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Experimental and Theoretical Study on the Ability of Microbial Fuel Cell for Electricity Generation

Ali, A. H. [1*], Al-Mussawy, H. A. [1], Hussein, M. J. [1] and Hamadi, N. J. [2]

1. Environmental Engineering Department, Faculty of Engineering, Mustansiriyah University Baghdad 10052, Iraq.
2. Environmental Engineering Department, Faculty of Engineering, Baghdad University, Baghdad 10071, Iraq.

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ABSTRACT: The present study aims at designing a promising Microbial Fuel Cell (MFC) to utilize wastewater in order to generate electricity. Two types of salt bridge have been used in MFC (KCl and NaCl). The maximum electricity generation with 1M KCl and NaCl has been 823 and 713 mV, respectively. Varied salt concentrations (0.5M, 1M, 2M, and 3M) of salt bridge in MFC have been analyzed with different factors like temperature, type of electrode, configuration, and surface area of electrode being studied. The optimum temperature is found to be 32C^o, with the optimum type of electrode being graphite rod, while the optimum configuration and surface area of electrode is graphite plate with surface area of 183.6 cm^2. Artificial Neural Network (ANN) has been employed to predict voltage production of MFC and compare it with the experimental voltage. Multiple correlation methodology has optimized the voltage production with the correlation coefficient (R^2) being 0.999.

Keywords: Artificial neural network (ANN), Multiple correlation, Salt bridge, Wastewater.

INTRODUCTION

Recent years have seen accelerated use of fossil fuels, particularly oil and gas, which in turn triggers a worldwide energy crisis. One of the ways to mitigate the current global warming crisis is renewable bioenergy, for which there have been major efforts to develop alternative electricity production methods. Without any net carbon dioxide, new electricity production from renewable resources is much desired (Davis and Higson, 2007; Ali et al., 2016). The use of Microbial Fuel Cells (MFCs) has attracted considerable interest among academic researchers in recent years (Allen and Bennetto, 1993; Gil et al., 2003; Moon et al., 2006; Choi et al., 2003). This technology changes the energy, saved in chemical bonds in organic compounds for electrical energy, accomplished through catalytic reactions by microorganisms. It is a promising way to treat urban wastewater, simultaneously producing electricity which can directly convert chemical energy of organic matter into electrical energy under anaerobic conditions (Larminie and Dicks, 2003). The principle depends on the fact that generation of current is in the nature of microorganisms, as they transfer electrons

* Corresponding author, Email: env.eng.dr.ahmed@uomustansiriyah.edu.iq

from a reduced electron donor to an electron acceptor at a higher electrochemical potential (Lovley, 2006; Ditzig et al., 2007). The anodic process uses bacteria to catalyze the electron transfer from organic electron donors to the anode electrode.

The electrons are then transferred through an external circuit to the cathode chamber where they reduce the final electron acceptor, typically oxygen (Li et al., 2008; Chae et al., 2008). MFC's characteristics are similar to traditional power sources as well as anaerobic reactors, which can be described on one hand by electrochemical parameters like power density, electrical current output and, cell voltage; and on the other, by biological parameters like the substrate (COD) removal efficiency (Rabaey et al., 2003).

There are many mathematical models to oxidize and reduce chemical agents, based on mass balance for MFCs. The outputs of these models involve time-dependent production of the current, voltage and power, and additionally the progression of chemical species concentration (Picioreanu et al., 2007). Prediction of MFC performance has been additionally developed by means of models that integrate macro-scale, time-dependent mass balances for solutes and biomass in the anodic solution with a micro-scale, individual, two-dimensional biofilm model (Picioreanu et al., 2010).

Mathematical models are highly developed and widely used in the field of chemical fuel cells (Kinoshita et al., 1988; Wang, 2004); however, their application for MFC is too scarce. Mathematical models for scientists, working with MFC, can assist detecting rate-limiting steps and take into account development of schemes to improve MFCs' design along with power production. Moreover, to test the hypothesis for microbial community composition, the biologist can use computers, size activity, and mode of electron transfer in MFC or he can design new experiments to enhance MFCs' performances. Furthermore, the computational models help by pointing to the most important MFC parameter that should be experimentally evaluated and described. Many types of neural network exist (Hagan et al., 1996) like multilayer perceptron (MLP), radial basis function (RBF) networks, as well as recurrent neural network (RNN), yet all of them consist of the same basic features: nodes, layers, and connections. Some of the artificial neural networks are popular like MLP and RNN (Movagharnejad and Nikzad. 2007).

