Microbial Fuel Cell: Optimizing pH of Anolyte and Catholyte by Using Taguchi Method

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In this study, the Taguchi method was used to optimize pH of anolyte and catholyte in terms of obtaining maximum power density of a microbial fuel cell (MFC). The anolyte pH and catholyte pH were selected as operating parameters, with their corresponding levels. L_{16} orthogonal array was selected for the experimental design. Each of experiments was repeated two times for calculating the signal-to-noise (S/N) ratio. However, based on Taguchi method, optimum anolyte and catholyte pH were observed 8 and 1, respectively. A confirmation experiment was done with the optimum conditions and based on that, maximum power density was observed at 2491.42 mW/m^3. Analysis of variance (ANOVA) was carried to recognize the percentage contributions of operating parameters in the process and accordingly it was found 53.59% for anolyte and 46.40% for catholyte pH. The optimization study of both pH suggests low internal resistances and high Coulombic efficiency that favored for both high power density. © 2016 American Institute of Chemical Engineers Environ Prog, 00: 000–000, 2016

Keywords: wastewater treatment, biofilm, optimization, Taguchi-ANOVA method, MFC

INTRODUCTION

A microbial fuel cell (MFC) can be defined as a system in which microorganisms work as a catalyst to convert chemical energy into electrical energy. It is also an alternative process for wastewater treatment [1]. In spite of lower power density than fuel cells, MFC has been considering as an alternative source for the wastewater treatment and energy production.

In MFCs, microorganisms use organics as food and produce electrons (e^-) and protons (H^+). These electrons are transported from an electron donor to an electron acceptor. Numerous substances are used as an electron donor (acetate, glucose, etc.) or electron acceptor (oxygen, permanganate, etc.) [1–4]. Electrons from the anode to the cathode are transported via an external electrical circuit, and finally received by molecular oxygen (as per Eq. (1)), which is generally supplied from the air [1].

$$O_2+4H^++4e^- \rightarrow 2H_2O \tag{1}$$

Performance of MFC is affected by many factors such as electrode material, electrode size, selection of electrolyte, pH of anolyte and catholyte, and type of membrane (proton exchange membrane, cation exchange membrane, etc.) [5–8]. All these factors are crucial for the performance of MFC. Nevertheless, inappropriate selection of all these factors results in losses such as activation losses, concentration losses, and ohmic losses [3]; and an ultimate reduction in power output.

Activation losses occur by reason of energy lost to initiate the oxidation or reduction reaction. Consequently, the electron takes maximum energy to transfer from the cell terminal enzyme to the anode surface [3]. Concentration losses arise when the flux of reactants to the electrode or flux of products from the electrode are insufficient, and, therefore, limits the rate of reaction. Ohmic losses rise when the solution and membrane produce resistance to ions (protons) conduction [3].

Activation losses can be reduced by improving electron transfer from bacteria to the anode and anode to the cathode. Hence, an appropriate pH condition is needed to make the favorable environment for bacteria. Concentration losses depend on the proton transfer from the anode to the cathode via a membrane. To mitigate the effect of concentration losses, there is a need to maintain a pH difference between the anodic chamber and the cathodic chamber. Otherwise, an accumulation of protons in the anodic chamber would reduce anolyte pH that adversely affects bacterial kinetics [9]. Limited proton transfer from the anode to the cathode can also limit the power generation; consequently, it is important to maintain catholye and anolyte pH [9]. The effect of anolyte and catholye pH has been explored by many researchers as given in Table 1.

In Table 1, several substances are used as electron donor or electron acceptor with different pH values. In most of the study, they used neutral or little alkaline pH values (6–9) in the anode chamber. It is because of controlling anodic medium close to the neutral pH condition would allow the electroactive biofilm to function better [15,19]. Behera and Ghagrekar [22], Behera *et al.* [23], and Yuan *et al.* [24] suggested that most anode-attached bacteria favor the alkaline pH conditions because of effective extracellular electron transfer and electrogenic bacterial growth.

Some researchers maintained cathode's chamber pH within the neutral range [12,18] which causes less number of protons available in the cathode chamber. As a result, poor transfer of electrons and protons from the anode to the cathode by an external circuit and through the membrane, respectively. However, some of them used acidic pH in the cathode chamber [4,17] which provided a higher availability of protons (H^+). These protons acted as a reactant in the cathodic reduction reaction. Hence, the number of electrons transfer from the anode to the cathode via an external circuit was increased [4]. Therefore, the presence of enough protons in cathode chamber also reduces the problem in the transportation of protons

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Table 1. Review for anolyte and catholyte pH with anode and cathode materials and power density.

