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Experimental study of direct bio-electricity generation from municipal waste-activated sludge simultaneously with its stabilization and modeling the process by KSOFM and MLP artificial neural networks

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ABSTRACT

In this study, direct bioelectricity generation from waste-activated sludge has been investigated simultaneously with its effective aerobic stabilization. In this regard, a noticeable number of experiments have been carried out and the results of the experiments have been used to model the process performance by Kohonen self-organizing feature maps (KSOFM) and multi-layer perceptron (MLP) modeling as artificial neural networks (ANNs). KSOFM modeling results showed that the highest VSS removal efficiency of the process and the generated electrical power density of the cell would be reached in the pH values near to 7 and the temperatures around 35°C. Also, the VSS removal and the generated electrical power density are higher when the VSS content of the added waste activated sludge is higher. The results of MLP modelling showed that the VSS content and the pH value of the added waste activated sludge as well as the temperature that the processes run within, have noticeable impact on the generated electrical power density (41%, 27%, and 32%, respectively), and the VSS removal efficiency of the MFC (28%, 27%, and 45%, respectively).

Keywords: Artificial neural networks; Direct electricity generation; Kohonen self-organizing feature maps (KSOFM); Microbial fuel cell (MFC); Multi-layer perceptron (MLP); Waste-activated sludge

1. Introduction

The concerns about the environmental issues are continuously increasing currently and makes the outstanding role of the strategies like waste management and reuse, more and more decisive [1,2]. On the other hand, the depletion of the fossil fuel sources and the threat of global warming made exploring for carbon-neutral renewable, green energy sources necessary and accelerated the proceedings in this field [3–6]. Waste-activated sludge is one of the most important organic wastes which has attracted attentions due to its potential to be reused. Due to the vast application of the biological wastewater treatment methods, waste-activated sludge is being produced in voluminous amounts and requires to be stabilized in order to be safely disposed into the environment due to its noticeable content of pathogens as well as various kinds of contaminants [5,7–10]. Recovering energy from organic wastes like waste-activated sludge has various advantages such as efficient management of the wastes, combating energy scarcity and reduction of greenhouse gas emissions, simultaneously [3,11,12]. Therefore, lots of studies have been carried on generating energy from sewage sludge [1,9,13–15] and various technologies have been eventuated from these studies [16–20]. In this regard, direct electricity generation from waste-activated sludge is one the issues that have been considered by researchers, recently. This process is done by converting the chemical energy of the sludge to electricity via microorganisms, called bio-electrochemical systems. These systems are able to simultaneously treat organic wastes and generate electricity [2,14,17,21–26]. To generate the electricity, organic compounds, such as carbohydrates, present in the

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waste-activated sludge are oxidized by specific microorganisms and the electrons produced in this oxidation process are transferred to the anode electrode (in the anode chamber) and then transported via an electrical wire to a cathode electrode (in the cathode chamber) and consumed by oxygen reduction reactions. The anode and cathode chambers of the reactor are connected to each other by a proton exchange membrane in order to let the protons produced in the anode area, transfer through it and can react with hydroxide ions generated in the reduction process of oxygen in the cathode area. The electron transfer from the bacteria to the anode comes to pass either directly by bacteria attached to the anode electrode surface or indirectly by the mediators or electron shuttles [27–32].

In this regard, the main goal of this study is to reach simultaneous effective stabilization of waste-activated sludge and optimized harvesting direct electrical energy from it to protect the environment from contamination. In order to approach these goals we designed and made a two-chamber microbial fuel cell (MFC) and utilized it to carry out the experiments in the laboratory. For evaluating the performance of the reactor and determining the optimized conditions of the process in various operational conditions, a noticeably high amount of experiments have been carried out and then artificial neural networks (ANNs) modeling has been benefited. ANNs are strong mathematical tools which are inspired by the learning process in the human brain [33–36] to define the effectiveness level of each parameter. According to the training algorithm, these methods are classified into two categories which are supervised and unsupervised learning. Unsupervised neural networks do not have the desired outputs and their main aim is to distribute inputs into groups which have similar characteristics. Multi-layer perceptron (MLP) is the most common type of supervised neural networks in the field of modeling and prediction. This model has been used for determination of the efficacy level of each parameter in the process. Also, for evaluating the operational conditions of the reactor considering all parameters, Kohonen self-organizing feature maps (KSOFM) have been utilized. These maps are the most popular type of unsupervised learning networks, which is a combination of one input layer and one output layer entitled as "competitive layer" [37]. Neurons are connected to each other based on the structure of the map by a neighborhood relation [38]. Besides above-mentioned duties of the unsupervised neural networks, KSOFM can be utilized at the same time for projecting the data nonlinearity onto a lower-dimensional display and for reducing the data dimension. In this article, in order to find regularities and correlations in the input variables, SOM Toolbox (www.cis.hut.fi/projects/somtoolbox/) has been utilized with MATLAB-TM. Inputs have been normalized, due to having diverse magnitude.

2. Materials and methods

2.1. Cell design and operation

Fig. 1 shows the schematic view of the two chamber MFC which has been utilized in order to carry out the experiments and the related various reactions, happening in its different parts.

