A comparative study of BQ2557 and LTC3108 as efficient ultra-low bioelectricity harvesters from soil microbes using microbial fuel cells.

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ABSTRACT
Microbial fuel cells (MFCs) are attractive bio-electrochemical transducers that can convert waste and organic substrates into usable energy through the metabolic activity of electroactive microbes. However, the power generated by MFCs is relatively low compared to other types of fuel cells. This poses a serious problem for the practical application of MFCs. Commercially available voltage boosters are not suitable for use with MFCs due to the low current capacity of the MFCs. Therefore, special amplifiers are needed to boost the power of MFCs. In this study, two ultra-low harvesters (BQ25570 and LTC 3108) were configured and tested for their efficiency in extracting usable energy from soil MFCs. The result showed that the BQ could harvest bioelectricity from three MFCs connected in series to charge a 0.22 F supercapacitor up to 3.5 volts, which in turn was used to power a light-emitting diode (LED). The LTC, on the other hand, boosted the voltage of a single MFC from 0.72 V to 3.3 V. The increased voltage was used directly to supply a white LED operating at a constant voltage of 2.5 V. The voltage at the LED remained constant even when the MFC voltage dropped to 20 mV. These results demonstrated the potential of soil microbes to generate free energy that can be harvested, amplified and used for practical applications. Compared to the BQ, the LTC performed better with the soil MFC, boosting the voltage of a single MFC unit to a usable level without the need for a battery or supercapacitor.

Keywords: *Bioelectricity, BQ25570, LTC 3108, microbial fuel cell, Power management system, soil microbes.*

1 INTRODUCTION

Microbial fuel cells (MFCs) are bio-electrochemical systems that generate bioelectricity through the metabolism of various microorganisms known as electroactive microbes. MFCs use microbes as catalysts to oxidize organic and inorganic materials to generate electricity (Simeon & Freitag, 2016; Zhou, Chi, Luo, He, & Jin, 2011). MFCs have gained research interest not only because of their diverse potential but also because of the ubiquity of microbes in nature. For example, the soil is teeming with mixed microbial communities, including the common electroactive bacteria (EAB) such as the genera *Geobacter* and *Shewanella* (Ye et al., 2016; Yee, Deutzmann, Spormann, & Rotaru, 2020), and is rich in organic material needed for microbial electroactivity in MFCs. It is estimated that the soil contains about 10^9 cells/g) and high organic content (about 100 mg/g) (Simeon, Raji, Gbabo, & Okoro-Shekwaga, 2016; Wang, Adekunle, Tartakovsky, & Raghavan, 2021). Therefore, soil can produce inexhaustible electron acceptors for the oxidation of organic pollutants (Li et al., 2014) while generating bioelectricity.

Microbial fuel cells have emerged as an alternative power source, especially for remote monitoring applications. However, due to their low voltage and power generation capacity, a single MFC cannot directly power most commercial electronic devices (Yang, Zhang, Shimotori, Wang, & Huang, 2012). The theoretically achievable voltage of a single MFC is in the range of 1.1-1.2 volts, as described by the thermodynamic characteristics of the MFC. In most cases, the practically achievable open circuit voltage of the MFC is in the range of 700-900 millivolts (Yamashita, Hayashi, Iwasaki, Awatsu, & Yokoyama, 2019). However, under load conditions, this value decreases drastically and sometimes reaches an unusable value, depending on the power generation capacity of the MFC and the connected load. Therefore, energy management strategies need to be optimized to bring the power of the MFCs to a practically usable value.

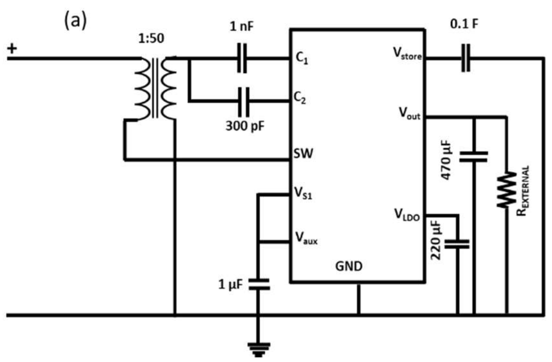
One possible strategy to increase the output power of MFCs is to use commercially available boost converters. A boost converter is a DC/DC switching power supply (Degrenne, Buret, Allard, & Bevilacqua, 2012) that can increase the input voltage of a power supply to produce a higher output voltage. In a simple arrangement, a boost converter contains an inductor, a capacitor, a diode and a transistor (power switching regulator). The main problem with using boost converters with MFCs is that some of the components of the boost converter (e.g. diode and transistor) usually require a minimum amount of energy to operate and the output power of MFCs is too low to meet the requirements of most commercial boost converters (Wang, Park, & Ren, 2015). Therefore, research into special integrated circuits capable of boosting ultra-low power to a higher value is an effective way to increase the performance of MFCs.

