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SCIENTIFIC PAPER

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ELECTROCHEMICAL HARVESTING OF MICROALGAE: PARAMETRIC AND COST-EFFECTIVITY COMPARATIVE INVESTIGATION

Article Highlights

- The current research highlighted the commercial feasibility of electrochemical harvesting
- The high harvesting efficiency was obtained in short electrolysis time with aluminum
- However, similar harvesting efficiency could be obtained with graphite with lower operating cost
- The operating cost can be optimized by controlling pH of the broth
- The operation cost achieved in this method is distinctly lower than that of traditional methods

Abstract

The cost of microalgae harvesting constitutes a heavy burden on the commercialization of biofuel production. The present study addressed this problem through economic and parametric comparison of electrochemical harvesting using a sacrificial electrode (aluminum) and a nonsacrificial electrode (graphite). The harvesting efficiency, power consumption, and operation cost were collected as objective variables as a function of applied current and initial pH of the solution. The results indicated that high harvesting efficiency obtained by using aluminum anode is achieved in short electrolysis time. That harvesting efficiency can be enhanced by increasing the applied current or the electrolysis time for both electrode materials, where 98% of harvesting efficiency can be obtained. The results also demonstrated that the power consumption with the graphite anode is higher than that of aluminum. However, at 0.2 A the local cost of operation with graphite (0.036 US\$/m^3) is distinctly lower than that of aluminum (0.08 US\$/m^3). Furthermore, the harvesting efficiency reached its higher value at short electrolysis time at an initial pH of 6 for aluminum, and at an initial pH of 4 for graphite. Consequently, the power consumption of the harvesting process could be reduced at acid- nature conditions to around 0.46 kWh/kg for aluminum and 1.12 kWh/kg for graphite.

Keywords: electrochemical harvesting, electrocoagulation, microalgae, sacrificial electrode, cost efficiency, energy consumption.

The growing concern for biomass as a source of renewable energy is a response to vast global demands for energy and uneasy prices of fossil fuels due to the deficiency of its reserve, beside the reinforcement of greenhouse gases resulting from utilizing fossil fuels[1].

Due to the high growth rate and lipid accumulation capability of microalgae, they are recognized as an important feedstock for biofuels, food, feed and fine chemicals. Furthermore, microalgae contribute in the reduction of greenhouse gas emissions employing their ability of CO_2 capture [2,3]. However, the biorefinery processing of biofuel production from microalgae sources is facing serious challenges that must be taken into consideration. The high cost of harvesting comes as the primary challenge for commer-

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cialization of the biofuel industry, which may require investment up to 30% of the total cost of biofuel production due to high-energy consumption [4].

The high capital cost and energy consumption of microalgae harvesting comes due to the fact that the algae concentration in the solution is very low (1-2 g/l); consequently, a large volume is required. The small size of microalgal cells, most of which are less than 10 μm in diameter, further complicate the separation process [5,6].

Researchers have adopted various microalgae harvesting techniques that include gravity flotation and flocculation, sedimentation, filtration and screening and centrifugation. However, all of these techniques have disadvantages associated with power consumption and process efficiency that affect the overall economic feasibility of the process [6-9].

Electrocoagulation accompanied with electroflotation of microalgae comes into view as a promising harvesting technique. The harvesting process starts with the formation of coagulants through dissolving of a metallic anode due to the electrochemical oxidation reaction. Simultaneously, hydrogen and oxygen microbubbles are produced on the anode and cathode [10-12].

The following reactions occur during the process at the anode when an aluminum anode is used:

$$Al \rightarrow Al^{+3} + 2e^{-}$$

$$2H_2O \rightarrow 4H + O_2 + 4e^{-}$$

$$x\,Al^{+3} + y\,OH^{-} \rightarrow Al_x\left(OH\right)_y^{z+}$$

The main reaction at the cathodes is reduction of water:

$$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$$

The flocs are formed by the reaction of the negative surface charge microalgae and the positive charge coagulants. These algal flocs can be lifted to the surface of the solution by the aid of the bubbles [5,6].

Low energy consumption and no direct addition of chemicals are the major advantages that distinguish this technique from the other traditional harvesting methods. The process is also considered eco-friendly, easy to control, and mostly cost-efficient [7]. However, the main drawback of the electrocoagulation process is the periodical replacement of the metallic anodes which are usually Al or Fe. Researchers also indicate the negative effect of the excessive doses of dissolved anode material on the biomass [8,9]. Consequently, electrochemical harvesting could be enhanced by adopting nonsacrificial anode material for the process.