pH		Anode		Cathode				
Anolyte	**Catholyte**	**Solution**	**Material**	**Solution**	**Material**	**MFC type**	**Power density**	**References**
8	2	Synthetic wastewater	Carbon fiber	0.5 M $KMnO_4$	Carbon fiber	Two-chamber	1270.12 mW/m^3	Present study
—	1.0	Acetate	Graphite	Seawater	Platinum coated carbon	Two-chamber	5 W/m^2	[4]
7	—	Acetate + potassium phosphate	Titanium plates	Potassium phosphate	Titanium plates	Bipolar stack two chamber	144 W/m^3	[10]
6–8	7.5	Mixed consortia	Graphite plates	Ferricyanide + phosphate buffer	Graphite plates	Two-chamber	62.70 mW/m^2	[11]
5.5–7.5	7.0	Synthetic wastewater (sucrose)	Stainless steel	Distilled water+ phosphate buffer	Graphite rod	Two-chamber	17.1 mW/m^2	[12]
6–10	—	Domestic wastewater	Graphite rod	Buffer solution	Carbon cloth with Pt-coating	Air-cathode SCMFC	660 mW/m^3	[13]
5.5–7	—	Synthetic wastewater (glucose)	Graphite rod	—	Graphite rod + Pt-coating	Air-cathode SCMFC	9.8 W/m^3	[14]
10	—	Swine wastewater	Graphite	—	Carbon fiber cloth	MFC stack	226.3 mW/m^2	[15]
6–9	—	Synthetic wastewater (sucrose)	Carbon paper	Phosphate buffer solution	Carbon paper	Two-chamber	181.48 mW/m^3	[16]
7–9	2–10	Cow dung and distilled water	Graphite fiber brush electrode	Potassium ferricyanide	Graphite fiber brush electrode	Two-chamber	0.46 W/m^3	[17]
6.5–7	7.0	Food wastewater	Graphite sheet	Phosphate buffer	Graphite sheet	Two-chamber	230 mW/m^2	[18]
4–9	—	Food waste leachate	Granular graphite	NaCl solution	Granular graphite	Two-chamber	657.80 mW/m^3	[19]
6–9	—	Sucrose	Carbon paper	Phosphate buffer solution	Carbon paper	Two-chamber	98.8 mW/m^2	[20]
6.0	7.5	Synthetic wastewater (glucose)	Graphite plates	Ferricyanide + phosphate buffer	Graphite plates	Two-chamber	82.77 mW/m^2	[21]

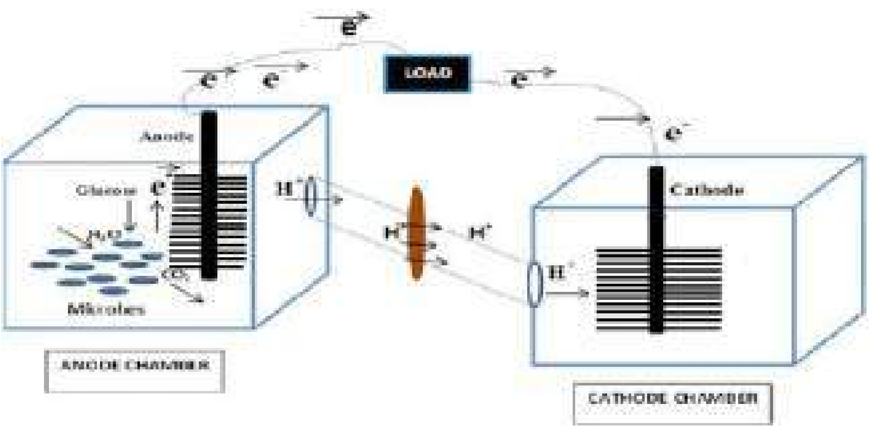

Figure 1. General schematic diagram of a two-chambered MFC. [Color figure can be viewed at **wileyonlinelibrary.com**]

Table 2. Factors and their levels for Taguchi method.

Factor	Levels			
Anodic pH, A	6	7	8	9
Cathodic pH, B	1	2	3	4

and electrons, and counter balance the ohmic losses caused by the membrane. Due to this, the power density was increased as a result of a reduction in internal resistances (ohmic losses).

However, most of the studies in Table 1 used one factor at a time, i.e. variation in anode pH or cathode pH. There is no any experimental study that considered variation in anode and cathode pH simultaneously and could suggest the optimum pH conditions in anode and cathode chambers at a time. However, to perform the experiment efficiently, too many experiments are needed, and they often results in factor effect bias. The design of experiment has drawn specific attention to cope with full factorial experiments design. In the design of experiment, the Taguchi method developed by Genichi Taguchi and popular for fractional factorial design has been using successfully in applied industries. Details about the Taguchi's orthogonal array can be found elsewhere [25–28].

Therefore, in this work, an H-type MFC was used with an anodic pH range of 6–9 and cathode pH range of 1–4. The response in terms of power density and treatment of wastewater was studied based on the variation of anodic and cathodic pH simultaneously. As per Taguchi, the L_{16} orthogonal array was selected according to two factors and four levels. The relation between factors and response was determined by signal-to-noise (S/N) ratio, and accordingly optimum pH combination was found. The analysis of variance (ANOVA) was also used to find the most affecting parameters on the response. And finally, for confirmation, optimized conditions were checked on experimental MFC set-up.

MATERIALS AND METHODS

Experimental Setup

Figure 1 shows the schematic diagram of the experimental MFC set-up used in the study. Experiments were performed in duplicate with operating two MFC set-ups in parallel. The anode and cathode chambers were separated by a proton-exchange membrane (PEM, Ultrex Membrane International) with an area of 4.15 cm^2. Each chamber had a total volume of 400 mL with a working volume of 350 mL. Carbon fiber brush electrodes (Jalark carbon products, Vadodara, Gujarat, India) were used in MFC reactors. The anode electrode was connected to an external resistor of 220 Ω with copper wire for an active biofilm generation by proper transport of electrons and protons. The external electric current was monitored with a digital multimeter. Chemical oxygen demand of influents and effluents was carried out by the close reflux method as per APHA [29]. pH, conductivity, and ORP was monitored with a digital meter (HACH). Total suspended solids (TSS) and volatile suspended solids (VSS) of sludge used in MFC were also measured as per APHA [29].