Yamashita et al. recently reported that a low-energy converter with MPPT (maximum power point tracking) based on BQ2504 can charge a 1mF supercapacitor to 1.8 V from an input voltage of less than 300 mV and power consumption of 2.09 µW (Yamashita et al., 2019). In a similar study, it was reported that a transformer-based integrated circuit from Linear Technology (LTC3108) could increase the power of a single MFC from 0.5 V to 3.3 V (Song et al., 2017). The most common substrates for the above MFCs are wastewater. Therefore, in the present study, a transformer-based ultra-low energy harvester (LTC 3108) and a non-transformer-based MPPT (BQ2557) were comparatively investigated as efficient bioelectricity harvesters from soil microbes.

2 METHODOLOGY

2.1 CONSTRUCTION OF THE ULTRA-LOW BIOELECTRICITY HARVESTERS

Two predesigned programable power management systems (PMS) based on LTC3108 (LTC-PMS) (Analog Devices, Inc.) and BQ25570 (BQ-PMS) (Texas Instruments, Incorporated [SLUSBH2, & G]) were constructed and tested with the MFCs. Figure 1 shows the circuit diagrams and the selection of components used as described in the data sheets of the integrated circuits. The circuit design of LTC3108 adopted in this study is designed by the manufacturer for boosting the power of a thermo-electric generator (e.g., a Peltier Cell) and it is capable of boosting voltage as low as 20mV depending on the step-up transformer used with it. Thus, the LTC-PMS requires a transformer to initially amplify the MFC voltage for further rectification and amplification. In contrast, according to the manufacturer, the BQ-PMS can amplify the voltage from 300 mV. A supercapacitor (0.22 F, 5.5 V) was used to store the energy gained from the MFCs with the BQ-PMS.



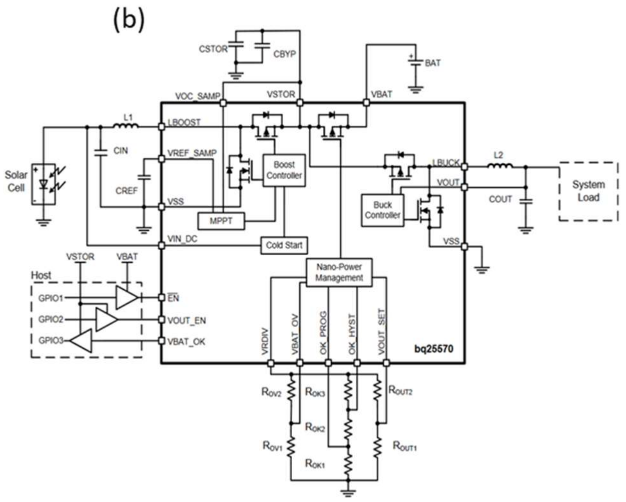


Figure 1: Schematic diagram of (a) LTC-PMS and BQ-PMS circuits.

The detailed design procedures for the BQ2557 and LTC3108, including the selection of circuit elements shown in Figure 1, are described in the data sheets (Analog Devices, Inc.; Texas Instruments et al.).

2.2 MFC ASSEMBLY AND OPERATION

The performance of the PMSs was tested with a single chamber soil microbial fuel cell (SCSMFC) constructed as previously described (Simeon & Freitag, 2022; Simeon, Weig, & Freitag, 2022). Briefly, the SCSMFC was constructed with biologically active soil as the bacterial source, the proton exchange membrane and the nutrient-rich substrate. The anode and cathode were fabricated using the bonding and reinforcement method described previously (Simeon, Herkendell, Pant, & Freitag, 2022). The electrode consists of an active layer of Vulcan-XC 72 (Quintech, Germany) bonded to a stainless-steel mesh support using a two-component epoxy as a binder(Simeon, Imoize, & Freitag, 2021). The anode and cathode were separated at a distance of 4 cm with about 300 g of soil slurry prepared as previously described (Simeon & Freitag, 2022).