The present study aims at investigating the capability of MFC to produce energy and to study the effect of agar salt bridge type, molar concentration, and temperature on MFC, along with the impact of configuration and electrode's surface area on MFC voltage production. It applies artificial neural network (ANN) to find out the most important parameters, affecting electricity generation of MFC.

MATERIALS AND METHODS

As Figure 1 shows, the constructed MFC, consists of a plastic container with 11 L of total volume, 8 L of working volume, used as an anode chamber. Wastewater samples were collected from influent of Al-Rustamiyah wastewater treatment plant in Baghdad, to be used in the anode chamber. Electrode was used in both anode and cathode chambers. Four types of electrodes were used in MFC (graphite rod, graphite plate, steel rod, and aluminum rod), which were put at both ends of the anode and the cathode. The dimensions of the graphite rod, graphite plate, steel rod, and aluminum rod were 10×1 cm, 1.5×8.5×0.3 cm, 1.3×7.5 cm, and 1.5×7cm, respectively, while each electrode's surface area was 31.5 cm^2. To provide the maximum surface area, three electrodes were placed parallel to one another in order to develop the biofilm on anode. They were linked with copper wire. Salt bridge was used in MFC and prepared by dissolving 5% of agar in the solution, containing a particular salt concentration of KCl or NaCl, which got boiled for 2 minutes and cast in PVC pipe. The salt bridge was properly sealed and stored in refrigerator. The electrode was placed on the open end of the agar salt bridge, acting as the cathode. The anode chamber (anaerobic chamber) was filled with wastewater as well as the cathode chamber (aerobic chamber where oxygen was used as electron acceptor). The copper wire between the anode and cathode was connected to a multi-meter (Model No. MS8268) to finish the circuit. The voltage in the multi-meter was read and jotted down every 24 hours throughout the 10 days of operation. The impact of different factors on MFC voltage was studied. Agar salt bridge was studied in order to determine the impact of the type of agar salt bridge on MFC. Here, the agar salt bridge was KCl and NaCl, both 1M in volume, while the temperature was kept constant at 30^{o}C. Furthermore, the molar concentration of the salt bridge was observed, with the best agar salt bridge type (either KCl or NaCl) obtained from previous experiments, while keeping the temperature at 30^{o}C and varying the molar concentration of the agar salt bridge between 0.5, 1, 2, and 3 M. The best molar concentration got selected for further experiments. Differences of temperature were studied, by using temperatures of 27, 30, 32, and 36^{o}C. In this way the best temperature that gives the maximum voltage, while using the best type of the agar salt bridge as well as the most appropriate concentration, got selected. In order to study the impact of the electrode type, three types of electrodes (i.e., graphite, steel, and aluminum rods) were used in MFC, each having a surface area of 31.5 cm^2 and total surface area of 94.5 cm^2. Other parameters, namely agar salt bridge type, molar concentration, and temperature, got fixed at best optimum values. What is more, the electrode's shape was studied, for which graphite rod and graphite plate were employed. The surface area of each electrode was 31.5 cm^2 and the total surface area, 94.5 cm^2. Also, surface area of electrode was studied by means of two graphite plates with different surface areas. The surface area of each electrode were 31.5 and 62.5 cm^2 and the total surface area, 94.5 and 183.6 cm^2. Other parameters, i.e., agar salt bridge type, molar concentration, temperature, type, and configuration, were set at their best optimum values. Figures below show the images and schematic representation of the constructed MFC.

