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RESEARCH ARTICLE - BIOLOGICAL SCIENCES

Configuration Analysis of Stacked Microbial Fuel Cell in Power Enhancement and Its Application in Wastewater Treatment

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Abstract The present study examined the performance of stacked microbial fuel cell for higher power generation and also for treating brewery waste effluent. The stackable microbial fuel cells are connected in series, parallel and series–parallel using standard glucose media produces increased power density of 813, 1546.57 and 2418 mW m^{-2}, respectively, corresponding to 288 mW m^{-2} from single cell as control. Series–parallel setup arrangement with brewery effluent produces maximum power density of 1345 mW m^{-2} with 81% of COD removal efficiency within 72 h of operation. The series–parallel configuration system shows significant COD removal and maximum power density due to their better stability of redox potential in overall cells. The significant reduction of TDS, TSS was also observed in series–parallel connection over other stacking MFCs. The results of the present study highlight the importance of combining electrical circuit along with stacking in generating stable and high power from MFC for practical applications.

Keywords Microbial fuel cell · Stacking · Wastewater · Voltage reversal · Power density

1 Introduction

Microbial fuel cells (MFC) are a bio-electrochemical system that employs bacteria for oxidation of organic and inorganic matters for current generation [1]. In anode, bacteria produces electrons and protons via anaerobic oxidation of organic matter along with CO_2 as a by-product. Electrons in the anode chamber transferred via an electrical circuit to cathode compartment and combine with proton to form water as by-product and release energy. Energy generation in MFC is always a continuous process until the substrate lasts in the anode chamber.

After first ever experimental proof of voltage generation from organic matter [2], MFC technology has lured many researchers on using this technology as an effective alternative solution to the energy crisis and wastewater treatment [3]. In the past decades, extensive research on applications of MFC and its usability into various other fields such as biological oxygen demand (BOD) sensor, wastewater treatment, seawater desalination [4–6] was reported. However, even after a considerable development in MFCs, researchers face many technical, scientifical and economical issues that need to be overcome by using various approaches like using cost-effective materials, working on large scale setup and generation of stable and useable power for practical applications [7]. A single unit MFC normally has an open circuit voltage (OCV) of ∼1 V, but it has working voltage of only 0.4–0.5 V which may due to bacterial metabolism, electrode over potentials and high impedance.

Various technical approaches have been used to improve the power generation in MFCs, among one is to stacking the multiple units of MFC in series and parallel shows a positive result in past. However, the power generation in these setups is also lower than required for practical applications as previous researchers focussed on stacking either in series or parallel at a time. Therefore, an altered approach has been attempted in this study by interconnecting MFC units in series–parallel connection and examining its effect on power generation.

Power generation from stacking many individual units together in series exhibits voltage reversal phenomena which further reduces the final voltage [8,9]. Voltage reversal phe-

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nomenon occurred only in one cell among multiple MFCs results in lowering of whole system efficiency [10]. Therefore, the present study also focused on using multiple capacitors-based circuit to overcome voltage reversal phenomena.

The improvement of power generation was tested by using series–parallel configuration along with series and parallel under batch mode and also investigated using brewery effluent treatment as an application.

2 Materials and Methods

2.1 Chemicals and Instruments

Glucose, Yeast extract, peptone, asparagine, KH_2PO_4 (potassium di-hydrogen phosphate), K_2HPO_4 (di-potassium hydrogen phosphate), KCl (potassium chloride), potassium ferricyanide, vitamins and amino acid solution were purchased from Himedia, India. COD digester, DRB200 pocket calorimeter, and COD reagents were purchased from Hach, USA. Cyclic voltameter (CHI instrument, USA) and Auto-range digital multimeter (MECO, USA).

2.2 Microorganism and MFC Configuration

Klebsiella pneumoniae, (KR061436) an efficient dissimilatory iron reducing bacteria, has been isolated and identified from sewage water collected from Cubbon park sewage treatment plant, Bangalore, India, as described by Yuvraj and Aranganathan [11]. The preserved stock culture was activated using glucose basal medium and used for further experiments.