2.3 DATA CAPTURING AND CALCULATION

A data logger (ADC-24, Pico Technology) was used to monitor the enrichment of the MFCs every 1 hour in terms of OCV. When a stable OCV was reached, indicating the maturation of the biofilm on the electrode surface, the maximum power of the MFCS was determined using the linear sweep voltammetry technique (Biologic VMP3, France).
The maximum power density (P_d) was estimated from equation 1.

$$P_d(mWm^{-2}) = \frac{P(mW)}{A(m^2)} \quad (1)$$

Where A = 0.00185 m^2 is the anode surface area. The MFCs were left at open-circuit to regain their equilibrium voltage before they were connected to the ultra-low PMSs. For the test, a single SCSMFC and three SCSMFCs connected in series were used, respectively. The energy (E) stored in the capacitor when it was charged from an initial voltage (V_i) to a final voltage (V_f) was calculated according to Equation 2.

$$E = \frac{1}{2}C(V_f - V_i)^2 \quad (2)$$

Where C is the capacitance of the capacitor in Farads. Similarly, the total charge (Q) accumulated in the supercapacitor was estimated according to Equation 3.

$$Q = C(V_f - V_i) \quad (3)$$

3 RESULTS AND DISCUSSION

3.1 PERFORMANCE OF THE MFCS BEFORE THE PMS ASSESSMENT

Before the evaluation of the PMS, the performance of the SCSMFCs was determined to select MFCs with similar performance indices. The power and polarization curves of the three MFCs used for the evaluation of the PMSs are presented in Figure 2.

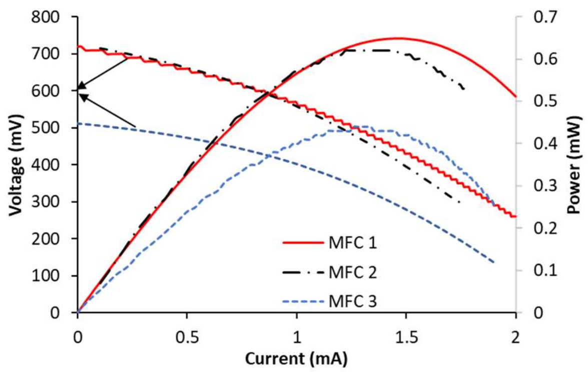


Figure 2

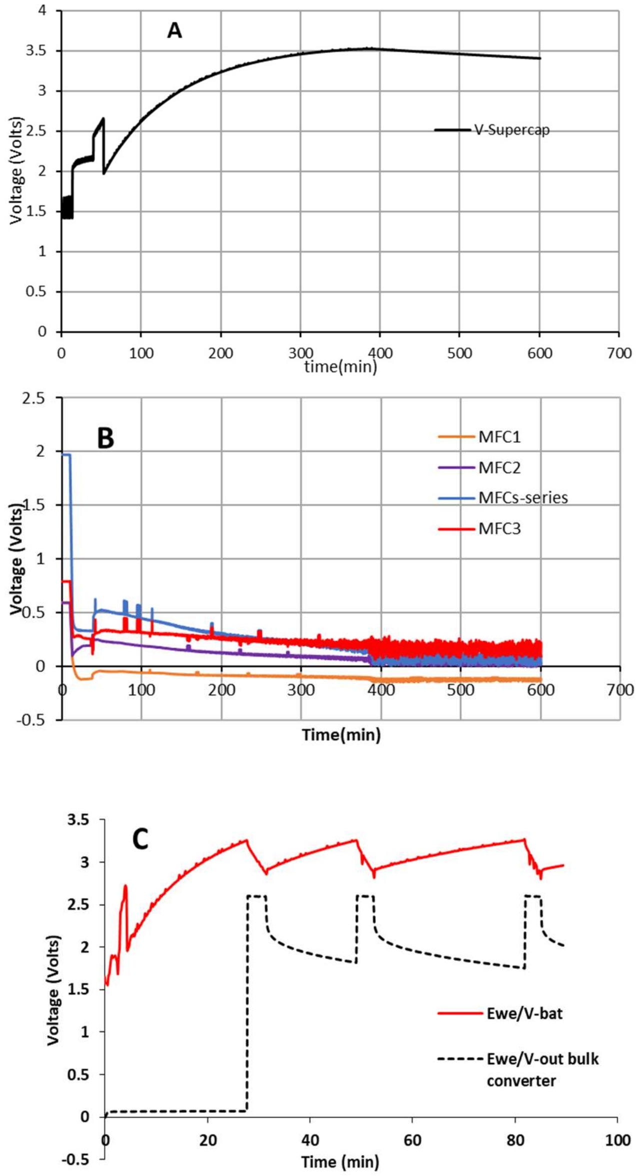
TABLE 1: PERFORMANCES PARAMETERS OF THE MFCS