According to Fig. 1, the cell contained an anode and a cathode chamber which were connected to each other by a proton exchange membrane (PEM) (PEM, Nafion TM 117, Dupont Co., USA). The net volumes of the chambers were about 2500 mL and they contain 3 electrodes which their height, width, and thickness were about 200 mm, 40 mm, and 1 mm, respectively. Also, the distance between the electrodes was 30 mm. In order to obtain the demanded dissolved oxygen for the aerobic processes in the cathode chamber, two aerators have been placed in at the bottom of the chamber and the longitudinally parallel to the electrodes. In order to keep the content of the anode chamber homogeneous, a magnetic bar mixer has been used. The water content of the chambers kept constant by adding deionized water (the water in the chambers was volatilized by aeration or mixing). The electrodes of the chambers were connected to an external resistance (R) by copper wire.

2.2. Waste-activated sludge collection

The waste-activated sludge used in this study was collected from the secondary sedimentation tank of Tehran southern municipal wastewater treatment plant which treats 450000 m^3 wastewater per day (Tehran, Iran). Table 1 shows the specifications of raw waste-activated sludge samples.

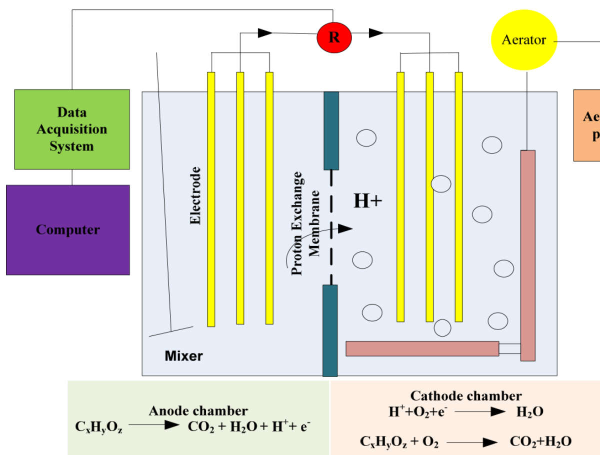

Fig. 1. A schematic view of the utilized laboratory set-up and its related reactions.

Table. 1
Waste-activated sludge specifications

Property	Value
pH	6.5–7.5
Temperature, °C	18–25
Chemical oxygen demand (COD), mg/L	6000–11200
Volatile suspended solids (VSS), mg/L	3500–7800
Total suspended solids (TSS), mg/L	4100–8550

2.3. Chemicals and parameters

The chemicals which have been used in this study were provided by Merck® Co. The duration of the start-up in this study was about 14 days and during this step, the temperature kept near to 40°C. At the start-up, acetate and glucose were added to the waste-activated sludge in anode chamber to help the electricity-generating microbial community to be dominated. These materials have been added to the waste activated sludge in one step and the mixture has been stirred for 15 min at a gentle speed before added to the anode chamber of the MFC. The amount of the added acetate was about 1.5% and glucose was about 3% based on the VSS content of the waste activated sludge.

The effects of pH and temperature (T) as operational parameters have been investigated on volatile suspended solid (VSS) and the power density (P) assumed as representative parameters of reactors performance.

As mentioned before, in order to train the software, it is essential to carry out various experiments. Table 2 shows the test conditions which have been designed to investigate the operational conditions of the reactor considering the literature [18,39–43]. Also, the dissolved oxygen (DO) in both chambers was measured in order to be considered in the evaluation of the results.

Experiments were repeated three times and all results are the means of replicate analyses.

2.4. Apparatus and calculations

The pH of the sludge was determined by a pH-meter (Elemetron pH-meter CP-411). A multimeter has been utilized (2700, Keithley, OH, USA) with a voltage across resistor recorded every 15 min intervals and a data acquisition system connected to a computer. The VSS removal efficiency of the reactor has been calculated based on the initial VSS of the sludge by Eq. (1) [44].

$$VSS\ Removal\ Efficiency = \frac{\left(VSS_{raw\ sludge} - VSS_{treated\ sludge}\right)}{VSS_{raw\ sludge}} \quad (1)$$

The power densities of the system (P) were calculated as Eq. (2) [45]:

$$P = \frac{\left(Voltage * Current\ density\right)}{anode\ volume} \quad (2)$$

where P presents the power density (W/m^3), Voltage is the measured produced voltage of the system, the current density is the produced electrical current per each m^2 of the electrode surface (A/m^2), and the anode volume is the net volume of the liquid in the anode (m^3). Polarization curves were obtained by measuring the voltages obtained with different external resistors (10 Ohm–1 Mega Ohm), after the voltage stabilization.

Table. 2
Operational parameters for experimental investigation of the performance of the reactors

Parameter	Range	Step range
Temperature (°C)	5–65	5
pH	3–10	1

Sampling carried out hourly from the bottom, middle and top of each chamber. Also, the VSS measurements performed on the prepared sample, containing equal parts of the mentioned samples. All tests are conducted according to "standard methods for examination of water and wastewaters" by APHA [46]. Artificial neural network (ANN) modeling has been used in order to evaluate the results.

3. Results and discussion

In this part, the results of the experimental investigations and the output of the models have been brought, compared and discussed.