Identical dual chambered MFCs were constructed using polycarbonate bottle with a working volume of 50 ml each, connected together by PVC tube (2 cm × 1 cm) as a salt bridge. Graphite blocks with a surface area of 0.0015 m^2 were pretreated with 1 M HCl, followed by rinsing with deionized water was used as electrodes and were placed 1 cm away from salt bridge. Anolyte is composed of optimized glucose basal media contains following components (g/l): glucose (28.91), asparagine (5.37), yeast extract (0.5), peptone (0.5), KH_2PO_4 (0.33), K_2HPO_4 (3) and KCl (0.2), whereas catholyte contains potassium ferricyanide along with 100 mM phosphate buffer solution of pH 7.0 [12].

Anode chamber was inoculated with 1×10^6 cells/ml of activated bacterial strain and open circuit voltage (OCV) measurement was taken up to 10 days. Once MFC units attainable OCV, individual units were stacked in various configurations like series (anode of one unit to cathode of another unit), parallel (anode and cathode of one unit connected to respective electrodes of another unit) and series–parallel (sets of equal units in series are interconnected in parallel i.e. 2 + 2 + 2) as shown in Fig. 1 and various electrochemical analysis were performed. All the experiments were carried out in triplicates, and results were reported as mean value.

2.3 Electrochemical Measurement

Open circuit voltage and other parameters defining electricity generation like current (mA) and power (mW) were recorded every 5 h using digital auto-range multimeter with the external load of 1 KΩ. On attaining stable OCV, maximum power density (MPD) and impedance were measured for all configurations. Polarization curve determining MPD was measured by using linear sweep voltammetry from electrochemical analyzer. Polarization experiment was conducted by setting initial OCV as zero at a rate of 0.01 $mV\,s^{-1}$, where anode acts as working electrode and cathode (+0.36 V) as both reference and counter electrode [13]. Power density can be calculated by dividing power generated to that by surface area of electrode (normalized anode surface area of 15 cm^2).

Electrochemical impedance of MFC system (anolyte resistance, charge transfer and diffusion resistance) was determined by performing electrochemical impedance spectroscopy (EIS) in open circuit condition. EIS measurement was performed at a frequency range of 100 kHz–100 MHz with AC amplitude of 5 mV as described by He et al. [14]. Projected point intersection of Nyquist plot and X-axis determines the whole cell impedance. All electrochemical measurement was carried out at an initial temperature of 25 °C.

2.4 Voltage Reversal in Stacked Operation

On connecting multiple MFC units in series occasionally final stack voltage is either lower than expected or nearly very low due to the process of voltage reversal (VR). Voltage reversal was investigated by connecting six individual cells (5 working + 1 dead cell) in series–parallel along with series and parallel connections in the presence of external resistance of 1 KΩ. Dead cell was fed with growth media except any carbon source, as this substrates disproportion leads to voltage reversal.

The fate of induced voltage reversal was investigated using simple circuit breadboard consisting of multiple capacitors (10,000 μF—4 Nos.) and relay switches (5VDC/1A SPDT, Micro Relay, Radioshack, TX, USA). Programmable microcontroller (Mega2560, Arduino, Italy) was used to control the activity of relay switches for charging and discharging. Circuits were connected in parallel to MFCs for testing the elimination of voltage reversal, while capacitors were discharged in series to array of LED bulbs.