It is well known that the electrode material has a massive effect on the electrochemical harvesting process, where it is directly related to the removal efficiency and energy consumption of the process [6]. Aluminum and iron have extensively been used as electrode materials in the electrocoagulation process for harvesting strains of microalgae. Electrochemical harvesting was also investigated using other anode materials like boron-doped diamond [6] and carbon electrodes [10,11]. However, limited information is available about the comparison of the electrochemical harvesting of microalgae with sacrificial and non-sacrificial anode material.

The current work focuses on exploration and comparison of the performance of electrochemical harvesting of microalgae with using sacrificial anode material (aluminum) and nonsacrificial anode material (graphite). The influence of key parameters, including applied current and initial pH of the solution on the harvesting process, was investigated. The results were assessed based on harvesting efficiency, energy consumptions, and the total operation cost. The operation cost was estimated according to local prices of energy input (kWh) and aluminum.

METHODS

Cultivation of microalgae

Chlorella microalgae were provided kindly by the department of Biology, Ibn-Haitham College of Education, University of Baghdad. First, the microalgae were inoculated in two 250 ml flasks in Chu-13 media at 25±2 °C. Then the microalgae were incubated into two 5-L glass containers in a fresh culture medium. Cultures were grown at 16/8 h light/dark at a controlled temperature of 25±2 °C. The light intensity was 2500 lux measured by a photometer (Milwaukee//China). The air was supplied to each reactor at 500 mL/min flowrate for six hours daily.

Electrocoagulation experiments

The experiments of microalgae harvesting were conducted using a cylindrical cell made of plexiglass with a diameter of 9 cm and a height of 10.5 cm. Two types of anode material were used in the current study which are graphite and aluminum. A horizontal aluminum plate was used as a cathode. All electrodes in experiments had the same dimensions of 9.5 cm×6 cm×1 cm.

The distance between the anode and cathode was 15 mm. The anode was connected to the positive pole and cathode was connected to the negative pole of DC power supply (Smart Power System, model EMA-01-32-15-P, USA). All experiments were conducted at constant current mode, and the applied current was changed in the range of (0.2-1 A).

The experiments were performed with 450 ml of broth at room temperature (25±2 °C). The effect of initial acidity of microalgal broth was studied by changing pH of the solution (2, 4, 6, 8 and 10). The initial pH of microalgal broth was adjusted by adding 0.1 M of H_2SO_4 and 0.1 M of NaOH. The pH of broth was measured by (Basic pH Crison, USA). The reactor was constantly stirred at speed of 200 rpm by a magnetic stirrer (Corning, model PC-410, USA).

Before each run, the aluminum electrode was kept in a 1 M HCl solution for a half-hour, mechanically ground with abrasive paper, and then washed with distilled water.

Determination of electrochemical harvesting efficiency

The microalgae harvesting efficiency was determined based on the change in optical density and the turbidity of the microalgal suspension. Samples were collected periodically during the ECH process. The samples were taken at a distance of 5 cm from the liquid surface. The flocs of microalgae floated to the top surface of microalgal broth by the action of gases formed at the anode and cathode.

After 10 min of salting time, the optical density of samples was measured using UV-Vis spectrometer (Bio-Rad, SmartSpec Plus, USA) measured at 680 nm.

The harvesting efficiency was subsequently calculated as:

$$ECH\% = 100\frac{OD_i - OD_t}{OD_i} \quad (1)$$

where OD_i is the optical density of the initial suspension, and OD_t is the optical density of the suspension at a time t.

Calculation of power consumption and operation cost

The power consumption PC (in kWh/kg of recovered microalgae) was estimated according to the following formula:

$$PC = \frac{Pt}{1000V\mu_a C_i} \quad (2)$$

where P is the power (W), t the electrolysis time (h), V the volume of the microalgal broth treated (m^3), μ_a the microalgae recovery efficiency, and C_i the initial microalgae biomass concentration (kg/m^3).

The operating costs OC in US\$/m^3 was expressed in terms of the energy consumption and electrode dissolved and is calculated by the following relation [15,16]:

$$OC = Ep_e + Wp_{Al} \quad (3)$$

The unit price of electricity p_e equivalent to 0.03 US\$/kWh in Iraq in 2019 [17], and the price of aluminum p_{Al} equivalent to 1.93 US\$/kg in Iraq in 2019.