3.1. Experimental evaluations on the effect of the operational parameters

Microorganisms and bacteria cultures have a significant role in the biological systems, like bioelectricity generating processes. The performance of this kind of processes is highly dependent on temperature and pH [18,39–43]. Considering this fact, the effects of temperature and pH as important operational parameters have been evaluated on the VSS removal efficiency and bioelectricity generation parameters from waste-activated sludge (generated electrical power density and voltage) as the performance indicators of the process.

3.1.1. The effect of temperature on the reactor performance

Fig. 2 shows the results of investigations on the effect of the temperature on the processes. The pH value of the waste activated sludge in the reactor was kept close to 7 during the experiments related to the evaluation of the temperature on the reactor performance. Also, the VSS of the added waste activated sludge into the reactor was about 4400 ± 100 mg/L at the initial time of these evaluations.

According to Fig. 2, temperature affects the responses of the process, remarkably. But the noticeable point about the behavior is that the VSS removal efficiency of the reactor

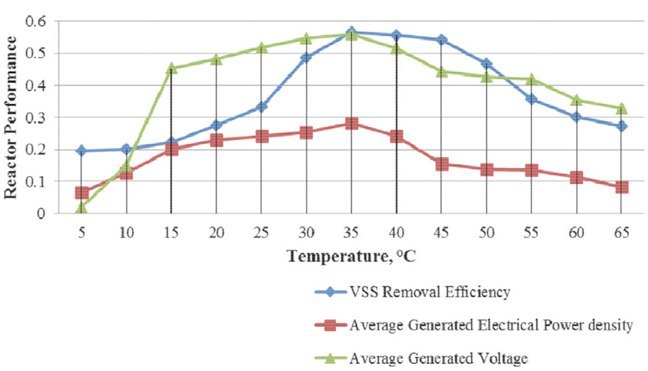

Fig. 2. the effect of the temperature on the reactor performance (pH = 7; the initial VSS of the waste activated sludge = 4400 ± 100 mg/L)

showed as approximately the same behavior as the generated electrical power density and the generated voltage. In other words, all of the variables demonstrate a growth by increasing the temperature from 5 until 35°C. The slope of this growth is higher at low temperatures especially from 5 to 10°C. But by increasing the temperature to higher than 35°C, this upward trend would be changed to downward and the increase of the temperature decreased the VSS removal efficiency, the generated electrical power density, and the generated voltage. In the temperatures lower than 5 and higher than 65°C, the advance of the process was negligible. The best VSS removal from waste-activated sludge was measured about 55% in 35°C. Also, the highest value of the generated voltage and power density were observed in this temperature, about 0.54 W·m^{-3}, and 0.29 V, respectively.

3.1.2. Effect of pH on the reactor performance

The process showed relatively high dependency to the pH value of the waste-activated sludge in the reactor. Fig. 3 demonstrates the effect of pH values (measured inside the MFC) of the waste activated sludge in the cathode chamber during the processes on the reactor performance. The pH value of the anode chamber was not changed in this study, because of the high sensitivity of the bio-electricity generating microorganisms in the anode chamber [47,48]. The pH value in this chamber has been adjusted on about 7, considering the literature and the related studies [47–49]. But in order to study the effect of pH, as one the most important operational conditions, the pH value of the waste-activated sludge in the cathode chamber has been changed and its effect on the VSS removal efficiency and the bioelectricity generation performance have been investigated. During these investigations, the temperature of the waste activated sludge in the reactor was kept close to 35 ± 2°C. Also, the VSS of the added waste activated sludge into the reactor was about 4400 ± 100 mg/L at the initial time of these evaluations.

According to Fig. 3, the best results have been observed in neutral conditions. It seems that in acidic or basic conditions the efficiency of the aerobic stabilization process, decreases and as a result the VSS removal efficiency shows a decrease in these conditions. This occurrence affects the bio-electricity processes negatively. Therefore the generated

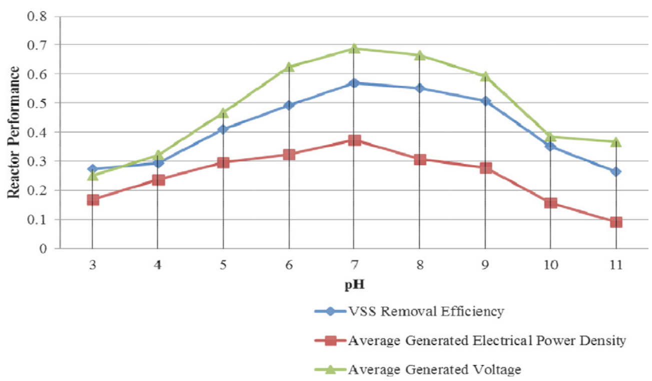

Fig. 3. the effect of the pH value on the reactor performance (T = 35°C; the initial VSS of the waste activated sludge = 4400 ± 100 mg/L).

electrical voltage and power reduces. According to the results, the highest VSS removal efficiency, the generated voltage, and electrical power density were about 56%, 0.39 W·m^{-3}, and 0.7 V, respectively (at the pH value near to 7). These results are remarkably close to the results of the temperature effect evaluations.