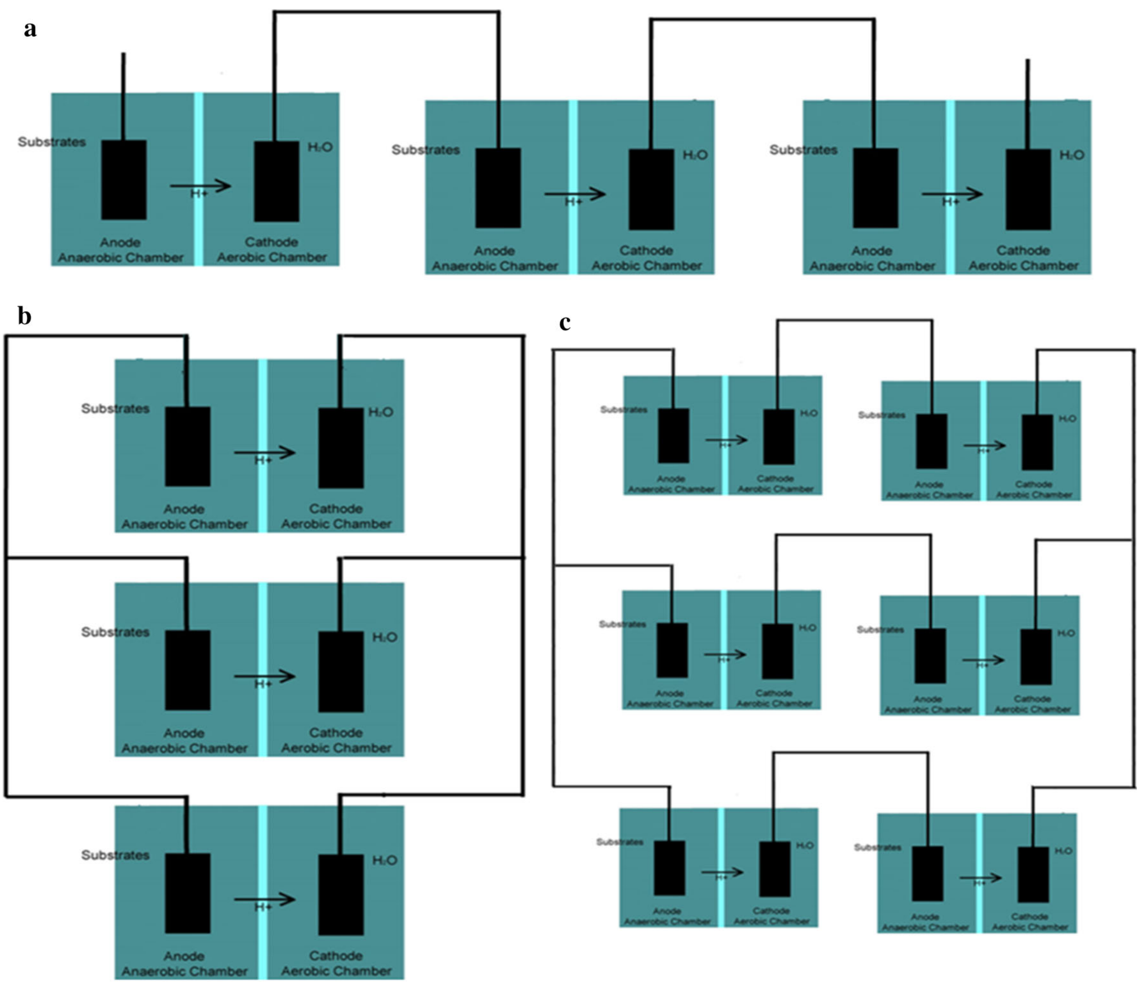

Fig. 1 Connection pattern of MFC units: **a** parallel, **b** series and **c** series–parallel configuration

2.5 Brewery effluent Treatment

Brewery effluent was used as organic source for electricity generation in various stacked configurations. Brewery industry effluent was collected from Khodays brewery industry, Bangalore, Karnataka, in an air tight container and stored at 4 °C prior to analysis. The physicochemical parameters of the sample were analyzed immediately after transported to the laboratory and used for MFC operation. After 72 h of MFC operation, the biodegradation process was monitored by measuring total suspended solids (TSS), total dissolved solids (TDS), biological oxygen demand (BOD) and chemical oxygen demand (COD) [15–17]. During this operation, polarization curve was generated on achieving stable OCV. COD removal efficiency of the anolyte was calculated using following equation

$$\text{COD removal efficiency (\%)} = \frac{\text{COD}_i - \text{COD}_f}{\text{COD}_i} \times 100 \quad (1)$$

where COD_i and COD_f are COD value before and after MFC operation, respectively.