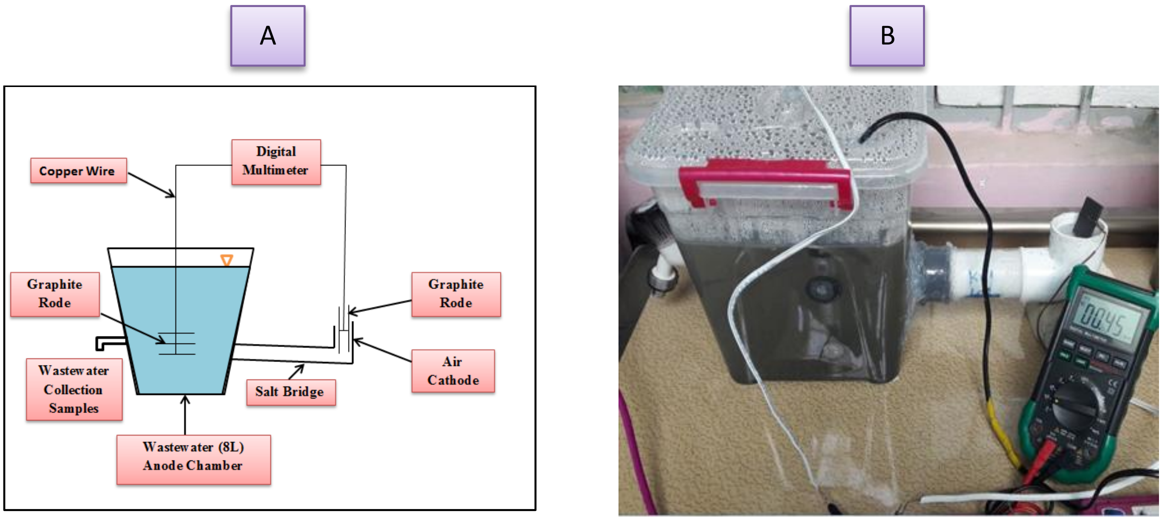

Fig. 1. (A) Schematic diagram of MFC. (B) MFC photo.

This study employed a multilayer Artificial Neural Network (ANN) as an effective means to find complex nonlinear relations. Hence, four layer feed forward neural networks were taken as a correlation model. The weighing coefficients of the neural network were calculated, using IBM SPSS programming. The ANN's structure was constructed as the input layer, a layer of neurons that receive data from external sources to pass them to the network for processing. These may be either signals or sensory inputs from other systems. This research used four input neurons in the layer, namely concentration of the agar salt bridge, temperature, surface area of the electrode, and total count of bacteria. The next layer was a hidden one, receiving data from the input layer and processing them in a hidden way, without any direct connection to the input or output of the external world. All connections from the hidden layer to other layers were within the system. There was only one neuron in the hidden layer which would make the network complicated, if there were more than one neurons in this layer. The results are likely to indicate that the present problem was not too complex to have a complicated network routing. Hence, the results can be accomplished by maintaining an appropriate number of neurons in the hidden layer. The final step was the output layer, receiving the processed data and sending output signals out of the system. This work had only one output neuron in this layer. Here, the output was MFC voltage. Also, there was a bias to provide a threshold for neuron activation. In the network, the bias input was connected to each of hidden neurons. Figure 2 illustrates the architecture of the multilayer ANN modeling.