The energy consumption E (kWh/m^3) can be calculated according to the following relation [5,10,11]:

$$E = \frac{IUt}{V} \quad (4)$$

where I is the applied current (A), U is the cell voltage (V) which assumed to be constant.

Faraday's Law was used to calculate the theoretical amount of aluminum dissolved W during the harvesting process [13]:

$$W = \frac{ItM}{nFV} \quad (5)$$

where W = aluminum dissolved (g/m^3); M = molecular weight of aluminum (M = 27 g/mol); n = number of electrons involved in the oxidation reaction (n = 3); F = Faraday's constant, 96,500 C/mol.

RESULTS AND DISCUSSION

Effect of applied current

The applied current is found to be an essential factor that influences the electrochemical harvesting process of microalgae as it affects process efficiency, time and power consumption.

In the investigation, the experiments of effects of current density on harvesting efficiency were carried out with a range of 0.2-1 A, at constant initial pH of 10. The microalgae concentration was fixed for all experiments.

For the aluminum anode, the removal efficiency of microalgae increased with the rising of current density, as shown in Figure 1. At a current density of 1 A, around 99% removal efficiency was achieved within the first 2 min and remained around this value for the rest of electrolysis time. Reducing the applied current to 0.2 A led to a decline in the removal efficiency, where it took 15 min of electrolysis time to reach around 95% efficiency.

That behavior could be attributed to the fact that the increase in current density resulted in an abundance of aluminum that was released from the electrodes according to Faraday's law. The amount of positively charged dissolved metal hydroxides neut-

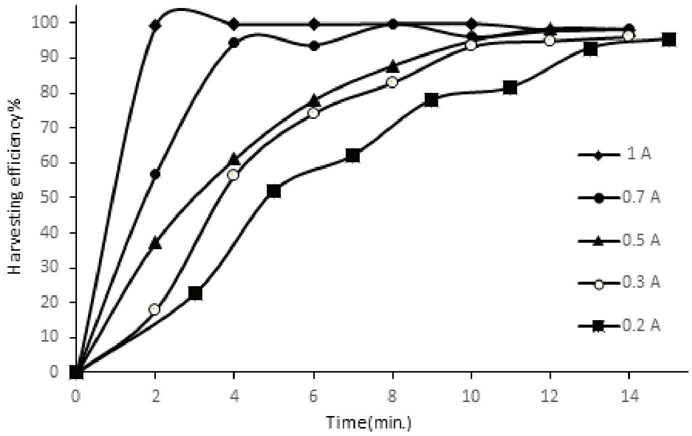

Figure 1. Effect of current on harvesting efficiency for aluminum electrode.

ralized the negative charge surface microalgae which promoted the formation of low-density flocs. In addition, increases in the applied current increase the microbubble producing rate by the electrodes, which results in higher upward momentum flux and speed up algae flotation [18].

The performance of aluminum and graphite electrodes for the effect of applied current is compared in Figure 2. The trend of removal efficiency for the graphite electrode is similar to that of the aluminum electrode where the efficiency increased with increasing of applied current; however, the removal efficiency for aluminum is higher than that of graphite for the same applied current. With applied current of 0.5 A, the graphite electrode achieved removal efficiency of 98.5% after 12 min of electrolyte time, while it was about 91% for the graphite in the same electrolysis time. Furthermore, for low applied current of 0.2 A, harvesting efficiency of 95% was achieved in 15 min, while it was around 85% for graphite during the same electrolysis time.

With nonsacrificial electrodes like graphite, the principle of electroflotation of microalgae is based on the migration of negative charge cells of microalgae by the action of the electric field. The algae accumulate on the positive anode's surface and the negative charge of the algae cells is neutralized resulting in the formation of algal aggregates. The microbubbles generated on both electrodes in electrolysis of water will cause flocculation and flotation of the microalgae aggregates [9,15]. With the increasing of applied current, the electrical charges produced by the electrode increase the generation of bubbles as well. This results in an increase in the effective harvesting of microalgae with applied current [20]. In electrocoagulation-flocculation, using a sacrificial electrode like aluminum, the process mechanism is different, when Al^{3+} released from the electrode react with water to form -BNm soluble monomeric and polymeric hydroxo-metal complexes which act as chemical flocculants [15,17]. In both types of anodes (sacrificial and nonsacrificial), the microbubbles do the same action.