3.2. Artificial neural network modeling

As mentioned before, two technics of the artificial neural networks (ANNs), Kohonen self-organizing feature maps (KSOFM) and multilayer perceptron (MLP) modelings, have been benefited to investigate the performance of the reactor and find the optimal conditions of the process in various operational conditions.

3.2.1. Kohonen self-organizing feature maps (KSOFM)

One of the significant advantages of this kind of neural network is its visualization sufficiency [37]. The kind of visualization used in this article is a component plane [50] which supports to determine the correlation between components simultaneously. In order to process, all variables were scaled to have the variance of 1 and the mean of 0. The map size through training was 7×5 nodes which have a hexagonal display. Fig. 4 demonstrates the correlations between the variables (operational conditions and the reactors performance indicators) by component plane visualization. In each component plane, each hexagon is considered as one map node and also, its color specifies the amount of the component in that node. In each place on different component planes, hexagons conform to the same map node [37]. In Fig. 4, Tmp, pH, DO, VSS_i, R_{emv}, P_{wt} represent temperature, the pH value of the cathode chamber, dissolved oxygen of the cathode chamber, the VSS content of the added waste activated sludge to the MFC, the VSS removal of the process, and the generated electrical power density of the reactor, respectively. According to Fig. 4, the highest VSS removal of the process observed when the pH is near to 7 (dark red parts) and the temperature is around 35ºC (light cyan hexagons) as well as the generated electrical power density. Also, according to the results, it seems that the VSS removal and the generated electrical power density of the reactor improve by increasing the VSS content of the added waste activated sludge to the MFC. Due to the biological nature of the reactions and the very important role of the DO concentration in aerobic systems, the effect of this parameter has been studied in the KSOFM model, too [51]. The results of the model demonstrated that the best VSS removal and electrical power generation were obtained in the medium values of DO (between 4.5–5.2 mg/L, light blue hexagons). Regarding the extended aeration of the cathode in this study, the DO concentration levels in the cathode chamber were noticeably high and the observed values of the DO in the optimal conditions were about 50–60% of the saturated level of the DO in temperatures between 30–40ºC. These results of the KSOFM model are highly compatible with the experimental results and confirm the accuracy of each other.

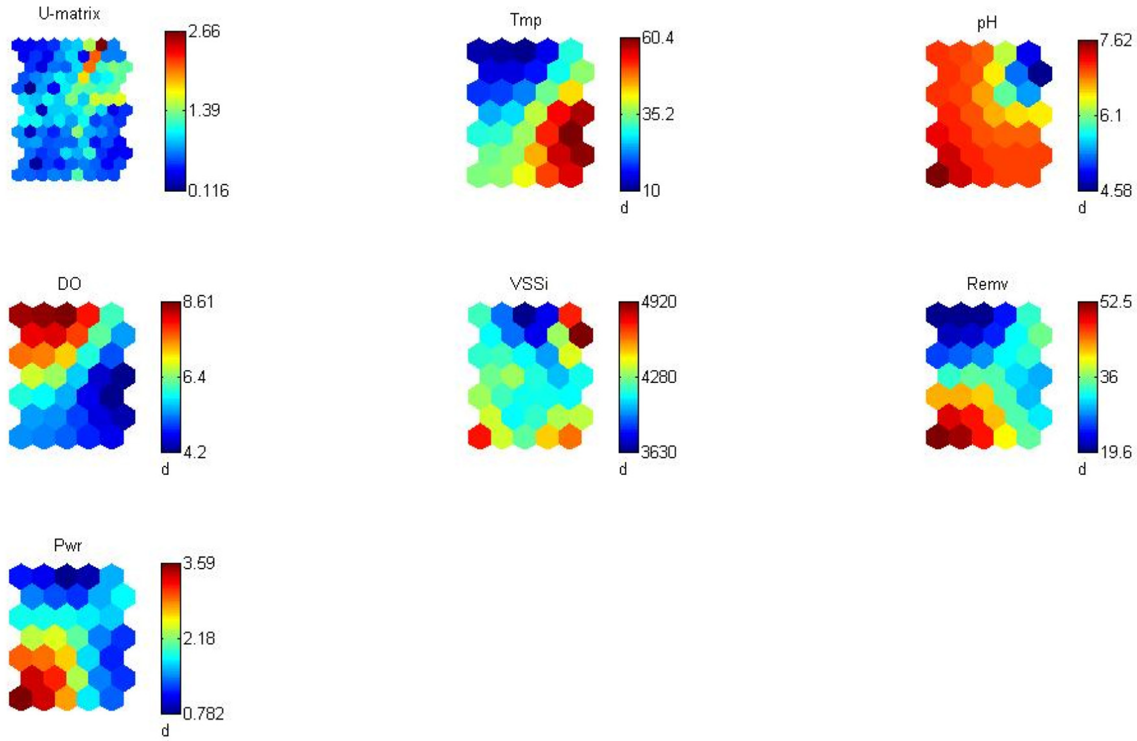

Fig. 4. The results of the visualization of the KSOFM (T_{mp}: temperature (°C), pH: the pH value of the added waste activated sludge to the MFC, DO: dissolved oxygen (mg/L), VSS_i: the VSS of the added waste activated sludge to the MFC (mg/L), R_{emv}: the VSS removal efficiency, P_{wr}: electrical power density (W/m³).