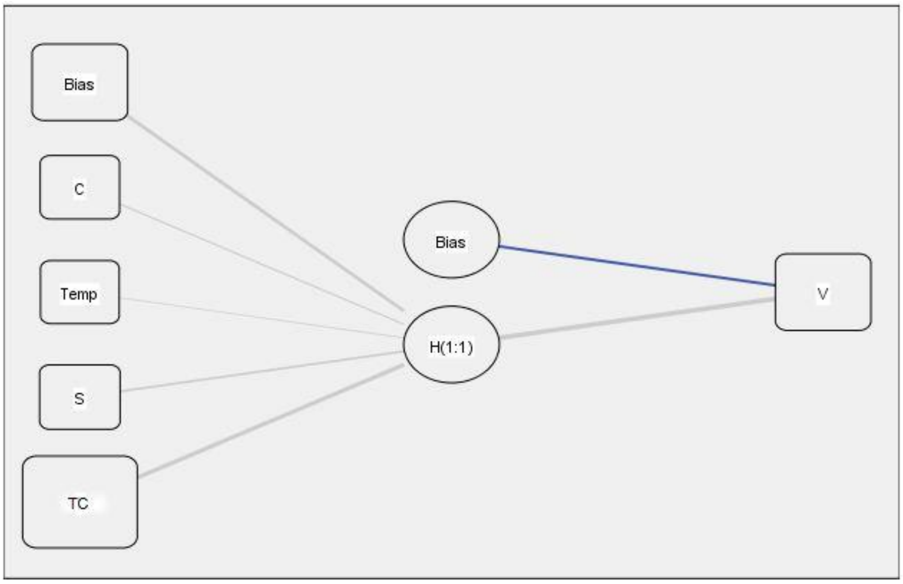

Fig. 2. Structure of a layer neural network

RESULTS AND DISCUSSION

The effect of agar salt bridge type is very important for efficacy to transport H^+ ions in the salt bridge. The maximum voltage, obtained from KCl and NaCl, was 823 and 713 mV, respectively, as shown in Figure 3. It was found that KCl was better than NaCl in MFC, since transfer rate of sodium in pure water was about 0.4, while that of K ion was about 0.49 (Liu and Logan, 2004). NaCl may render imbalance ions in the electrochemical cell and KCl very soluble, thus providing the needed positive K^+ ions and negative Cl^- ions. These results were in agreement with those of others (Ramanavicius et al., 2008).

The effect of salt bridge molar concentration was also observed. It was found that maximum voltage obtained, from 0.5, 1, 2, and 3M KCl, was 1012, 1056, 1005, and 830 mV, respectively. Moreover, it was found that the voltage production dropped as molar concentration of agar salt bridge was increased. Optimum molar concentration turned out to be 1M with maximum voltage of 1056 mV, as shown in Figure 4. Molar concentration of salt was critical since proton transfer through the salt bridge was facilitated by its dissociated ions (Anand et al., 2015).

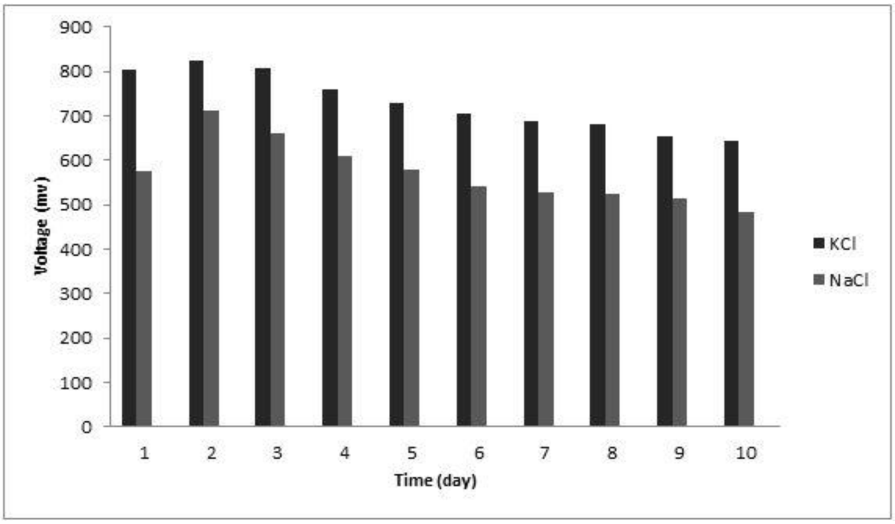

Fig. 3. Voltage (mV), generated in MFC for 1M KCl and 1M NaCl, with respect to time (days).