3 Results and Discussion

3.1 Voltage Generation from Individual and Stacked MFC

Polarization and power density curve of single and stacked MFCs is shown in Fig. 2a–d. At stable operation, individual MFC was achieved a maximum OCV of 0.950 ± 0.03 V with a corresponding power density of 288 mW m^{-2}, whereas connecting 6 MFCs electrically in series–parallel connection was achieved a maximum OCV of 1.85 V with a corresponding power density of 2418 mW m^{-2} which is nearly 7.4-fold higher than a single cell. The observed result was significantly higher than series (813 mW m^{-2}) and parallel (1546 mW m^{-2}) stacked MFC. Higher power generation in series–parallel connection is due to the addition of both volt-

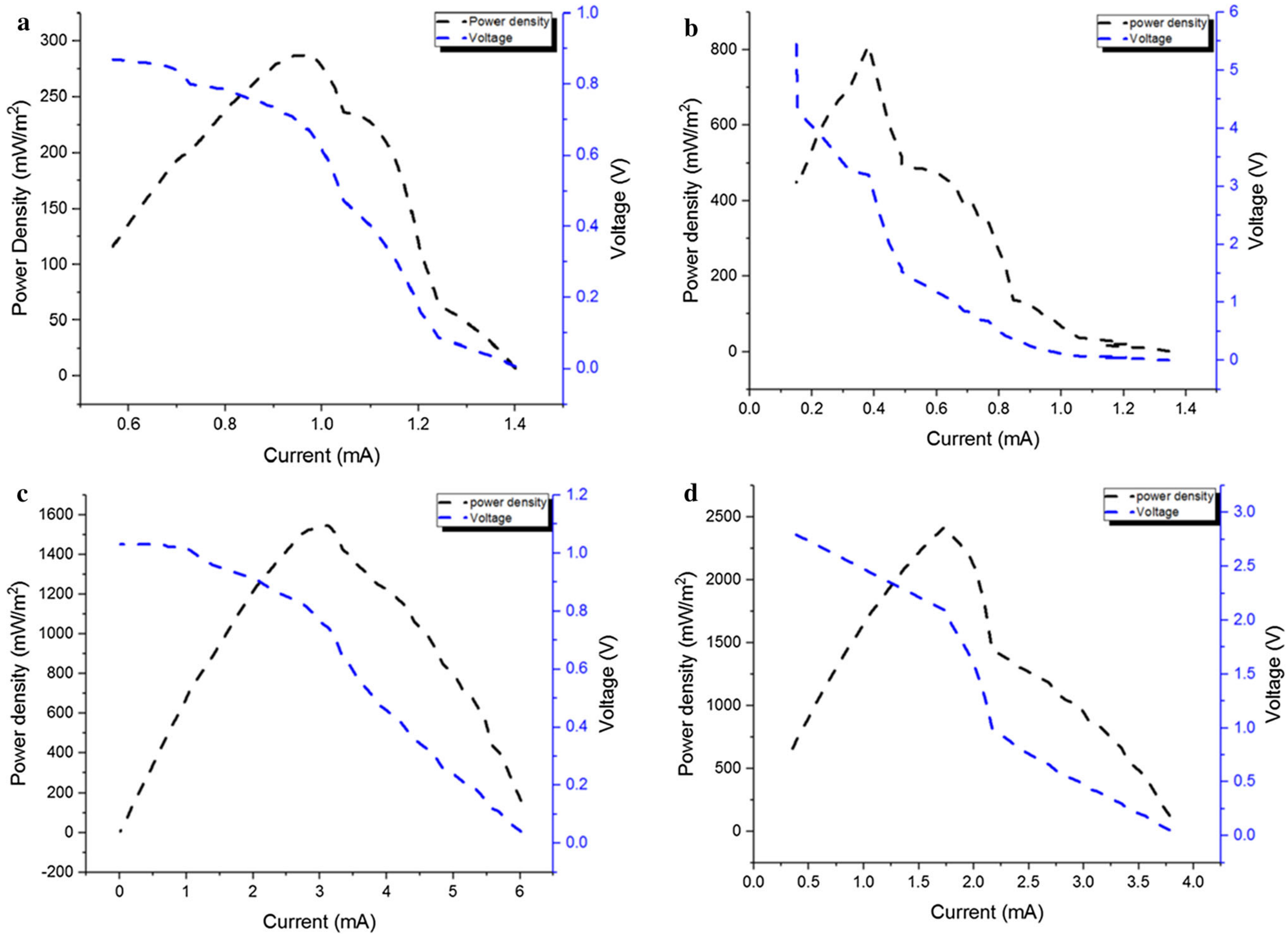

Fig. 2 Polarization and power density curve. **a** Single cell, **b** series, **c** parallel and **d** series–parallel (2 + 2 + 2)

Table 1 Performance parameters of different stacked MFC configuration

MFC connection type	OCV (V)	Voltage (V)	Current (mA)	Power (mW)	Power density (mW m^{-2})
Single	0.95	0.67	0.97	0.64	288.73
Series	5.70	3.202	0.38	1.21	813.25
Parallel	0.95	0.74	3.14	3.32	1546.13
Series–parallel	1.85	2.09	1.73	3.63	2418.72

age and current. Other electrochemical parameters defining the performance of stacked MFCs are shown in Table 1.

Previous researchers have studied the effect of stacking MFCs in power generation; Jafary et al. [18] connected three cells in series containing different carbon source and generated a maximum OCV of around 2 V with corresponding MPD of 109.45 mW m^{-2}. Furthermore, in the same study parallel combination generated an OCV of 0.687 V with corresponding power density of 128.72 mW m^{-2} which is much lower than MPD achieved by a single cell in the present study. In another study conducted by Gurung and Oh [19], three individual dual chambered with working volume of 300ml was connected in parallel generated MPD of 135 mW m^{-2} which is lesser than the present study.

EIS measurement reveals overall internal resistance of series–parallel combination of 114 Ω. Series configuration showed higher internal resistance of 1.1 KΩ over series–parallel combination (Fig. 3). Internal resistance of a MFC setup has significant impact on power generation.

Sathishkumar et al. [20] had reported very high internal resistance of 2.3 KΩ in single chambered microbial fuel cell which is nearly 20 times higher than the present observation. In another study conducted by Ieropoulus et al. [21] was also reported an internal resistance of 300 Ω on connecting