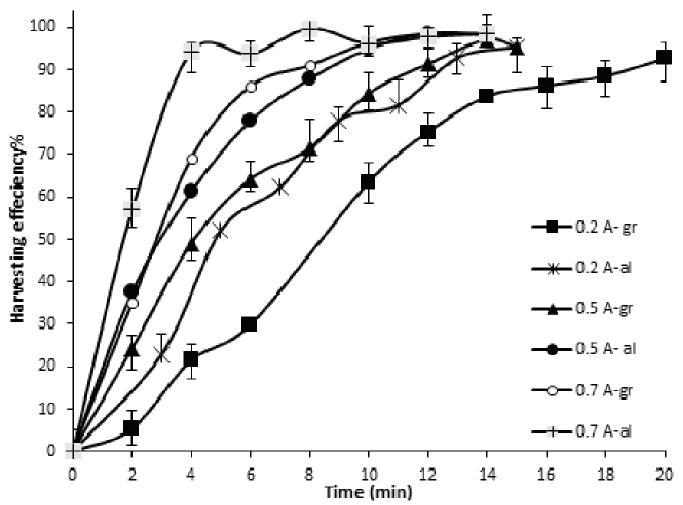

Figure 2. Removal efficiency of microalgae at different applied currents for aluminum and graphite anodes, at initial pH of 10.

From the results above, it seems that the physical and chemical process involved in electrocoagulation-flocculation with sacrificial anodes (aluminum) has an advantage over the electro-flotation with sacrificial anodes, where the harvesting efficiency of aluminum achieved higher values than that obtained with graphite at the same operating conditions.

The results of the influence of applied current on the harvesting process in the current work were found to be harmonious with those observed in several researches that used aluminum, carbon and other anode materials [8,9,16,18]

Effect of acidity

The influence of initial pH has been recognized to be a decisive parameter on the microalgae harvesting process. Natural acidic conditions were found to be optimum for harvesting processes using carbon anode [20]. In addition, with the aluminum anode, the microalgae harvesting efficiency could be enhanced by decreasing the initial pH of the solution [5,19]. Despite that, some researchers found that alkaline conditions are more suitable for algal harvesting [17,20]. The effect of broth acidity on electrocoagulation was investigated by varying the starting of acidity from 2 to 10. From Figure 3, it can be observed that the harvesting efficiency reached its higher value at natural acidic conditions. For an initial pH of 6, the removal efficiency achieved 94% after 10 min of electrolysis time and around 98% after 13 min. On the other hand, in the alkaline range of initial pH, the efficiency process faded. The harvesting efficiency decreased to 81% after 10 min with increase of pH to 8 and reached 88% after 13 min.

In acidic and neutral conditions, the aluminum hydroxide precipitates and monomeric hydroxoaluminum and polymeric cations like $Al_{13}O_4(OH)_{24}^{+7}$, $Al_6(OH)_{15}^{+3}$, $Al_7(OH)_{17}^{+4}$, $Al_8(OH)_{20}^{+4}$, $Al_{13}O_4(OH)_{24}^{+7}$ are present significantly in the bulk. Consequently, the negative surface charge microalgae are readily neutralized by those cations. Increasing initial pH to alkaline conditions, the negatively charged aluminum hydroxide $Al(OH)_4^-$ is dominant in solution, which does not react with the surface of microalgae, resulting in slower removal of microalgae [5,19,21]. The $Al(OH)_4^-$ species are not active for most water treatment applications [26]. However, for extremely acidic conditions of pH 2, it seems that the removal efficiency reached its lowest value. It may be due to the changing in microalgae surface properties at this pH value. The cell surface charge of microalgae is a result of the existence of ionizable functional groups, which are part of the cell wall, or may be found in the attached extracellular algogenic organic matter (AOM). The pH value of the surrounding medium forces these groups to become protonated or deprotonated. For green algae, zeta potential was found to be electronegative for pH 4-10, while for pH around 3-4, isoelectric point is determined [15,22]. In addition, it is found that the surface charge of the cell is a function of the species life cycle [19].