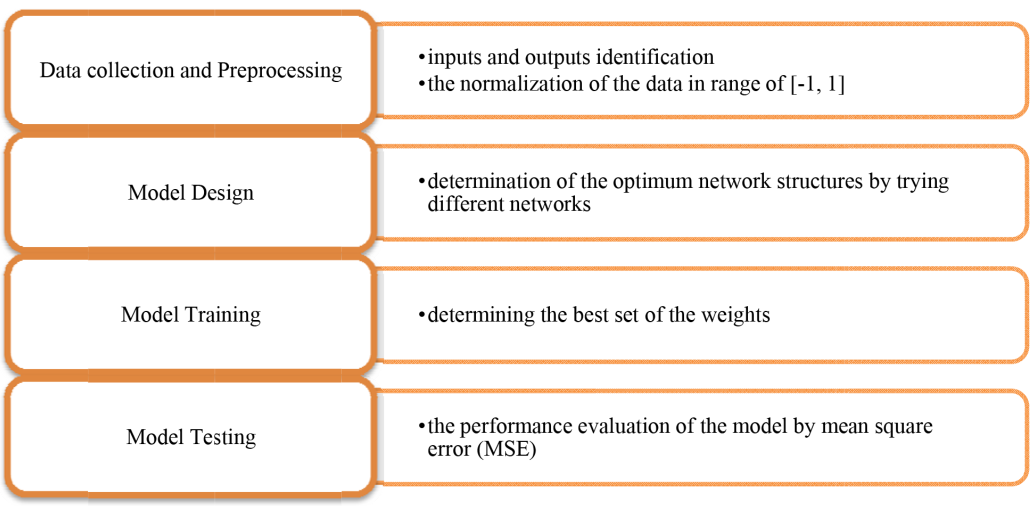

Fig. 5. Steps of the model development process.

3.2.2. Multi-layer perceptron (MLP)

MLP modeling method has been utilized to specify and compare the effect of the operational parameters of the processes and the reactor performance. As mentioned before, multi-layer perceptron (MLP) is the most common type of supervised neural networks in the field of modeling and prediction. This network is composed of an input layer, an output layer, as well as at least one hidden layer. Like the other types of the neural networks, this process should be trained. Training is the process of determining the best set of weights [52] with the aim of minimizing an error function by searching for a set of weights that causes the network to generate the exact or nearest outputs to targets [53]. Fig. 5 shows the development process of the model.

In order to normalize the preprocessing data in the range [–1, 1] the data have been scaled with respect to minimum and the maximum of whole data, by MATLAB™ function

Mapminmax [33]. About 82 runs have been carried out in the laboratory in order to generate the demanded data in various operational conditions. The data normally divided into three groups which were training, validation, and testing subsets. In this study, 60% of data were used for training, 15% for validation, and 25% for testing. To avoid random correlation, these subsets were randomly selected from the whole data. For comparing predictions and experimental data, all of the outputs should be converted inversely by scaling them to their original values [33]. In order to reach proper model configurations, the numbers of hidden neurons were varied from 6 to 20 and for activation function, hyperbolic tangent (tansig), logarithmic sigmoid (logsig), and linear (purelin) were used and compared with the same training, testing, and validating data. There are many algorithms to train neural networks. In this study, Levenberg–Marquardt has been used as one of the most common training methods and MATLAB™ "trainlm" learning algorithm was used for this purpose. Training process continued automatically until the error on validation data started to increase [54]. The mean square error (MSE) (Eq. (3)) was used as the performance function in this analysis separately for the VSS removal efficiency and generated electrical power density.

$$MSE = \frac{1}{n}\sum_{k=1}^{n}(Ti - Oi)^2 \quad (3)$$

where T and O are targets or experimental data and network outputs or predicted data, respectively.

The optimum conditions of VSS removal efficiency and generated power density have been investigated considering the input variables influent VSS, temperature, and pH. Regression analysis was used for a better understanding of the match quality between the ANN responses and target values [53].

Fig. 6 demonstrates that the correlation coefficients (R) for training, validating, and testing subset data were more than 0.95, 0.98, 0.84 and 0.95, respectively. These observations mean that there are good agreements between the experimental data and the prediction data of ANN.

Although Fig. 7 compares the output data of the model versus the targets. The purpose of the training process is to find the set of weight values that will cause the output from the neural network to match the actual target values as closely as possible. According to Fig. 7, the output and target values of the VSS removal of the MFC are relatively close to each other.

Similar to the VSS removal efficiency, Fig. 8 shows the correlation coefficients (R) for training, validating, and testing subset data for the generated electrical power density which were more than 0.95, 0.98, and 0.84 and 0.95, respectively. These values mean that there are good agreements between the experimental data and the prediction data of ANN.

Fig. 9 demonstrates the high compatibility of output data of the model versus the targets for the generated electrical power density.