Voltage and current were measured by a digital multimeter (UNI-T brand digital multimeter 1000 V). Current density and power density were calculated by Eqs. (2) and (3), respectively. Coulombic efficiency (CE) was calculated by Eq. (4). The polarization slope method was used for calculating internal resistances [3].

$$\text{Current density} = I/V \tag{2}$$

$$\text{Power density} = \text{Voltage} \times \text{Current density} \tag{3}$$

$$\text{CE} = \frac{M\int_0^t I\,\mathrm{d}t}{Fbv_a\Delta\text{COD}} \times 100 \tag{4}$$

Where CE is Coulombic efficiency (%), M is the molecular weight of oxygen (32 g/mol), I is the electric current (A), F is the Faraday's constant (96,485 C/mol), b is the number of electrons exchanged per mole of oxygen (4), ΔCOD is the removal of COD (mg/L), and V is the working volume of the anode chamber (L).

Experimental Procedure

Synthetic wastewater was used as the anodic substrate in the MFC reactors. It contained following components: glucose (1000 ± 10 mg/L); protein (85 ± 5 mg/L); $CaCl_2$ (18 ± 3 mg/L); $MgSO_4.7H_2O$ (24 ± 5 mg/L); NH_4Cl (60 ± 5 mg/L); KH_2PO_4 (14 ± 5 mg/L) in distilled water [30]. The COD of synthetic wastewater was 1020 ± 50 mg/L. $KMnO_4$ solution (0.5 M) was used as catholyte [2]. MFCs were operated in batch mode (Figure 1). The anode chambers having 350 mL of synthetic wastewater were initially inoculated with anaerobic digester sludge (100 mL/d capacity up-flow anaerobic sludge blanket (UASB)-based sewage treatment plant, Surat, Gujarat). The desired pH of electrolytes in MFCs was set by using 0.1 M NaOH and 1 N HCl solutions [4,17]. In this study, MFC was operated for 30 days to develop biofilm on anode at neutral pH with synthetic wastewater for proper acclimatization of microbes. After stabilization of MFC pH was varied