The effect of initial solution pH was also investigated using graphite anode. Figure 4 shows that the harvesting efficiency increased by decreasing initial solution pH, except for pH 2. The highest removal efficiency of 90.2% is achieved at pH 4 at electrolysis time of 13 min. Similar behavior was also obtained at electrolysis time of 10 min, where the curve has a

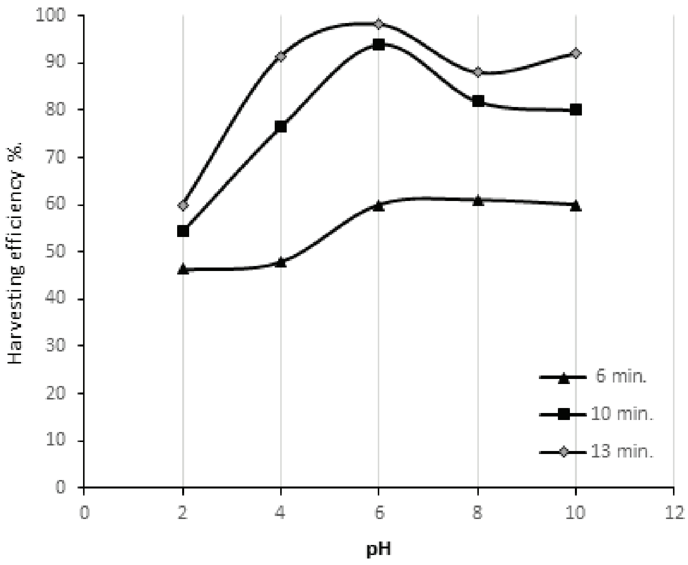

Figure 3. Effect of pH on the harvesting efficiency for aluminum electrode.

sharp peak at pH 4 and the removal efficiency of 78.3%. The current results are concordant with those obtained in electrochemical harvesting of oleaginous green microalgae *S. obliquus* [20]. It was found that the harvesting efficiency achieved maximum values at pH 5, and it has been attributed to the formation of positively charged ions in acid conditions. However, increasing the electrolysis time results in increasing of harvesting efficiency, which applied for both types of anode material.

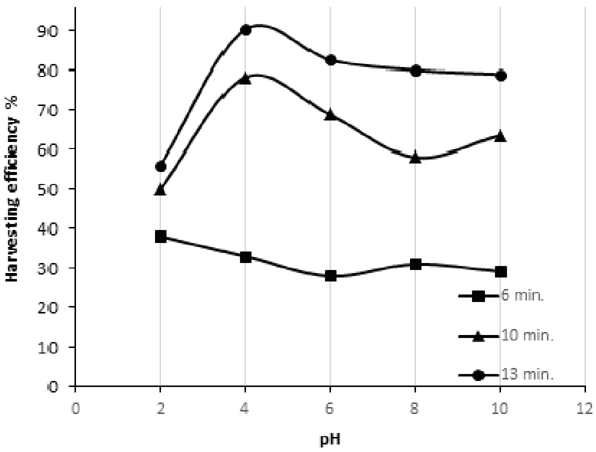

Figure 4. Effect of pH on harvesting efficiency for graphite electrode.

From the results obtained with the aluminum and graphite electrodes, it seems that the acidic to natural conditions are the most favorable for harvesting *Chlorella* microalgae by using both electrodes, except in extremely acidic conditions, around pH 2, where the harvesting is inhibited.

The experimental results also show that the recovery efficiencies achieved with applying a high current or low pH during a short electrolysis time could be obtained by applying a low current density or high pH during a longer electrolysis time. Bearing in mind that when an industrial scale is the aim, a long electrolysis time requires a bigger reactor volume and may affect the quality of the microalgae in the process [23].

Power consumption and operation cost

Assessing the economic feasibility of the harvesting process using both types of electrodes is the ultimate goal of the research. In addition to the harvesting efficiency, the effect of the key parameters should be highlighted in terms of electrical energy consumption and local cost of operation.

The results demonstrate that the high removal efficiency of microalgae obtained with aluminum electrodes is accompanied with low energy consumption during the harvesting process. Figure 5 shows the average energy consumption for both types of anodes with different applied currents. The estimation of the average energy consumption based on 92% harvesting efficiency.

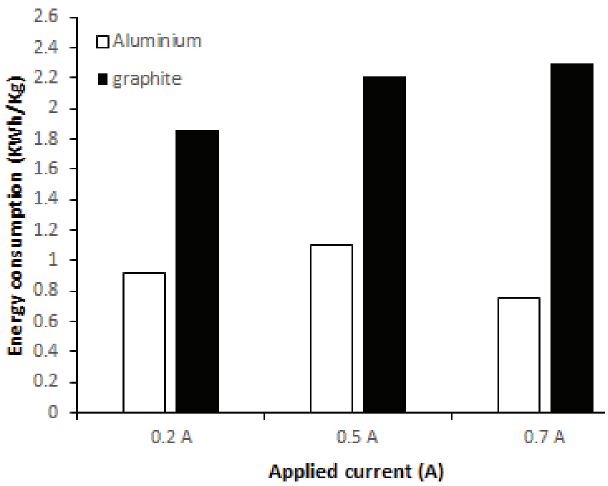

Figure 5. Power consumption with different applied currents for aluminum and graphite anodes.