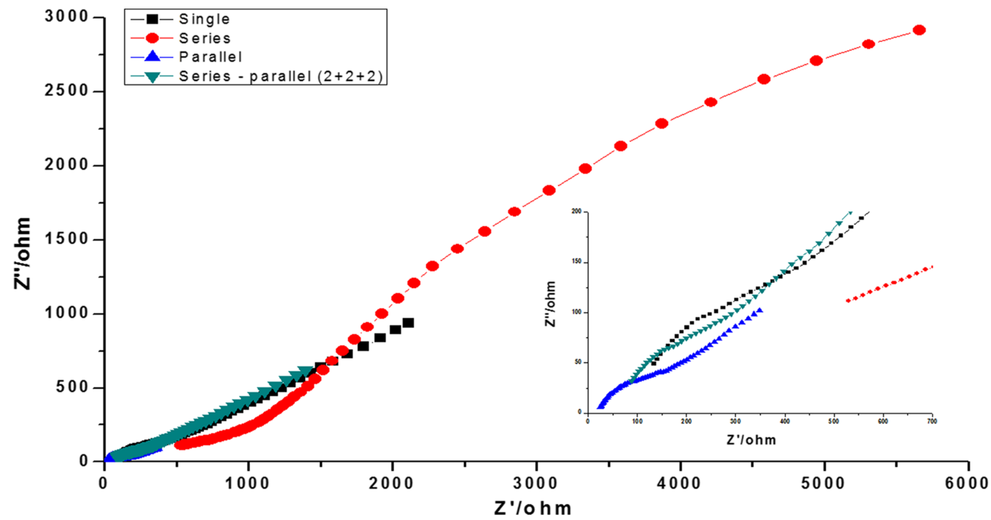

Fig. 3 EIS measurement of single and stacked configuration (*Inset* graph showing zoomed view of Nyquist plot)

5 cells in parallel configuration. The increasing power output in series–parallel configuration was achieved may due to a decrease in total internal resistance. Therefore series–parallel MFC configuration can be useful on connecting multiple cells together for its better performance.

3.2 Voltage Reversal Control

Open circuit voltage and closed circuit voltage of dead cell were found to be 0.15 and 0.007 V, respectively, at stable operation. On connecting the stacked MFCs with external resistance of 1 KΩ, series–parallel combination showed little decrease in voltage after 12 h of constant operation whereas in series showed drastic decrease after 9 h only. The moment voltage reversal phenomenon was observed stacked MFC was immediately connected to a series of capacitors. As soon as capacitor circuit was connected, voltage of the cells again reaches back to maximum stable voltage (Fig. 4).

Additionally, array of LED bulbs were connected to stacked configuration both with and without capacitors. Intensity of LED bulbs reduces suddenly on reaching voltage reversal stage, whereas intensity of LED bulbs restored on connecting to capacitor charged circuit.

Voltage reversal phenomenon was noticed in dead cell of stacked MFC after a particular time due to negative charging of dead cells, thus making the anode potential positive. VR occurs also due to low substrate concentrations in one cell relative to next cell; as a result anode potential became positive or equal to cathode potential of the adjacent cell [22]. An et al. [23] were successfully controlled voltage reversal by maintaining actual current density lower than critical threshold current density. Capacitor-based circuit employed in combination with stacked configuration for elimination

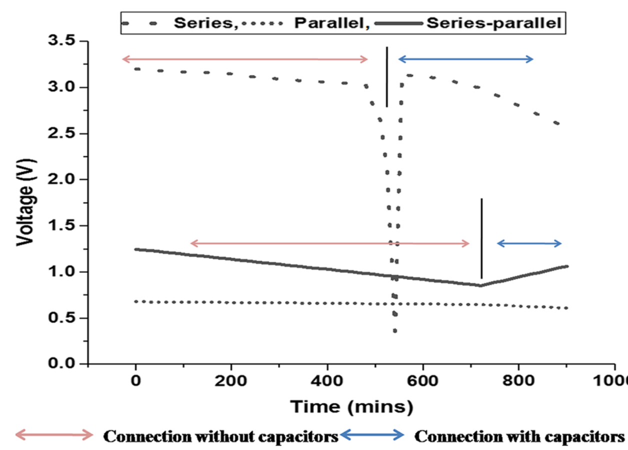

Fig. 4 Voltage reversal of stacked configuration and elimination its using capacitors circuit

of voltage reversal process is in accordance with the result reported by Kim et al. [24].

3.3 Performance of Stacked MFC in Wastewater Treatment

MFC can generate electricity by using wastewater; the physiochemical parameters of brewery effluent before inoculation in MFC were found to be pH of 6.2, 3226 mg/l of COD and 128 mg/l of BOD. COD/BOD removal assay is important parameters that define MFC characteristics of being a potential biodegradation. Figure 5 shows the COD removal efficiency of wastewater after 72 h of operation in MFC. Series–parallel configuration showed a significant removal efficiency of wastewater COD with 81% reduction whereas in series and parallel connection shows only 56 and 69%, respectively. Higher COD removal in series–parallel con-