Parameters	MFC 1	MFC 2	MFC 3
E_{oc} (mV)	720	714.01	512.64
E_{cell} (mV)	443.95	460.99	333.29
I_{cell} (mA)	1.46	1.35	1.31
P_{max} (mW/m^2)	195.39	187.70	131.40
R (Ω)	304.0753	341.4741	254.4198

The performance indices of the MFCs used for the PMS evaluation are shown in Table 1. MFC 1 and MFC 2 had similar performance, with a percentage difference of only 4.01 % in power density. On the other hand, MFC 3 had lower power than the first and second with a percentage difference of 39.16% and 35.29%, respectively. The average current generated by the three MFCs was 1.37 ± 0.063. The low standard deviation of the current showed that the three MFCs were suitable for series connection.

3.2 POWER HARVESTING FROM THE SMFCS USING THE BQ-PMS.

The performance characteristics for the BQ-PMS are shown in Figure 3.



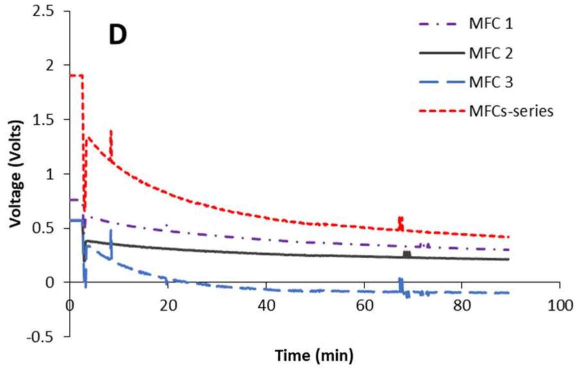


Figure 3 Performance characteristics of BQ2557. Power harvesting from 3 MFCs in series: A) with bulk converter disabled, B) voltage characteristics of the MFCs during power harvesting, C with bulk converter enabled and connected to a light emitting diode, D) voltage characteristics of the MFCs with the bulk converter enabled.

Figure 3 (A) shows the charging of a supercapacitor by the BQ-PMS using three SCSMFCs connected in series. The bulk converter was disabled so that the supercapacitor was fully charged without drawing current from the output of the PMS. It took about 5 hours to charge the supercapacitor to the predesigned voltage of 3.5 volts. The total voltage of the MFCs dropped drastically from 1.97 to 0.53 Volts during the start-up phase and dropped further to about 100 mV after 10 hours. At the third MFC (Figure 3 B), the voltage reversed, indicating that the current drawn from the MFCs by the PMS was higher than the metabolic response of the microbes could deliver.

Figure 3 (C) shows the voltage characteristics of the BQ-PMS during the period when the supercapacitor was charged to a predetermined value and discharged via a white LED. The BQ2557 is a maximum power point tracking PMS that disables the charging and discharging of the battery or capacitor when the voltage rises above or falls below a certain value, which depends on the system design. The PMS in this study was designed to keep the capacitor voltage in the range of 3.3 - 2.8 volts. Once the supercapacitor was charged to 3.2 Volts, the bulk converter was activated to turn on the LED, and when the voltage dropped below 2.8 V, the bulk converter was deactivated until the supercapacitor was recharged to the maximum voltage. With three MFCs connected in series, it took only 33 minutes for the supercapacitor to charge to the maximum designed voltage, the point at which the bulk converter was activated and the LED lit up. Interestingly, the supercapacitor was continuously charged by the MFCs after each discharge cycle, indicating that the electroactive bacteria were active in the SCSMFCs and further demonstrating the potential of soil microbes to generate free energy that can be used for practical applications. The energy stored and the overall charge accumulated in the supercapacitor by charging it from a voltage of 1.4 Volts to a voltage of 3.3 and 3.5 Volts are presented in Figure 4.