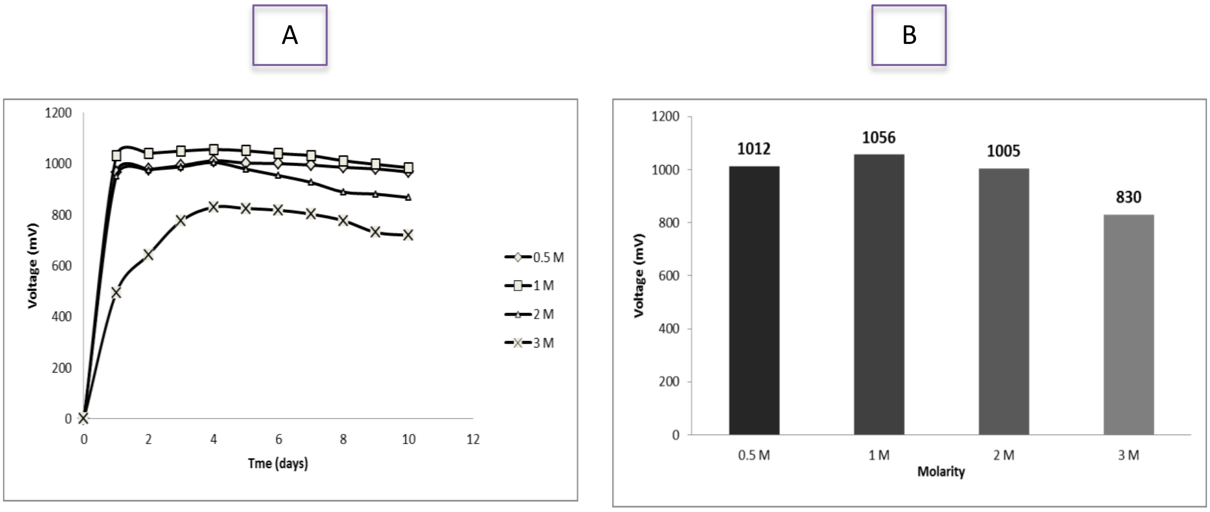

Fig. 4. (A) Voltage production (mV) with time (days) (B) Maximum voltage, obtained at different molar concentration

The impact of various temperatures of 27, 30, 32, and 36 ^{o}C on MFC performance was studied with the maximum voltage (712 mV), generated at 32 ^{o}C. As for 27, 30, and 36 ^{o}C, the generated voltage was 520, 605, and 698 mV, respectively, as demonstrated in Figure 5. It was found that anode performance in an MFC was influenced by the temperature. However, just as in chemical fuel cells, increasing temperature also improved the kinetics of oxygen reduction, reducing the internal cell resistance, likely to result in greater current densities and greater columbic efficiency, e.g., 43% at 30 °C, compared to 8% at 22 °C (Min et al., 2008). The higher the temperature, the greater the biochemical reaction rate, and –consequently—the higher biomass growth rate as a result of the increased substrate utilization rate. Higher growth rate would also lead to faster microbial attachment of the electrode (Zhan et al., 2008).

The effect of electrode type on MFC was studied too, using three types of electrodes, i.e., graphite, steel, and aluminum rods wherein the surface and total surface areas of each electrode were 31.5 cm^2 and 94.5 cm^2, respectively. It was found that the maximum voltage produced in graphite, steel, and aluminum rods was 1010, 145, and 52 mV, respectively, as shown in Figure 6. Furthermore, graphite rod turned out to be a good electricity conductor, compared to steel and aluminum, since graphite rod contained carbon in its composition which increased electrical conduction of MFC (Ieropoulos et al., 2005; Mustakeem, 2015). Carbon-based materials are widely used for their high conductivity, biocompatibility, and chemical stability, not to mention the low costs they charge (Huaining.,2009).