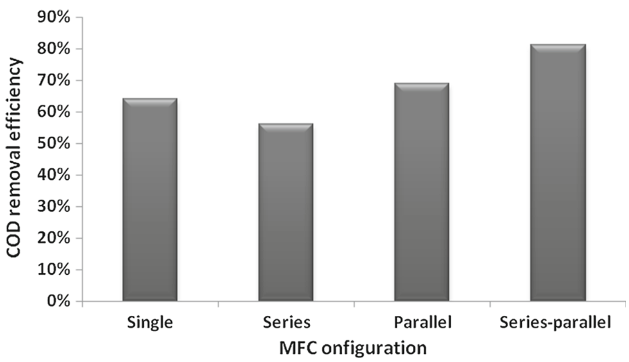

Fig. 5 Percentage COD removal efficiency in different MFC configuration

nection attributes to uniform and the stable voltage across each individual cell during stacked operation. Table 2 represents the physicochemical characteristic of effluent before and after treatment using different stacked configuration. A significant decrease in other parameters like BOD, TDS, and TSS was also observed in series–parallel stacked configuration over other configurations.

Polarization and power density curve of single and stacked MFCs inoculated with brewery effluent is shown in Fig. 6a–d. During the treatment process, OCV of MFC reactors increases gradually and attains maximum OCV of 0.8 ± 0.020 V in a single cell with the corresponding MPD of 191 $mW\,m^{-2}$. Series–parallel configuration generated a

Table 2 Physicochemical parameters of Brewery effluent before and after MFC

Brewery wastewater	pH	Before treatment				pH	After treatment (72 h)			
		COD	BOD	TDS	TSS		COD	BOD	TDS	TSS
Single	6.2	3226	128	1500	280	6.9	1165	78	845	187
Series						7.1	1419	100	970	205
Parallel						6.85	1000	68	797	168
Series–parallel						7.05	610	61	653	132