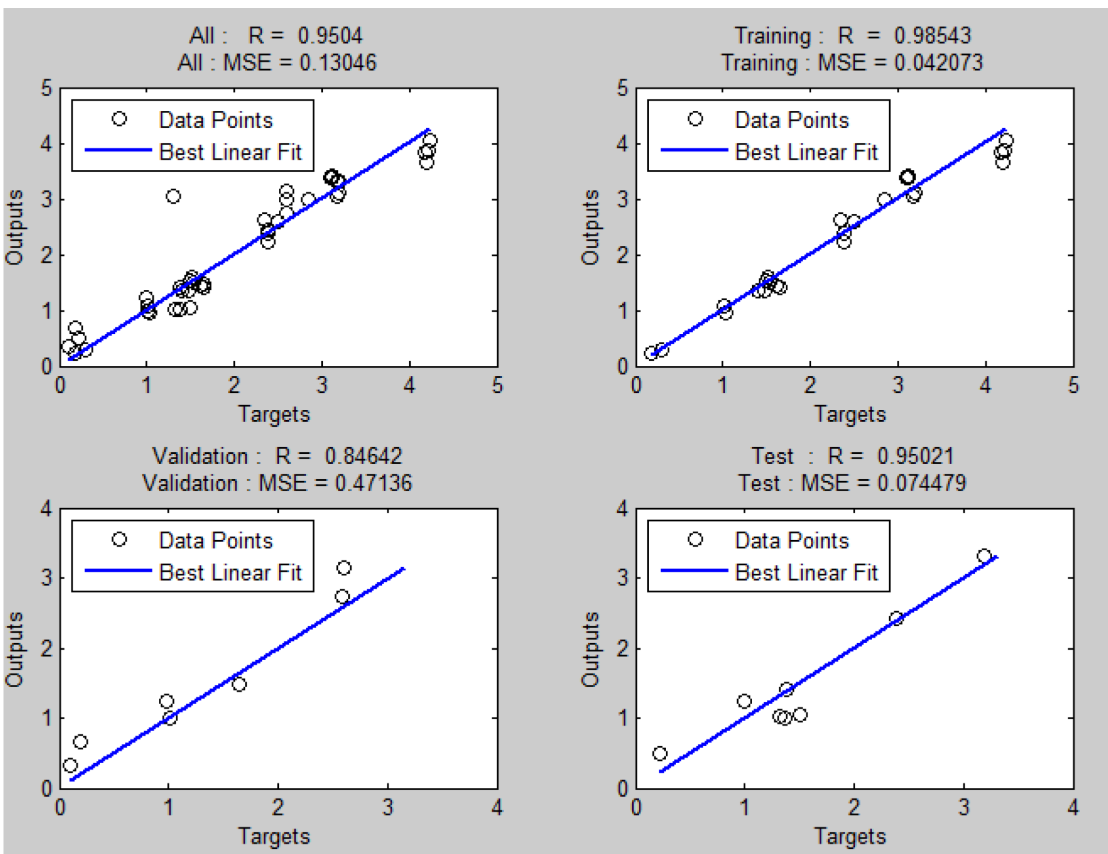

Fig. 6. the correlation coefficients (R) for training, validating, and testing subset data considering the VSS removal efficiency.

Table 3 demonstrates the results of the modeling by MLP and the determined impact level of each operational parameter on the reactor performance.

According to Table 3, the VSS content of the added waste-activated sludge to the MFC has the highest effect on the generated electrical power density. It seems that higher content of the VSS of the added waste activated sludge to the MFC provides higher feed for the electricity-generating microorganisms. Therefore, they would be able to generate more electricity. The impacts of the temperature and the pH value on the generated electrical power density of the MFC are remarkable (32% and 27%, respectively), too.

Also, all of the operational parameters affect the VSS removal of the process. Among the parameters, the temperature has the highest impact on the VSS removal efficiency of the process. Also, the impacts of pH and the VSS content of the added waste activated sludge

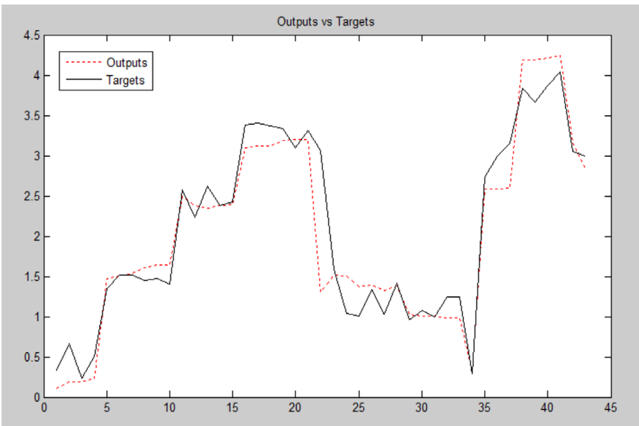

Fig. 7. The comparison of outputs versus targets of MLP model considering the VSS removal efficiency.