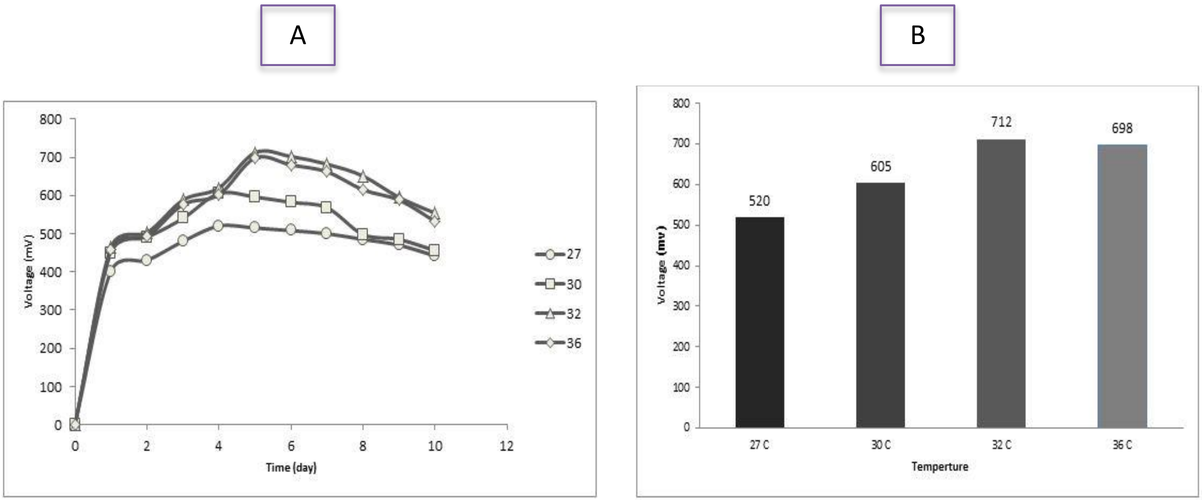

Fig. 5. (A) Voltage generation (mV) with time (days) at different temperatures (B) Value of maximum voltage, obtained at different temperatures

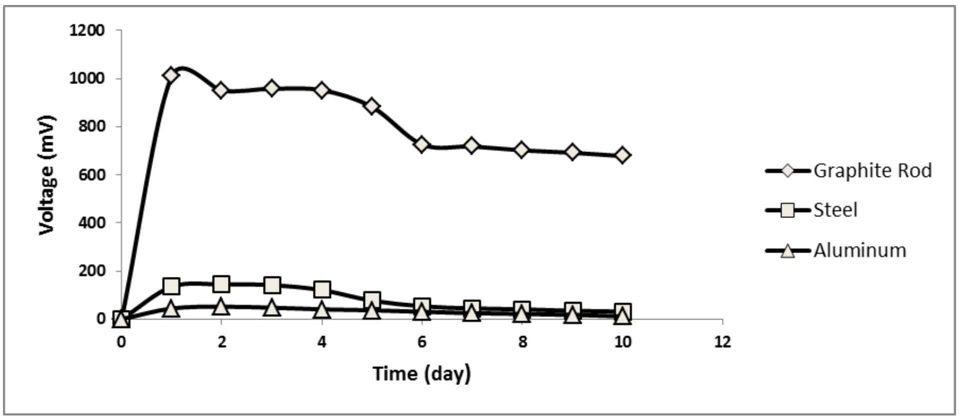

Fig. 6. Voltage generation (mV) with time (days) by different electrode type

The effect of electrode shape on MFC voltage is quite important. It was studied by using graphite rod and plate. The maximum voltage, produced by graphite rod and graphite plate, was 820 and 1009 mV, respectively, as shown in Figure 7. Thus the graphite plate was better than a graphite rod, which could be justified by the fact that graphite plate attached bacteria better than graphite rod. This, in turn, reflects its ability to decompose and increase the electrons released (Lee et al., 2002; Logan and Regan, 2006). Also, impact of electrode surface area was observed, using two graphite plates with surface areas of 94.5 and 183.6 cm^2. The maximum voltage, generated in surface area of 94.5 and 183.6 was 1009 and 1012 mV respectively, as shown in Figure 8. It was found that, increasing surface area of electrode was very important to increase the amount of voltage for MFC, since the process of bacteria attachment in big surface area was better than smaller ones (Rismani, et al., 2008; Wang, et al., 2011).

Artificial neural networks (ANN) were applied to predicate the effect of temperature, concentration of the agar salt bridge, surface area of electrode, and total count of bacteria on MFC voltage. When predicting MFC voltage, the network consisted of four input neurons corresponding to the state variables of the system with one hidden neurons and one output neuron, as illustrated in Figure 2. All neurons in each layer were fully linked with those of the adjacent layer. The ANN suggested a good result for the comparison of experimental and predicted results, showing a correlation coefficient (R^2) of 0.985.