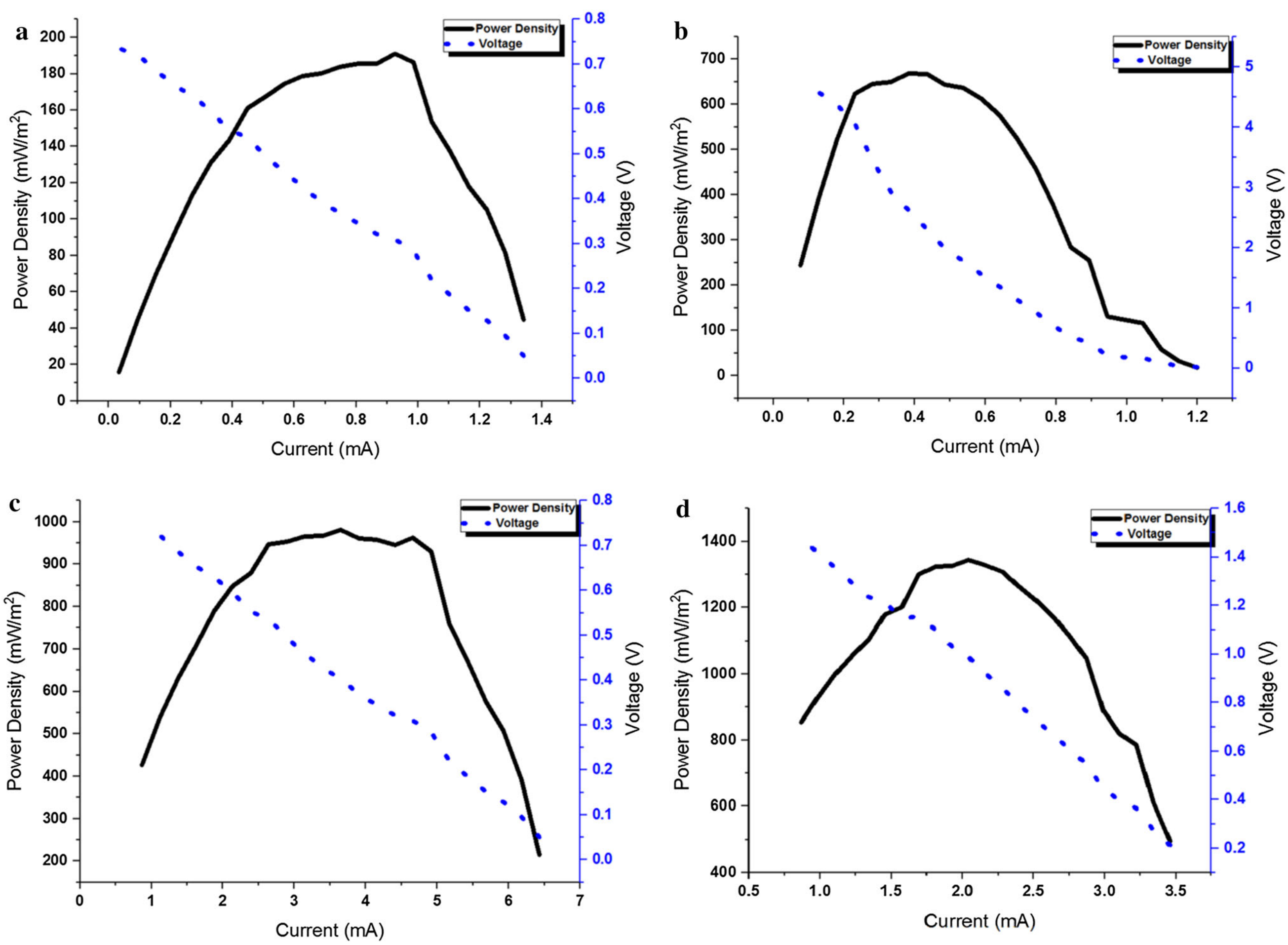

Fig. 6 Polarization and power density curve: **a** single cell, **b** series, **c** parallel and **d** series–parallel inoculated with brewery wastewater

Table 3 MFC performance of difference configuration inoculated with Brewery effluent

MFC connection type	OCV (V)	Voltage (V)	Current (mA)	Power (mW)	Power density ($mW\,m^{-2}$)
Single	0.81	0.31	0.93	0.2862	191.10
Series	4.85	2.61	0.38	1	668.91
Parallel	0.8	0.43	3.39	1.45	966.87
Series–parallel	1.54	0.98	2.04	2.01	1345.08

maximum OCV of 1.54 V with the corresponding MPD of 1345 $mW\,m^{-2}$ which is sixfold higher than a single cell and 2, 1.4-fold than series and parallel configuration, respectively (Table 3).

MPD achieved from the series–parallel combination in the present study is very much higher than MPD of 175.5 $mW\,m^{-2}$ achieved by connecting 5 units in parallel previously reported by Zhuang et al. [25]. In another study conducted by Wen et al. [26], MPD of 264 $mW\,m^{-2}$ was attained in continuous mode MFC system when inoculated with brewery waste effluent. Zhuang et al. [25] also reported increase in overall voltage and current from series and parallel MFC configuration with simultaneous swine wastewater treatment. In another study conducted by Ahn and Choi [7] MPD of 420 $mW\,m^{-2}$ was achieved in parallel connection mode with COD removal efficiency of 44% in continuous flow mode. The result of the present study shows a significant and promising output over the previous researches.

4 Conclusion

The importance of stacking configuration with respect to improve power and voltage generation was demonstrated in this study. Series–parallel staking was proved to be better among other configurations in terms of electricity generation and stable power output. Capacitor-based circuit was successfully employed to eliminate voltage reversal phenomena, a major limiting factor in producing stable power generation. Therefore, stacking MFC units in series–parallel configuration incorporation with capacitor-based circuit can be a promising approach for higher power generation and can be utilized for various practical applications like wastewater treatment.

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