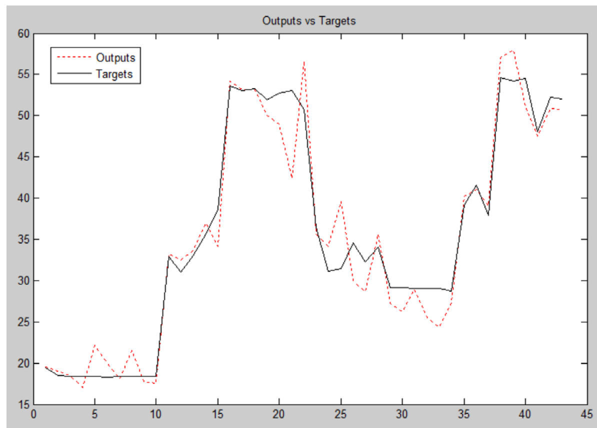

Fig. 9. The compatibility of outputs vs. targets of MLP model considering the generated electrical power density.

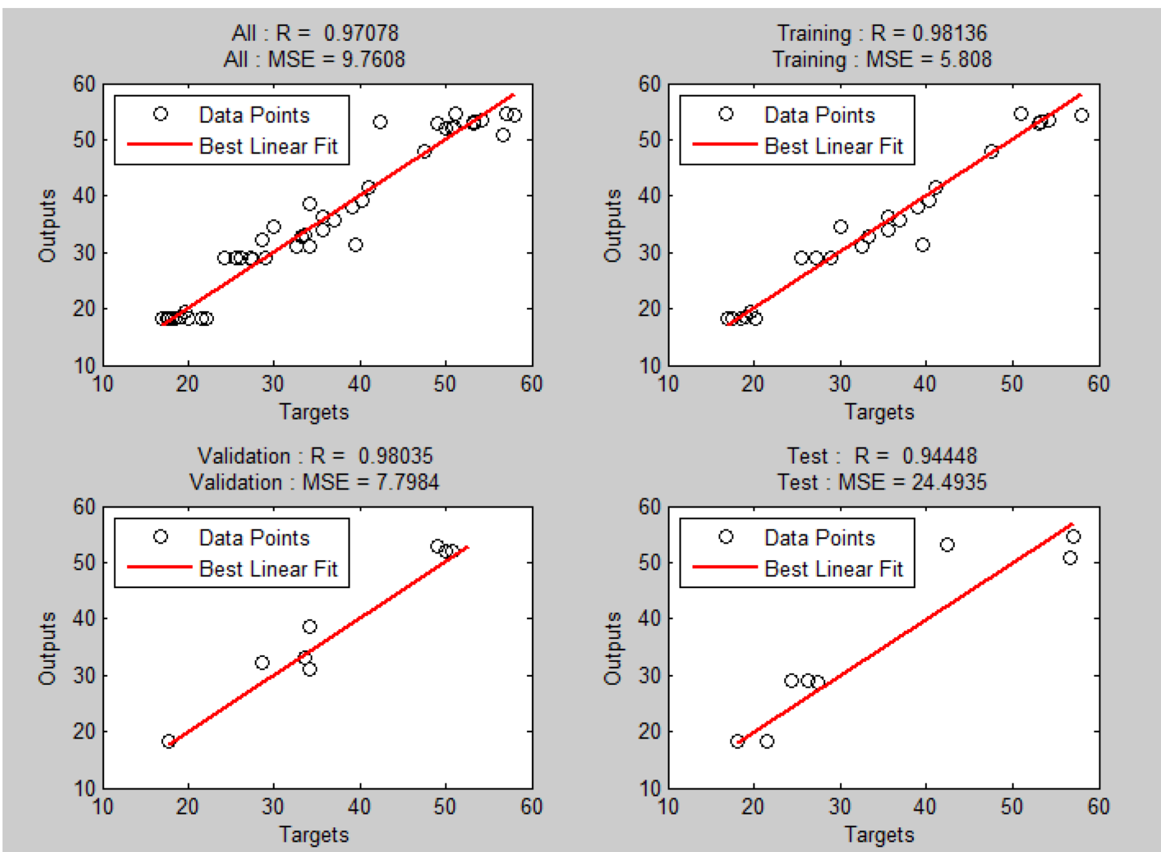

Fig. 8. The correlation coefficients (R) for training, validating, and testing subset data considering the VSS removal efficiency.

were remarkable on the VSS removal performance of the MFC.

3.3. The investigation and the comparison of the model's results and the experimental observations

Table 4 compares the KSOFM modeling outputs and the results of the experiments. According to the table, the determined ranges by KSOFM modeling process are highly compatible with the experimental evaluations which prove this fact that the designed model is reliable enough to be considered in prediction or investigation the performance of the reactor in different operational conditions.

The results of MLP modeling demonstrated that all of the evaluated operational parameters have noticeable impacts on the generated electrical power density and the VSS removal efficiency of the MFC. Regarding the results of MLP, among the operational parameters, the temperature has the highest impact level on the VSS removal efficiency and the VSS of the added waste activated sludge has the highest impact level on the electrical power generation of the MFC. Also, according to both of the experimental results and the outputs of the models, the electricity generating performance of the cell by changes in the operational conditions demonstrates approximately the same trend with aerobic stabilization process. Also, the optimal operational conditions ranges for the VSS removal and the electricity generation processes have high compatibility and overlap with each other.