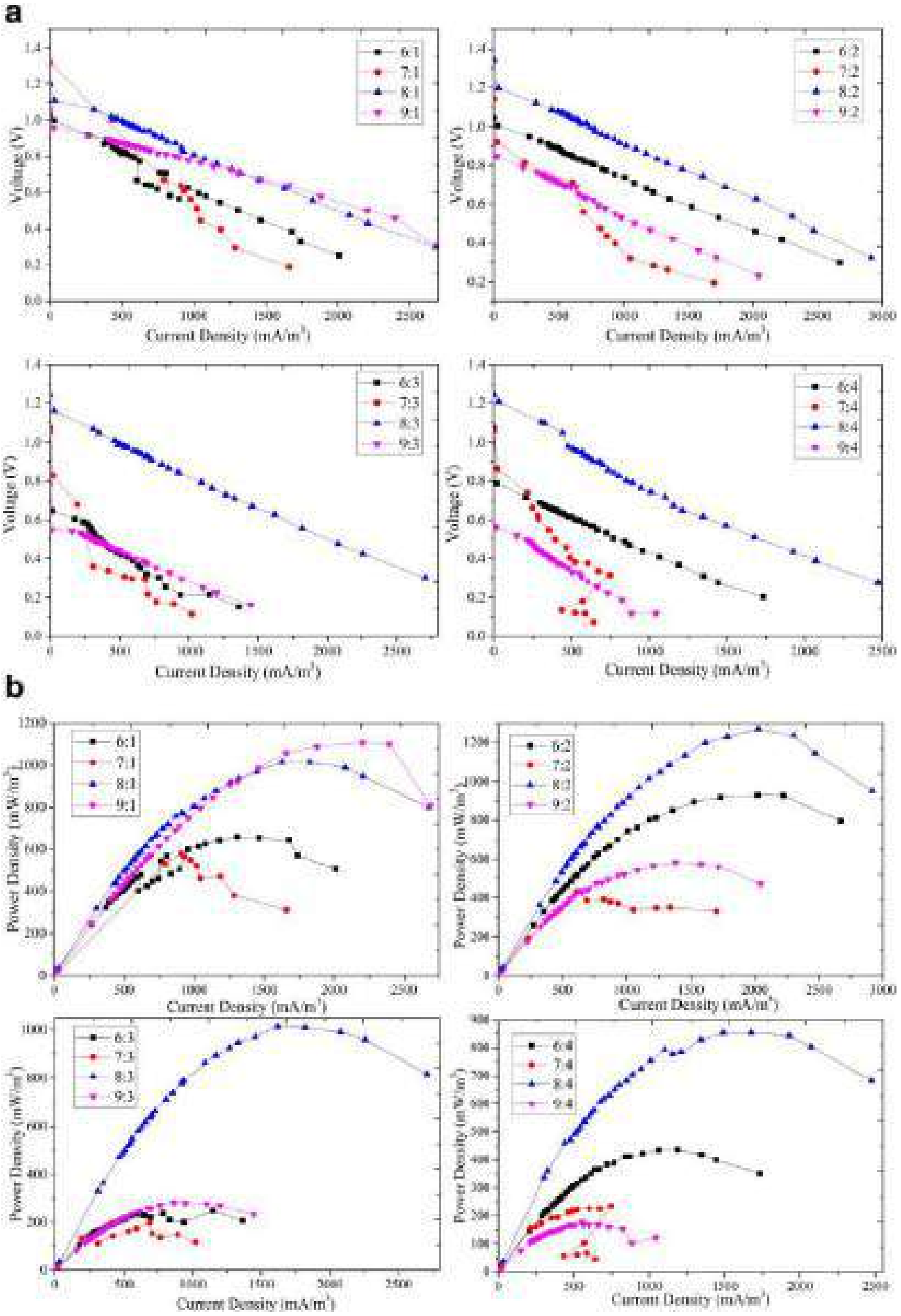

Figure 2. (a) Polarization curves recorded for L_{16} orthogonal array current density versus voltage. (b) Polarization curves recorded for L_{16} orthogonal array current density versus power density. [Color figure can be viewed at **wileyonlinelibrary.com**]

in anode and cathode. The first experiment was repeated thrice on the MFC for the duration of 24 h. Every time pH of the feed solution was changed, a voltage increased continuously for two and half to three hours after which it got stabilized. When a stable output was obtained from the MFC, biofilm was considered stabilized. This implies that biofilm acclimatize in two

Table 3. Internal resistance in L_{16} orthogonal experiment.

pH		Current density (mA/m^3)	Power density (mW/m^3)	Internal resistance (Ω)
Anolyte	Catholyte			
6	1	2011.42	659.52	1086.47
6	2	2668.57	929.2	775.98
6	3	1362.85	236.5	1540.98
6	4	1731.42	436.20	1002.7
7	1	1662.85	579.66	2167.7
7	2	1700	350.48	1509.47
7	3	1020	199.39	2307.35
7	4	645.71	234.90	2173.91
8	1	2677.14	1016.22	865.22
8	**2**	**2914.29**	**1270.12**	**842.83**
8	3	2702.85	1013.94	914.08
8	4	2474.28	853.23	1008.59
9	1	2685.71	1107.26	611.76
9	2	2042.85	582.18	917.8
9	3	1442.85	282.08	892.12
9	4	1042.85	178.66	1437.2

and half to three hours with respect to the voltage. Successively, experiments were performed two times at all pH conditions for a duration of 24 h, which was found suitable for acclimatized biofilm and stable voltage output. The COD, ORP, and conductivity of system were measured after completion of experiment (after 24 h).

Taguchi Method

Experimental parameters and their levels were determined by using literature and preliminary tests as given in Table 2 [11, 13, 16, 19–21]. The L_{16} (4^2) orthogonal array was accepted as the most proper method to determine the experimental plan for two parameters of each four levels [25–28]. The performance of MFC could be affected by factors known as controllable (signal) or uncontrollable (noise). The ratio of the effect of controlled factors to the effect of noise factors is known as the S/N ratio [26]. In this process, each experiment was repeated two times with same condition. Performance characteristics selected to be the optimization criteria were divided into three categories, the larger-the-better, the smaller-the-better, and the nominal-the-best. The quality output of this work was the maximum power density, which fit into the larger-the-better characteristics [31].

For larger-the-better condition:

$$\mathrm{S/N} = -10 \times \log 10 \left(\frac{1}{n_r} \sum_{i=1}^{n_r} \frac{1}{Y_i^2} \right) \tag{5}$$

Analysis of Variance

Process parameters, which greatly affect the power density, were determined through ANOVA [32]. The Minitab 17® software was used for analyzing the collected data. In ANOVA, we find the effect of parameters and their contribution to the performance of the process. It is derived from separating total variability of S/N ratio into contribution for each pH values and error, and usage of *F*-test for comparison of factors of the total deviation. *F*-value is a tool that delivers a decision at some confidence level as to whether these evaluations are significantly different or not. *F*-value is a ratio of sample variances. Now, total variability of S/N ratio is computed by the sum of squared deviation (SS) from the total mean of S/N ratio for two factors at four different levels.

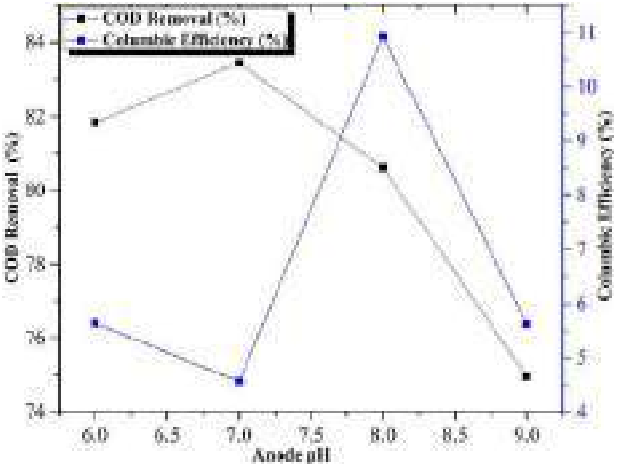

Figure 3. Dependency of COD removal and Coulombic efficiency on the anode pH value. [Color figure can be viewed at **wileyonlinelibrary.com**]

$$SS_T = \sum_{p=1}^{n} SS_p + SS_e \tag{6}$$

Here, total sum of square deviations SS_T is divided into two types, for example, sum of square deviation of the pH process parameter (SS_P) and sum of square errors (SS_e) [33].