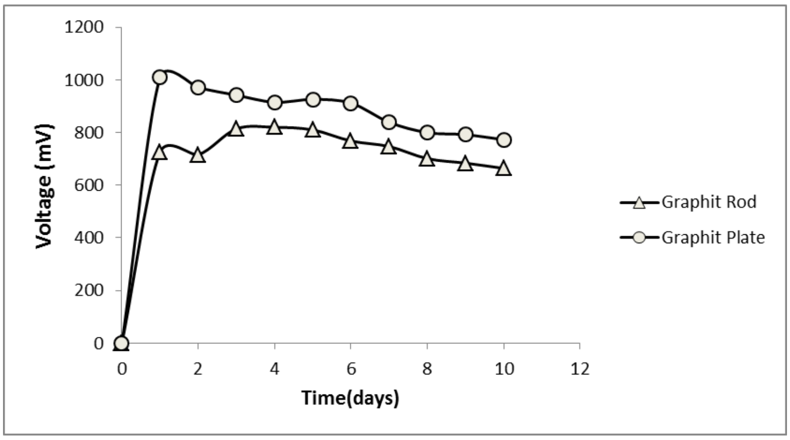

Fig. 7. Voltage (mV) of graphite rod and graphite plate

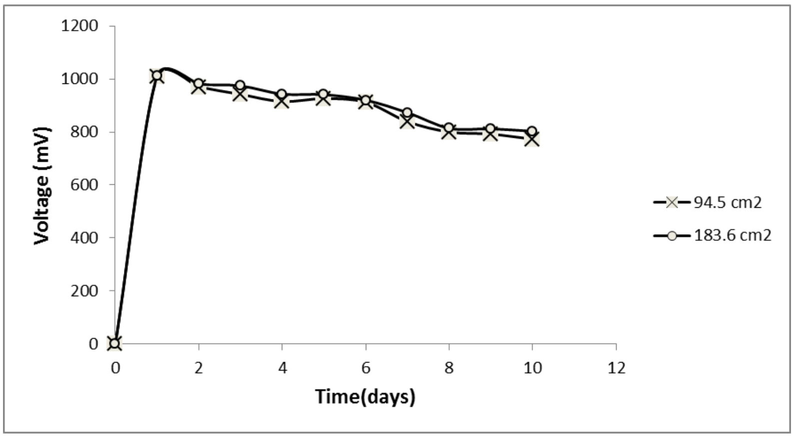

Fig. 8. Voltage (mV) with time (days)

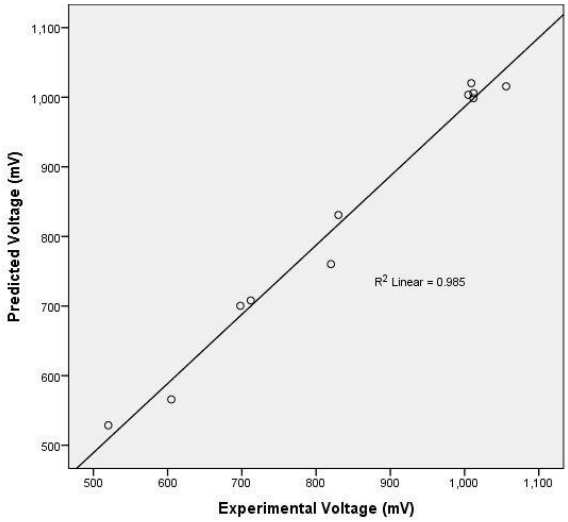

Fig. 9. Maximum experimental voltage with the predicates voltage of MFC.

Fig. (10) illustrates the importance of independent variables (inputs), a measure of how greatly the network's model could predict the changes in output voltage for different values of the independent variables. It can be seen that total count of the bacteria play a major role in voltage generation (100%), followed by the surface area of electrode, concentration of the agar salt bridge, and temperature (10.4%, 7.3%, and 5.8%, respectively), as shown in Table 1.