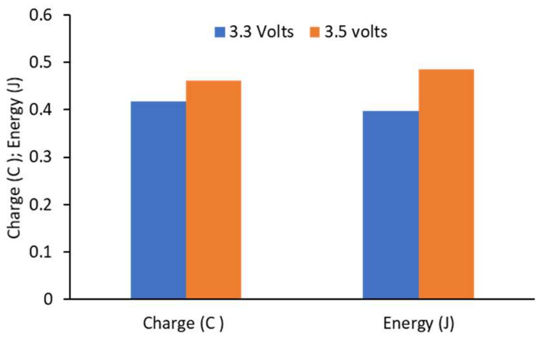


Figure 4. Charge and energy storage in a supercapacitor of 0.22 F by harnessing the power of soil microbes.

3.3 POWER HARVESTING FROM THE SMFCS USING THE LTC-PMS

The LTC-PMS was tested with two different SCSMFCs (MFC 1 and MFC 2). Figure 5 shows the performance characteristic of the PMS at open-circuit voltage and under external load.

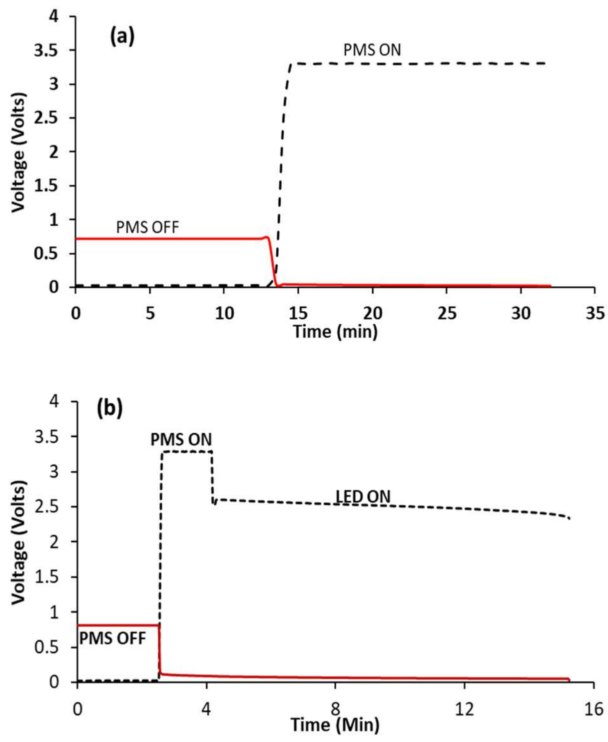


Figure 5: Performance characteristics of LTC-PMS (a) at no load, (b) at load condition.

MFC 1 produced a constant voltage of 721± 0.11 mV before it was connected to the LTC-PMS. The output voltage of the PMS was 2.5 Volts within 30 seconds and 3.3 Volts after 60 seconds, which corresponded to the preset output voltage of the PMS. During activation of the PMS, the MFC voltage dropped to 50 mV and further to about 21 mV, while the amplified output voltage remained constant at 3.3 volts. In the second test, MFC 2 produced a constant OCV of 808 mV before it was connected to the input of the PMS. When the MFC was connected to the converter, there was a quick response as the voltage immediately increased to 1.35 V and further to 3.3 V, but the voltage of the MFC dropped sharply to 145 mV and then to 50 mV when the LED was turned on. Down to a voltage of 20 mV, the SMFC was still able to drive the LTC to power the LED, as shown in Figure 5 (b).

4 CONCLUSION

The present study has shown that the teeming populations of electroactive microbes in the soil can be electrochemically stimulated to generate electricity that can be amplified for practical application. A comparison of the suitability of BQ2557 and LTC3108 as efficient bioelectricity collectors from soil MFCs showed that the amplified power of the MFCs can be harvested using the BQ25570 and stored in a supercapacitor or amplified and used directly. While the BQ25570 required a combination of more than one MFC to charge a supercapacitor to 3.3 V, the LTC3108 boosted the voltage of a single soil MFC from as low as 20 mV to 3.3 mV. This result shows that the power of a single MFC can be increased with a PMS for direct application without the need for batteries or supercapacitors, which normally increase the cost of manufacturing and operating the MFCs. However, improvements in system design and further material optimization are still required if the goal is to maintain the increased performance of the MFC for direct application over an extended period.

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