A verification experiment is important for investigating the presence of interaction among controlled parameters. Therefore, optimized conditions were verified in MFC reactors. MFC reactors were fed with anolyte and catholye and left for 3 days for biofilm generation. Subsequently, pH was maintained and observed at 4th day for both of reactors.

RESULTS AND DISCUSSION

Effect of Anodic and Cathodic pH on Polarization and Power Density Curves

According to the L_{16} array, MFC was run, and accordingly polarization curves were obtained by varying the external resistance from 100,000 Ω to 200 Ω at all pH conditions. The relation between the cell voltage and the current (density) can be visualized by the polarization curves as presented in Figures 2a and 2b. It can be observed that with increasing external resistance, current generation decreases which displays typical fuel cell behavior.

Figure 2a displays the variation in voltage produced in the MFC. Under all pH conditions, the voltage drop was very quick when external resistance was very low, and it got stabilized at higher resistance. From Figure 2a, at the initial stage, a sharp fall in the voltage can be seen which is due to activation over-potential. Furthermore, a straight line after sharp fall attributed to the combine effect of mass transport efficiency and ohmic losses. These losses arise as a result of internal resistances of MFC. Table 3 is prepared for showing the performance (current and power density) of MFC based on different pH combinations in anolyte and catholyte as per Figures 2a and 2b. Internal resistances were also calculated for each combination of Figure 2a and given in 5th column of Table 3. Anolyte pH value 8 gave high voltage and current, with all catholyte pH condition as a result of minimum internal resistance as shown in Table 3. Anolyte pH 8 and catholyte pH 2 combinations gave a high open circuit voltage of 1.34 V with high current density 2914.29 mA/m^3. For all combinations of pH 6, 7, and 9, a low current generation

Table 4. L_{16} orthogonal array, power density, and S/N ratio for pH effect.

Exp. no.	A	B	Y1 mW/m^3	Y2 mW/m^3	S/N	Standard deviation	Mean mW/m^3
1.	6	1	659.52	653.71	56.35	4.11	656.62
2.	6	2	929.20	917.43	59.31	8.32	923.32
3.	6	3	248.09	233.48	47.62	10.33	240.78
4.	6	4	436.20	434.70	52.78	1.06	435.45
5.	7	1	579.66	567.24	55.17	8.78	573.45
6.	7	2	434.11	390.85	52.27	30.58	412.48
7.	7	3	199.39	175.06	45.39	17.20	187.22
8.	7	4	226.67	225.88	47.09	0.55	226.27
9.	8	1	1016.23	1015.09	60.13	0.80	1015.66
10.	8	2	1270.12	1236.63	61.95	23.68	1253.38
11.	8	3	1013.95	1008.73	60.09	3.69	1011.34
12.	8	4	853.66	853.23	58.62	0.30	853.45
13.	9	1	1107.26	1100.28	60.85	4.93	1103.77
14.	9	2	582.18	572.99	55.23	6.49	577.58
15.	9	3	282.08	279.83	48.97	1.59	280.95
16.	9	4	178.66	171.11	44.84	5.34	174.88

Table 5. Response table for S/N ratio based on larger is better.

Level	Anodic pH, A	Cathodic pH, B
1	54.01	58.13
2	49.98	57.19
3	60.20	50.52
4	52.48	50.84
Delta	10.22	7.61

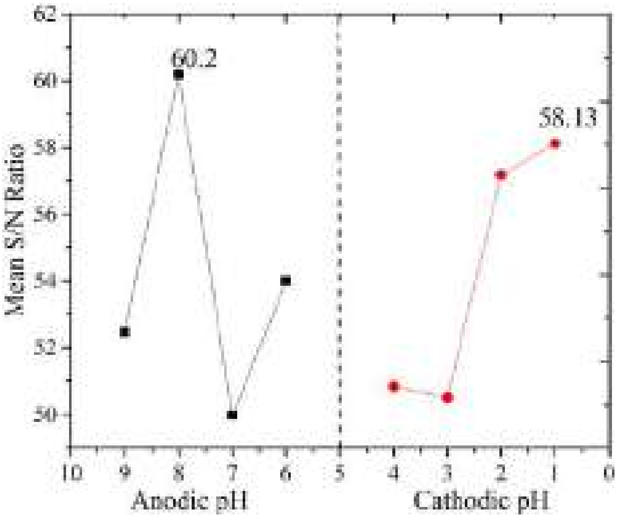

Figure 4. The mean effect plot for S/N ratio. [Color figure can be viewed at **wileyonlinelibrary.com**]

was observed because of poor electron and proton transfer as a result of high internal resistances as shown in Table 3.

The relation between current densities and power densities is shown in Figure 2b. For all pH conditions, it was found that power density first increases with current density up to a certain resistance, where internal resistance equal to the external resistance, after which the power density starts decreasing. The power density achieved during polarization at pH greater than 2 (i.e., 3 and 4) were 4 times lower than the maximum value (1270.12 mW/m^3) achieved in MFC at cathodic pH 2. Power densities at pH 8 were 2 times higher than at pH (6 and 7), and 1.46 times higher than pH 9. Therefore, results show that pH value 8 in the anodic chamber and 2 in the cathode chamber will be suitable pH value for treating synthetic wastewater (glucose).