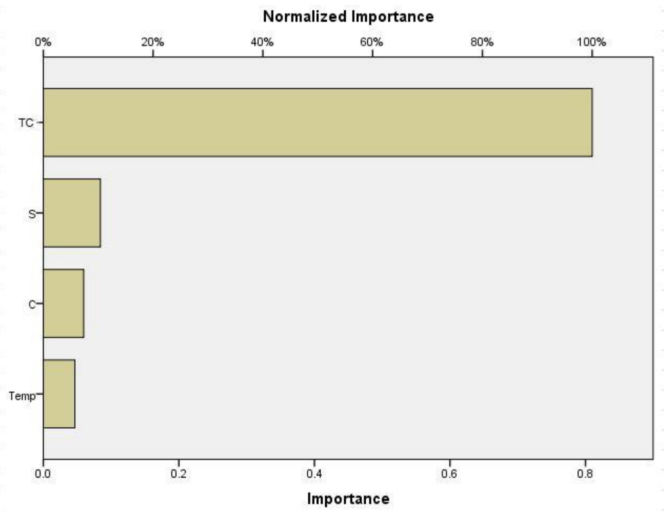

Fig. 10. The importance of independence variables of concentration, temperature, surface area of electrode, and total count of bacteria, estimated by ANN

Table 1. Independent variable importance

Independent Variable Importance		
	Importance	**Normalized Importance**
Concentration (M)	.059	7.3%
Temperature (C)	.047	5.8%
Surface area of electrode(cm^2)	.084	10.4%
Total Count (bacteria/mL)	.810	100.0%

The multiple correlation methodology was employed to find the relation between voltage generation and optimum agar salt bridge concentration, temperature, and surface area of the electrode. Equation ($Y=aX_1^bX_2^c X_3^d X_4^e$) was solved to find out these relations, by applying the Excel program.

Based on the experimental data, the independent variable coefficients could be calculated. The correlation coefficient (R^2) turned out to be a desirable value of 0.999, which was to 1, meaning better correlation between the experimental and predicted values. The experimental maximum voltage production, obtained at optimum conditions was close to the rate, obtained from multiple correlations. These optimal conditions included agar salt bridge concentration of 1M at a temperature of 32 C^o, with an electrode whose surface area was 183.6 cm^2 and with a total bacteria count of 1350 bacteria/mL. The obtained equation is as follow:

$$Y = 10^{2.30147} \times \left(X_1^{0.00743} \times X_2^{-0.50113} \times X_3^{0.03759} \times X_4^{0.43683} \right) \quad (1)$$

where Y is voltage production (mV); X_1, agar salt bridge concentration; X_2, the temperature (^oC); X_3, surface area of the electrode (cm^2); and X_4, total count of the bacteria (bacteria/ml).

The practical voltage, generated at optimum conditions, was 996 (mV), very close to the theoretical voltage, calculated from the abovementioned equation by multiple correlation, which was 999.359 (mV).

CONCLUSION

The present study employed MFC to produce electricity, expressed in voltage. In the first part of the study, KCl and NaCl were compared for their use as strong salt in the salt bridge. The molar concentration of salt was studied and the experiments showed that by increasing molar concentration, the voltage would decrease. Optimum results were obtained for salt bridge with 1M KCl and NaCl, generating a maximum voltage of 823 and 713 mV respectively. Electrode materials had a great impact on the performance of MFCs. It was found that, graphite electrode was the best choice for electricity production, compared to steel and aluminum electrodes and it was found that the increase in surface area of electrode contributed to greater voltage of MFC. The maximum value of voltage, generated at optimum conditions, which included molar concentration of 1 MKCl for the agar salt bridge at a temperature of 32 C^o and with an electrode surface area of 183.6 cm^2. The Artificial Neural Network (ANN) and multiple correlations were applied to predict the theoretical voltage as well as the importance of different parameters. A multiple correlation equation was applied to give a desired value of correlation coefficient (R^2), equal to 99.98%, which means better correlation between the experimental and predicted values. The ANN demonstrated a good result in comparison between experimental and the predicted results, showing a correlation coefficient (R^2) of 0.985.

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