Table 3
The impact level of the operational parameters on the MFC performance

Variables	The impact level of the operational parameters, %		
	Temperature, °C	pH of the cathode chamber	The VSS of the added waste activated sludge, mg/L
Electrical power generation	32	27	41
VSS removal	45	27	28

These observations are proved by the literature. Increasing the temperature has two opposite effects on the behavior of MFC reactor. By elevating the temperature, the activity of various microorganisms would be intensified and this event improves the VSS removal efficiency as well as the generated power density of the reactor. Also, the internal resistance of the system against proton exchange decreases, remarkably [39,55–58]. These trends can be explained considering this fact that at high and low values of the temperature and pH, the electricity generating microorganisms are not able to work properly. Therefore, the processes in the MFC which are majorly biological will not be able to proceed in these conditions [59–61]. But, because the processes in the cathode chamber are aerobic, this growth in biological activity increases the demand of DO. On the other hand, any increase in temperature decreases the concentration of available oxygen in the solutions remarkably especially at temperatures higher than 45ºC [42,59–61]. Also, at higher temperatures, the biological activity of the reactor both in the aerobic digestion and electricity generation processes reduces and this parameter controls the effectiveness of the processes [60,62–67]. Also, at low temperatures, the biological activity of the MFC decreases and this parameter controls the effectiveness of the both aerobic digestion and electricity generation processes at low temperatures [51,64, 68–69]. In very high and very low values of pH, the microorganism's activities and the ion exchange processes would be limited and as a result, the electricity generation would be decreased [18,51,65]. Also, the number of the species that can work efficiently in neutral conditions is remarkably higher than acidic or basic conditions [18,70–72]. So, the maximum value of generated power density of the cell achieved at 35°C. Also, as mentioned before, in higher values of the VSS of the added waste activated sludge to the MFC, the amount of the generated electrical power density increases. This result is completely reasonable because the VSS of the waste-activated sludge provides food and energy for electrogenic microorganisms. Changing the operational conditions to optimal temperatures and pH values for electrogenic microorganisms increase their metabolic reactions and therefore, improves occurring processes in the cell chambers [2,18,40,71–73]. It means that higher consumption of the volatile organic content of the sludge and as a result, the generation of the higher amounts of electricity by the MFC [29,42,47,74–76].

Table 4
The comparison of the results of KSOFM modeling and experimental investigations

Parameter		Determined operation conditions for the best performance of the reactor		Clarifications
		KSOFM	Experimental	
Operational conditions	pH	6.3–7.5	7 ± 0.1	Compatible
	Temperature, °C	35–41	35 ± 2	Compatible
	The VSS content of the added waste activated sludge, mg/L	4310–4920	4410 ± 250	Compatible
	Dissolved Oxygen (DO), mg/L	4.5–5	4.8 ± 0.05	Compatible
Responses	The VSS removal efficiency, %	48–52.6	54 ± 5	Compatible
	The maximum generated power density, W/m^3	3.1–3.62	3.282 ± 0.05	Compatible

Table 5
The reported electrical power density, generated from various substrates by MFC

Source of the substrate		Maximum generated power density, $mW \cdot m^{-3}$	MFC configuration	Reference
Waste activated sludge	Dairy industry wastewater	621	Two chamber	77
	Food processing wastewater	230	Two chamber	78
	Chocolate industry waste	1500	Two chamber	79
Anaerobic sludge		203–488	Single chamber	80–81
Domestic wastewater		718–727	Single chamber	82–83
Aerobic and anaerobic sludge		360	Single chamber	84
Petroleum refinery wastewater		330	Two chambered	85

3.4. The comparison of the generated electricity in current study with the reported results in literature

Table 5 shows the maximum values of the generated power density from various substrates by single or two chamber MFCs, reported in the literature.

The maximum amount of the generated electrical power density in optimal conditions of the current study is determined about 320 $mW \cdot m^{-3}$. Comparison of this value with reported values in Table 5 shows that the waste activated sludge of the municipal wastewater treatment plant is an acceptable substrate for electrogenic microorganisms in the MFCs.

4. Conclusion

The two-chambered MFC with municipal waste-activated sludge demonstrated its effectiveness for electricity generation and VSS removal. The study results showed that the use of waste-activated sludge as both anolyte and catholyte for the electricity generation is promising in the optimal conditions. Also, the results of the experiments validated by Kohonen self-organizing feature maps (KSOFM) and multilayer perceptron (MLP) as two kinds of artificial neural network (ANN) techniques. According to the experimental data validated by KSOFM modeling, the MFC shows its best performance in the pH values close to 7 and the temperatures around 35°C for both VSS removal and electricity generation. The VSS removal and the generated electrical power density of the MFC are higher when the VSS content of the added waste-activated sludge is higher, too. Also, all of the investigated operational parameters showed a noticeable impact level on the MFC performance, according to the results of MLP modeling. But among the operational parameters, the VSS of the added waste-activated sludge and the temperature showed the highest impact level on the electricity generation and the VSS removal efficiency of the MFC, respectively. Overall, the findings of this study suggest that the waste-activated sludge of municipal wastewater treatment plants has a potential for future MFC practical applications as it can provide a biodegradable waste source for electricity generation.

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