This study shows that an appropriate pH combination would surely improve the MFC performance. In this study, maximum power and current density output were achieved at the pH combination of 8 and 2. Increased anolyte pH (higher than neutral pH) leads to a shift toward more negative anode potential thus resulting in improved performance of MFC [13]. Moreover, under a little alkaline condition, the exoelextrogens at the anode have a better chance of outcompeting methanogens for the degradation of organic matter in the wastewater.

High alkaline pH condition (beyond pH 8), deceased in current and power density. As a result, leads to reducing bacterial activity as well as a slower electric discharge activity of bacteria. Subsequently, low catholyte pH gave a better performance of the MFC because of protons are available in high concentrations and participate as the reactants in the cathodic reaction. A presence of sufficient protons in the cathode chamber also eliminates the limitation caused by the transport of protons and counter balancing the ohmic losses caused by the membrane. Based on this study, a little alkaline and acidic pH condition in anode and cathode chamber, respectively, were favorable for high power density in MFC. In Table 1, Kaushik and Chetal [17], also checked the effect of pH in MFC; however, there was not any interaction study between anolyte and catholyte pH. That study; Kaushik and Chetal [17], considered one factor at a time (anolyte pH or catholyte pH). The present study considers the interaction between anolyte and catholyte pH along with finding the optimized condition.

Effect of Anodic pH on Percentage COD Removal and Coulombic Efficiency

Figure 3 shows the COD removal efficiency and Coulombic efficiency (CE) based on anolyte pH and with its corresponding cathodic pH. Coulombic efficiency can be defined as the fraction (or percent) of electrons recovered as current versus number of electrons removed as oxidation of the substrate as Eq. (4) [3].

From Figure 3, it can be observed that peak Coulombic efficiency of 10.92% was achieved at pH 8. At pH value 7, we got higher COD removal (83.45%), however, low Coulombic efficiency on account of poor proton transfer at a reduced proton concentration gradient across the membrane

Table 6. Result of variance analysis for the maximum power density value of experiment.

	Degree of freedom	Sum of square	Average of squares	*F*	*P*	Percentage contribution
A	3	227.37	113.68	7.23	0.009	53.59
B	3	196.89	98.45	6.26	0.014	46.40
Error	9	94.90	47.45			
Total	15	518.66		13.49		

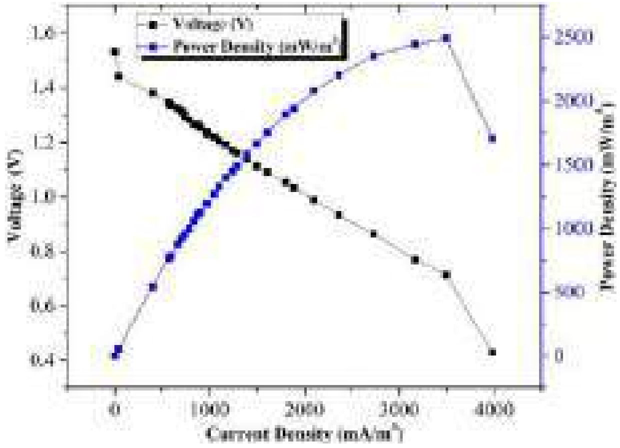

Figure 5. Polarization curve for verification experiment at optimized condition. [Color figure can be viewed at **wileyonlinelibrary.com**]

[34]. This pH value (7) is favorable for methanogenesis that contributes high COD removal [14]. At pH value 9, decrease in Coulombic efficiency, as well as COD removal, might be attributed to reducing the bacterial activity of bacteria at highly alkaline pH [11].

Optimization Study

Based on Taguchi method, larger-the-better performance characteristics (Eq. (5)) was used for computing S/N ratio. Table 4 presents S/N ratio values, where A and B are factors that represent anolyte pH and catholyte pH, respectively. Y1 and Y2 are the observed maximum power densities at first and second run, respectively, at same operating conditions.

Table 5 displays response table for S/N ratio. Here, we calculated the total variation in S/N ratio by factors (anolyte pH and catholyte pH). Total variation (S_T) can be calculated by Eq. (7) [25,27].

$$S_T=\left[\sum_{i=1}^{n}\left(\frac{S}{N}\right)_t^2\right]-\left[\frac{\sum_{i=1}^{n}(\frac{S}{N})_i}{n}\right]^2 \qquad (7)$$

Here, n is the total number of experiments, t is the total sum of S/N ratio, and i is the S/N ratio at particular pH condition.

Figure 4 was prepared for predicting the influences of parameters on the performance characteristics by using data from Table 5. The optimum values of both parameters for obtaining maximum power density are the highest S/N ratio value calculated by Eq. (5). The numerical value of the maximum point in both graphs gives the best value for that parameter.

From Figure 4, we found an optimized pH value for anolyte and catholye. However, based on L_{16} experimental analysis, anolyte pH value 8 and the catholyte pH value 2 gave a maximum power density among all sixteen experiment as a result of low internal resistances. But Taguchi method shows high S/N ratio for optimized condition 8 (A_3) and 1 (B_1) for anolyte and catholye pH, respectively. Therefore, these should be the optimized condition and should give maximum power density.

