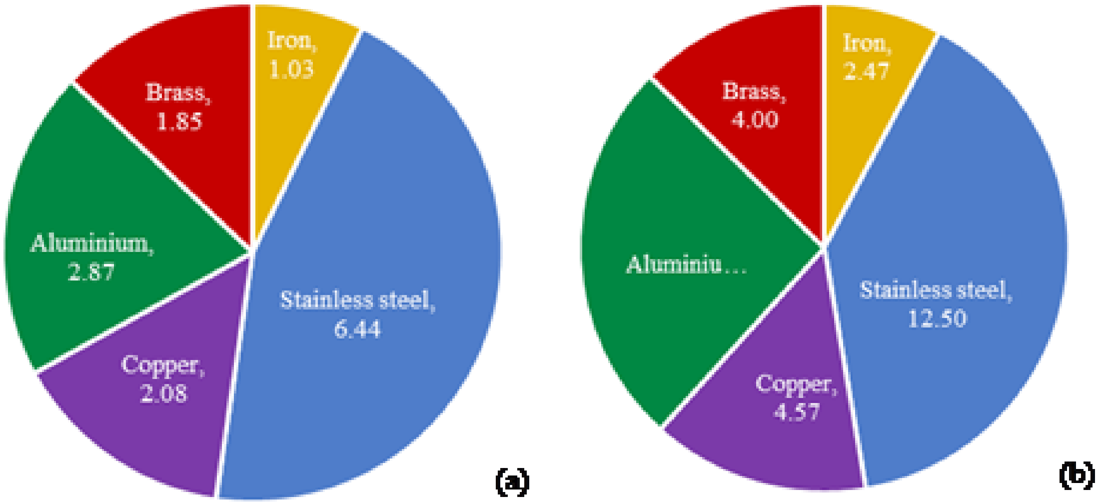


Fig. 6. Minimum (a) and maximum (b) amount of electrical energy consumption for a pH unit revival by all materials at 0.20 A.

Table 6
Concentration of released metals in solution by each electrode material at the same conditions

Electrode material	Experimental conditions				Concentration of released metals in solution (mg L^{-1})			
	Volume (cc)	Voltage (V)	Current density ($mA\cdot cm^{-2}$)	Electrolysis time (min)	Fe	Cu	Al	Ni
Iron	500	10.0	5.52	35.1	76.36	0.00	0.06	0.00
Stainless steel	500	10.0	4.02	199.6	97.87	0.00	0.13	0.24
Copper	500	10.0	4.57	59.9	7.94	34.57	0.49	4.05
Aluminium	500	10.0	3.69	90.3	1.12	0.23	162.00	0.00
Brass	500	10.0	4.40	50.7	7.92	58.26	2.31	0.00

Table 7
Comparison between preparation cost of electrode materials

Electrode material	Density (g cm^{-3})	Price of a unit mass (\$·kg^{-1})	Total cost (\$)
Iron	7.86	0.538	0.061
Stainless steel	7.86	3.226	0.365
Copper	8.96	9.140	1.179
Aluminium	2.70	5.376	0.209
Brass	8.26	7.124	0.847

were from a plate type. For the purpose of performing the economic evaluation and comparison of the electrodes preparation cost, which is in fact the initial investment cost, for each of the selected options, considering equal dimensions (12×6 cm and 1 mm thickness), the density, and the price of a unit mass, the cost of a pair of electrodes have been determined. The results of which are given in Table 7. The price of a unit metal mass is considered for its common type in the Iranian market.

Given the obtained results, it can be found that the most economical electrode material is the iron, in terms of the purchase cost and, consequently the system upgrading cost by replacing the new electrodes.

4. Conclusions

Based on the results, it can be concluded that the best material for the electrolysis process in general and in particular for the anaerobic reactor upgrading is iron due to its better performance than the other electrodes. The results of this research can be summarized as following:

1. Regarding the cost of the electrode purchase, iron is significantly different from the others. This causes the initial investment cost to be decreased. Also, depending on the nature of the electrolysis process leading to the gradual consumption of the anode, at specified intervals, the electrodes should be replaced. So by using the iron electrode, the cost of the electrode replacement can be deducted at any time.
2. In terms of the electrical energy, the electricity consumed by the iron electrode is the least possible value among the available options. Thus, the operating cost is less than the others, which highlights the economic justification for the iron application.
3. Due to the electrolysis process, the metal ions are separated from the electrode surface and dispersed in the environment. These ions play different roles in the environment. Two types of specific processes occur among the research options: one is the negative effect of copper and brass electrodes, which release copper and increase the total concentration of copper presented in the wastewater. This concentration enhancement can disturb the function of methanogens. Another issue is the positive effect of the iron electrode on the flocculation process and thereby eliminates the part of the organic load in the wastewater.
4. For a single electrode material, augmenting the distance between the electrodes and the contact surface of the electrodes leads to decrease and increase the electrical current density, respectively, which is important from the perspective of the economics and the energy consumption.
5. Augmenting the distance and contact surface of electrodes with the wastewater increases the amount of the wastewater control volume under the influence of the electrolysis process and improves the system efficiency.
6. It is expected that the application of an electrolysis system using iron electrodes in the clinging state to the wall of the baffles at the maximum distance would have the best performance in order to revive the pH in an anaerobic baffled reactor.

Abbreviations

SFABR	—	Split-feed anaerobic baffled reactor
PABR	—	Periodic anaerobic baffled reactor
CABR	—	Carrier anaerobic baffled rector
MABR	—	Modified anaerobic baffled reactor
HMABR	—	Hybrid aerating membrane – anaerobic baffled rector
ABFR	—	Anaerobic baffled filter reactor
EABR	—	Electrochemical anaerobic baffled reactor
IABRGAC	—	Integrated anaerobic baffled reactor granular activated carbon
COD	—	Chemical oxygen demand
ABR	—	Anaerobic baffled reactor
UASB	—	Up-flow anaerobic sludge blanket
EABR	—	Anaerobic baffled reactor equipped with electrolysis

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