It is obvious from Eq. (2) that the energy consumption increased with the increasing of applied current for both electrode materials, which isusually accompanied by increases in total cell potential. However, the time required to reach to the desired harvesting efficiency is an effective parameter to determine energy consumption. The results reveal that the graphite associated with high energy consumption in comparison with that obtained with aluminum. It can be observed from Figure 5 that with aluminum anode, the energy consumption is 0.759 kWh/kg of microalgae for applied current of 0.7 A, while it's around 2.3 kWh/kg of microalgae for the graphite anode. Likewise, at a low applied current of 0.2 A, the energy consumption for the aluminum anode is 67% lesser from that obtained with graphite. The reason behind relatively low energy consumption of aluminum anodes maybe due to a high overpotential of oxygen evaluation for graphite anodes. Also, Al^{3+} released by aluminum anodic oxidation increases the electrical conductivity of the solution that reduces electrical power consumption.

The optimization of process energy consumption is crucial to reflect its impact on the total cost of operation and the economic feasibility of the process. The operation cost of microalgae harvesting in the current study is expressed by Eq. (3), which expresses the total cost in terms of the energy cost and the cost of consumable anode materials. The microalgae separation efficiency of 92% is taken as a reference to estimate the total cost of operation. Figure 6 shows the operation cost of aluminum and graphite anodes at different applied currents. The figure demonstrates that the cost of operation is obviously high for aluminum for the applied currents of 0.2, 0.5 and 0.7 A, despite that the time for achieving the required separation efficiency is obviously shorter, and the power consumption is much lower, which can be noticed from Figures 1 and 6. The high cost of power consumption obtained with the graphite anode is vanquished by the cost of aluminum dissolved during the harvesting process, which raises the total cost operation of the aluminum electrodes. The percentage of dissolved electrode cost is about 78% of the total process cost at applied current of 0.2 A, while this percentage increases to about 82% when the applied current increases to 0.7 A.

However, it has been recognized that the operation cost of electrocoagulation process using aluminum electrodes is obviously lower than that of iron electrode at different applied currents [15].

It can be observed from Figure 7 that alteration of microalgae broth acidity from an energy consumption point of view, the harvesting process with aluminum anode shows a clear superiority over the graphite anode. Generally, the energy consumption (kWh/kg) is reduced with the decrease of pH values, where the values energy consumption for pH 4 and 6 are lower than those obtained with pH 8 and 10 for both aluminum and graphite. That may be due to the addition of H_2SO_4 that enhances the conductivity of the mixture, which typically reduces the overpotential. In addition, the power consumption estimated at the point in time corresponded to 92% recovery efficiency, which gives lower energy consumption for the acidic region. Consequently, the power consumption achieved minimal value for aluminum of 0.46 kWh/kg at pH 6, which is due to shorter electrolysis time to reach 92% recovery efficiency.

The high cell potential obtained with graphite anode reflects on the overall behavior of power

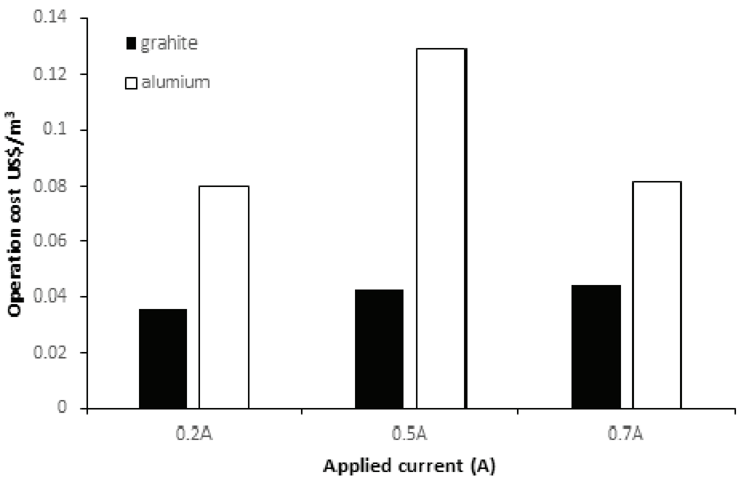

Figure 6. Operation cost at different applied currents for aluminum and graphite anodes.