Analysis of Variance

The *F*-value for both parameters is simply a ratio of the mean of the square error. A parameter that have large *F*-value, that parameter have a greater impact in obtaining maximum power density. The optimal combination of both parameters can be predicted by using performance characteristics and ANOVA. The results of variance analysis for experiments are given in Table 6.

Degree of freedom for the factors computed by the number of levels (called k) minus 1 (k−1). *P*-value is used for calculating null hypothesis. If *P*-value is less than 0.05 then we can reject the null hypothesis and can conclude that pH is imposing significant difference on process. From Table 6, it can be concluded that both parameters (anolyte pH and catholyte pH) are important for the process. On account of both have approximate equal percentage contribution (53.59% anolyte pH and 46.4% catholyte pH) in the process which shows the interaction between parameters. However, anolyte pH have a large impact on the process due to high percentage contribution; but, catholyte pH should also be considered as an important parameter because it also have an approximate same impact on the process.

According to optimized conditions, i.e. anolyte pH 8 and catholyte pH 1, we organized two sets of reactor for verification experiment. Reactors were fed with anolyte and catholyte and left for 3 days for a better biofilm generation. Subsequently, pH was maintained, and data were observed at 4th day for both of the reactors. Average values from the system are displayed in Figure 5, which gave high power density (2491.42 mW/m^3) and current density (3494.28 mA/m^3). As a result of 3-day duration, it gave an active biofilm and minimum internal resistance (629.67 Ω) due to optimum conditions. Whereas at anolyte pH 8 and catholye pH 2 gave the power density of 1270.12 mW/m^3 and the current density of 2914.29 mA/m^3 with a high internal resistance of 842.83 Ω. Because of the continuous run of MFC at optimum conditions (8 and 1), it gave better microbial activity and proper proton transfer from the anode to the cathode.

CONCLUSIONS

It is important to optimize operating factors affecting the performance of MFC. Therefore, in this work, the Taguchi method was used to optimize anodic pH and cathodic pH for maximum power density. The orthogonal array L_{16} was used for experimental design, and it reduced experimental time and cost. The most influencing factor was evaluated by ANOVA. Results can be summarized as follows:

- The optimum parametric condition within the selected factor values are 8 for anodic pH and 1 for cathodic pH. From verification experiment, 2491.42 mW/m^3 power density was obtained at optimum pH conditions.

- According to ANOVA, both anodic and cathodic pH have been found the most influencing factors affecting the performance of MFC.
- This study may be very useful for commercialization of MFC.

ACKNOWLEDGMENT

Both authors acknowledge the financial support from the Institute (SVNIT, Surat) Research Grant [Dean (R&C)/1503/2013-14] from the project entitled "Treatment of Combined Textile and Municipal Wastewater by Bio-Electrochemical Processes using Novel Cross-linked Microbial Fuel Cell" for carrying out research work.