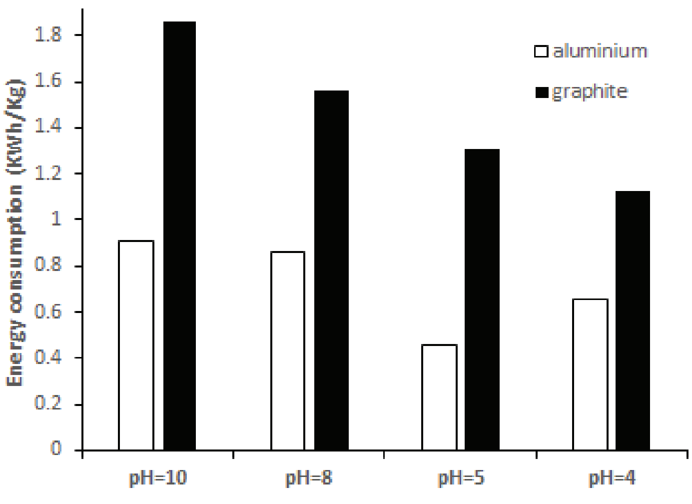

Figure 7. Power consumption at different initial pH for aluminum and graphite anodes.

consumption for the harvesting process. Where at pH 4, the power consumption of graphite is 1.127 kWh/kg and for aluminum 0.657 kWh/kg, that disparity in energy consumption is applied for all pH range. However, the power consumption at pH 2 is eliminated from the calculation due to insufficient harvesting process efficiency at that pH value.

In spite of effective harvesting of algae and minimal power consumption achieved by using aluminum anode for all pH range, the harvesting process provided higher operation cost values in comparison to that obtained with graphite which can be observed clearly from Figure 8. The lowest operation cost for graphite anodes was at pH 4 which is 0.0218 US$/m^3, while it was 0.075 US$/m^3 for the aluminum anode at the same conditions, while the lowest operation cost for aluminum is 0.056 US$/m^3 obtained at pH 6, which refers to the best broth pH condition.

However, the medium of microalgae growth is usually in alkaline condition, and accordingly, lowering the pH of the medium toward the acidic-natural region will require additional cost. It's required to add chemicals to adjust the required pH value for the broth, *i.e.*, H_2SO_4 (24 $/L), which adds extra cost to the process. However, this cost was equal for both modes of operation with both electrodes (Al or graphite) at a certain pH value. For instance, it required ~0.28 $/m^3 to adjust the broth acidity to pH 2, ~0.2 $/m^3 for pH 4, ~0.14 $/m^3 for pH 6 and ~0.06 $/m^3 for pH 8.

Both electrolysis time and cell potential played important roles in the optimization of operation cost. However, the local prices of the aluminum and the electricity power, which differ from place to another, have the lion's share of the impact on optimization of the operation cost.

In comparison to other harvesting technology, the performance of the electrochemical harvesting process of microalgae could be optimized to be a promising harvesting technology in which minimum energy is consumed [9]. Technologies like tangential flow filtration, polymer flocculation, and centrifugation require high energy for operation [14,23]. On the other hand, pressure filters and vacuum filters require to be periodically replaced [29]. Sedimentation may require low power for operation but it is denoted with low separation efficiency (up to 66%) [30]. The present work showed that the target of low energy consumption and long-life parts could be met in the electrochemical harvesting process.

The operation cost obtained in current study was relatively lower than in other electrocoagulation processes. That comes from low applied current, the high harvesting efficiency in relatively low electrolysis time, the local prices of electrical energy, local electrodes materials, and the composition of electrolyte. The operation cost for electrocoagulation process of kaolinite and bentonite suspensions using aluminum electrode was 0.1-1 US$/m^3 and depends on operation conditions [31]. The operation cost reduced to 0.768 US$/m^3 when the technique was applied for the treatment of waste metal cutting fluids [26]. It was concluded that around 1.190 US$/m^3 was required for the electrocoagulation process of metalworking fluid wastewater treatment at the optimum study conditions [32]. Similarly the operating cost of treatment of dyehouse wastewater using aluminum electrode was 1.851 US$/m^3 [33].

Generally, for non-sacrificial anode like graphite, the low cost of operation compensates the relatively long electrolysis time to fulfill high harvesting efficiency. In addition, the metallic electrodes as aluminum will need periodic process shutdown for electrode replacement, while with the non-sacrificial electrode like graphite the replacement process will be omitted. Furthermore, the graphite electrodes will not conta-

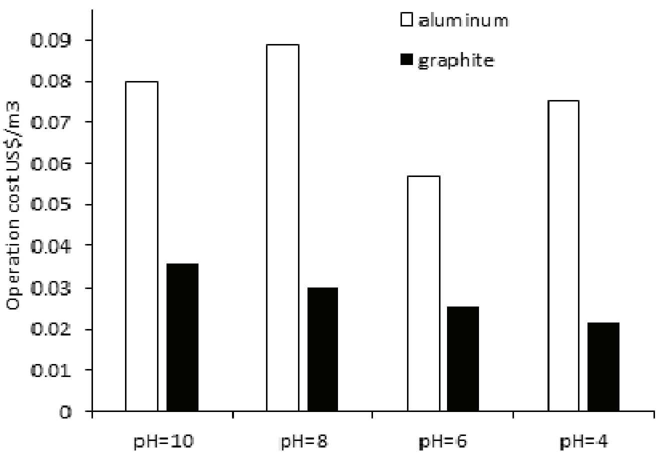

Figure 8. Operation cost at different initial pH for aluminum and graphite anodes.

minate the water or microalgae biomass as will metallic electrodes [8,22].

CONCLUSION

The electrochemical harvesting of microalgae was investigated using two types of anode materials, aluminum and graphite anodes. Based on the experimental results, the study concluded that high harvesting efficiency could be achieved either by applying high current at short electrolysis time and *vice versa*. Consequently, the electrolysis time and the applied current can be optimized to obtained lower power consumption. The comparison between the behaviors of the two types of electrodes showed that a higher harvesting efficiency could be obtained with electro-coagulation-flotation using aluminum anode with relatively short electrolysis time.

Despite the power consumption obtained, the graphite was generally higher than that of the aluminum, and the operation cost of the harvesting process with the graphite was considerably lower.

The electrochemical harvesting exhibited higher harvesting efficiency under acidic-natural initial pH conditions for both anode materials. Consequently, the power consumption can be reduced to lower values. In addition, the operation cost could be shifted to a lower value at the optimum pH values.

The process of microalgae electrochemical harvesting could be optimized to be cost-competitive and an environment-friendly process with a lower operation cost of 0.037 US$/m^3, which may contribute to the development and deployment of the marketing of this biorefinery process.

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NAUČNI RAD

ELEKTROHEMIJSKO IZDVAJANJE MIKROALGI: UPOREDNO ISTRAŽIVANJE EFEKTIVNOSTI PARAMETARA I TROŠKOVA

Troškovi izdvajanja mikroalgi predstavljaju veliko opterećenje za komercijalizaciju proizvodnje biogoriva. Ovaj rad se bavio ekonomskim i parametarskim upoređivanjem elektrohemijskog izdvajanja pomoću žrtvene (aluminijum) i nežrtvene (grafit) elektrode. Efikasnost izdvajanja, potrošnja energije i operativni troškovi korišćeni su kao objektivne promenljive u zavisnosti od primenjene struje i početnog pH rastvora. Rezultati su pokazali da se visoka efikasnost izdvajanja postiže aluminijumskom anodom za kratko vreme. Ova efikasnost izdvajanja može se povećati povećanjem primenjene struje ili vremena trajanja elektrolize za oba elektrodna materijala, pri čemu se može postići efikasnost izdvajanja od 98%. Rezultati su, takođe, pokazali da je potrošnja energije većas sa grafitnom nego sa aluminijumskom anodom. Međutim, pri 0,2 A, okalni troškovi rada sa grafitnom elektrodom (0,036 USD/m^3) su znatno niži od troškova rada sa aluminijumskom elektrodom (0,08 USD/m^3). Dalje, efikasnost izdvajanja dostiglo je bila veća za kratko vreme elektrolize pri početnom pH 6 za aluminijumsku elektrodu, odnosno pri početnom pH 4 za grafitnu elektrodu. Shodno tome, potrošnja energije procesa izdvajanja može se smanjiti u uslovima kisele sredine na 0,46 kWh/kg za aluminijumsku elektrodu i 1,12 kWh/kg za grafitnu elektrodu.

Ključne reči: elektrohemijsko izdvajanje, elektrokoagulacija, mikroalge, žrtvena elektroda, efikasnost troškova, potrošnja energije.