LITERATURE CITED

1. Kishimoto, N., Hachiro, H., Fukunaga, H., Yoshioka, N., & Murakami, Y. (2013). Effect of active control of air-cathode pH on the performance of a microbial fuel cell, Journal of Water and Environment Technology, 11, 453–461.
2. You, S., Zhao, Q., Zhang, J., Jiang, J., & Zhao, S. (2006). A microbial fuel cell using permanganate as the cathodic electron acceptor, The Journal of Power Sources, 162, 1409–1415.
3. Logan, B.E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., & Rabaey, K. (2006). Microbial fuel cells: Methodology and technology, Environmental Science & Technology, 40, 5181–5192.
4. Erable, B., Etcheverry, L., & Bergel, A. (2009). Increased power from a two-chamber microbial fuel cell with a low-pH air-cathode compartment, Electrochemistry Communications, 11, 619–622.
5. Rozendal, R.A., Hamelers, H.V., & Buisman, C.J. (2006). Effects of membrane cation transport on pH and microbial fuel cell performance, Environmental Science & Technology, 40, 5206–5211.
6. Du, Z., Li, H., & Gu, T. (2007). A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy, Biotechnology Advances, 25, 464–482.
7. Sun, G., Thygesen, A., Ale, M.T., Mensah, M., Poulsen, F.W., & Meyer, A.S. (2014). The significance of the initiation process parameters and reactor design for maximizing the efficiency of microbial fuel cells, Applied Microbiology and Biotechnology, 98, 2415–2427.
8. Boas, J.V., Oliveira, V.B., Marcon, L.R.C., Pinto, D.P., Simões, M., & Pinto, A.M.F.R. (2015). Effect of operating and design parameters on the performance of a microbial fuel cell with *Lactobacillus pentosus*, Biochemical Engineering Journal, 104, 34–40.
9. Kim, B.H., Chang, I.S., & Gadd, G.M. (2007). Challenges in microbial fuel cell development and operation. Applied Microbiology and Biotechnology, 76, 485–494.
10. Dekker, A., Heijne, A.T., Saakes, M., Hamelers, H.V., & Buisman, C.J. (2009). Analysis and improvement of a scaled-up and stacked microbial fuel cell, Environmental Science & Technology, 43, 9038–9042.
11. Raghavulu, S.V., Mohan, S.V., Goud, R.K., & Sarma, P.N. (2009). Effect of anodic pH microenvironment on microbial fuel cell performance in concurrence with aerated and ferricyanide catholytes, Electrochemistry Communications, 11, 371–375.
12. Jadhav, G.S., & Ghangrekar, M.M. (2009). Performance of microbial fuel cell subjected to variation in pH, temperature, external load and substrate concentration, Bioresource Technology, 100, 717–723.
13. Puig, S., Serra, M., Coma, M., Cabré, M., Balaguer, M.D., & Colprim, J. (2010). Effect of pH on nutrient dynamics and electricity production using microbial fuel cells, Bioresource Technology, 101, 9594–9599.
14. Martin, E., Savadogo, O., Guiot, S.R., & Tartakovsky, B. (2010). The influence of operational conditions on the performance of a microbial fuel cell seeded with mesophilic anaerobic sludge, Biochemical Engineering Journal, 51, 132–139.
15. Zhuang, L., Zheng, Y., Zhou, S., Yuan, Y., Yuan, H., & Chen, Y. (2012). Scalable microbial fuel cell (MFC) stack for continuous real wastewater treatment, Bioresource Technology, 106, 82–88.
16. Wei, L., Han, H., & Shen, J. (2012). Effects of cathodic electron acceptors and potassium ferricyanide concentrations on the performance of microbial fuel cell, International Journal of Hydrogen Energy, 37, 12980–12986.
17. Kaushik, A., & Chetal, A. (2013). Power generation in microbial fuel cell fed with post methanation distillery effluent as a function of pH microenvironment, Bioresource Technology, 147, 77–83.
18. Mansoorian, H.J., Mahvi, A.H., Jafari, A.J., Amin, M.M., Rajabizadeh, A., & Khanjani, N. (2013). Bioelectricity generation using two chamber microbial fuel cell treating wastewater from food processing, Enzyme and Microbial Technology, 52, 352–357.
19. Li, X.M., Cheng, K.Y., & Wong, J.W. (2013). Bioelectricity production from food waste leachate using microbial fuel cells: Effect of NaCl and pH, Bioresource Technology, 149, 452–458.
20. Jia, Q., Wei, L., Han, H., & Shen, J. (2014). Factors that influence the performance of two-chamber microbial fuel cell, International Journal of Hydrogen Energy, 39, 13687–13693.
21. Mohan, S.V., Saravanan, R., Raghavulu, S.V., Mohanakrishna, G., & Sarma, P.N. (2008). Bioelectricity production from wastewater treatment in dual chambered microbial fuel cell (MFC) using selectively enriched mixed microflora: Effect of catholyte, Bioresource Technology, 99, 596–603.
22. Behera, M., & Ghangrekar, M.M. (2009). Performance of microbial fuel cell in response to change in sludge loading rate at different anodic feed pH, Bioresource Technology, 100, 5114–5121.
23. Behera, M., Jana, P.S., More, T.T., & Ghangrekar, M.M. (2010). Rice mill wastewater treatment in microbial fuel cells fabricated using proton exchange membrane and earthen pot at different pH, Bioelectrochemistry, 79, 228–233.
24. Yuan, Y., Zhao, B., Zhou, S., Zhong, S., & Zhuang, L. (2011). Electrocatalytic activity of anodic biofilm responses to pH changes in microbial fuel cells, Bioresource Technology, 102, 6887–6891.
25. Ross, J. P. (1988). Taguchi techniques for quality engineering, New York: McGraw-Hill.
26. Logothetis, N., & Wynn, H. P. (1989). Quality through design: Experimental design, off-line quality control, and Taguchi's contributions, Oxford: Clarendon Press.
27. Phadke, M. S. (1989). Quality engineering using robust design, NJ, USA: Prentice Hall PTR Upper Saddle River.
28. Roy, R. K. (2001). Design of experiments using the Taguchi approach: 16 Steps to product and process improvement, John Wiley & Sons.
29. Eaton, A. D., & Franson, M. A. H. (2006). Standard methods for the examination of water and wastewater, Washington, DC: American Public Health Association.
30. Pardeshi, P., & Mungray, A. (2014). High flux layer by layer polyelectrolyte FO membrane: Toward enhanced performance for osmotic microbial fuel cell, International

Journal of Polymeric Materials and Polymeric Biomaterials, 63, 595–601.

31. Kaytakoğlu, S., & Akyalçın, L. (2007). Optimization of parametric performance of a PEMFC, International Journal of Hydrogen Energy, 32, 4418–4423.
32. Maiyar, L.M., Ramanujam, R., Venkatesan, K., & Jerald, J. (2013). Optimization of machining parameters for end milling of Inconel 718 super alloy using Taguchi based grey relational analysis, Procedia Engineering, 64, 1276–1282.
33. Gandhi, P.J., Murthy, Z.V.P., & Pati, R.K. (2012). Optimization of process parameters by Taguchi robust design method for the development of nano-crystals of sirolimus using sonication based crystallization, Crystal Research and Technology, 47, 53–72.
34. Gil, G.C., Chang, I.S., Kim, B.H., Kim, M., Jang, J.K., Park, H.S., & Kim, H.J. (2003). Operational parameters affecting the performance of a mediator-less microbial fuel cell, Biosensors and Bioelectronics, 18, 327–334.