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RESEARCH ARTICLE

SOLAR ENERGY ASSISTS SEDIMENT MICROBIAL FUEL CELL TO GENERATE GREEN ENERGY FROM LIQUID ORGANIC WASTE

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ABSTRACT

Simultaneous liquid organic waste disposal and electricity generation were achieved by a solar-assist sediment microbial fuel cell (S-SMFC) in terms of an ecological and economical perspective. In this respect, 840 mL house environment liquid organic wastes which contains 10% juice + 90% deionized water and 10% sugary tea + 90% deionized water were disposed by electrogenic bacteria and converted electricity with solar energy. A 100 F capacitor was easily charged 29 times with generated electricity. S-SMFC was disposed 10 mL more waste than control due to more electrical bacteria density on the graphite electrode. In this case, Proteobacteria and Firmucutes were categorized dominate bacteria groups, and they were found in the S-SMFC as 54% and 28%, respectively. Importantly, solar energy increased population density of these groups in the S-SMFC and the density on the graphite electrode increased more than 19% according to control. Some bacteria which were associated with electricity production in the S-SMFC were to *Azospirillum fermentarium*, *Clostridium sp.*, *Pseudomonas guangdongensis*, *Bacteroides sp*., *Azovibrio restrictus*, *Clostridium pascui*, *Levilinea saccharolytica*, *Seleniivibrio woodruffii*, *Geovibrio ferrireducens*. Consequently, S-SMFC presents innovative, crucial and simple methodology in order to convert liquid organic waste into the green energy.

Keywords: Green energy, Sediment microbial fuel cell, Electrogenic bacteria, Organic waste

1. INTRODUCTION

Uncontrolled liquid organic waste may create potential environmental pollution in the ecosystems when these wastes reach into surface waters [1]. High-polluted organic waste are generally produced house environment (i.e. kitchen), and then join in sewage system or receiving environment after being processed in a central treatment plant [1, 2]. Unfortunately, these type of wastes are directly discharged into receiving environment following the deep sea discharge system without any treatment in recent months due to the inadequacy of the treatment plants [3]. Moreover, the spent time of people at home because of Covid-19 pandemic, the discharge of such waste in the sewage systems increase nowadays. In this respect, some crucial environmental problem (i.e. sea snot or marine mucilage) associated with uncontrolled liquid organic wastes that contain nitrogen and phosphate have often appeared both in world and Turkey [4, 5]. Correspondingly, the marine mucilage has intensively detected in Marmara Sea in Turkey in March-May 2021, and 12,741.94 ha of sea area covered by mucilage [4].

Although this kind of liquid waste can be treated or controlled by conventional techniques (biological treatment, reverse osmosis, ion exchange systems, etc.), these methods requires high chemical use (i.e. barium chloride lime), high energy needs (0.5 kwh for 1 ton of wastewater purification) and expensive equipment (i.e. cationic membranes) [6, 7]. Furthermore, these conventional techniques have only treatment efficiency between 70% and %80 in the purification process[7, 8]. In this respect, new holistic approach and innovation techniques need to on-side control of this type waste prevent from clean water sources or asses this waste for bioenergy sources in terms of secondary benefits [9, 10]. Sediment microbial fuel cell is a simple, cost effective, and environmental friendly method to assess organic substrate (wastewater, rhizosphere excretion) for fuel and generate green energy simultaneously [11,

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12]. Briefly, sediment microbial fuel cell is based on the idea of imitating the physical, chemical and biological mechanisms that occur in wetland matrix, and the liquid organic wastes can easily disposal to produce clean energy from organic substrates through electrogenic bacteria without generating any secondary waste [11, 13]. Correspondingly, the liquid organic wastes released into the nature are not considered as waste for sediment microbial fuel cell, this kind of waste are defined as a new energy fuel source to generate green energy in the waste management strategy [9, 14]. In order to eliminate the energy shortage that may occur in the near future, the sediment microbial fuel cell devices provide crucial strategy associated with electrochemical activity comes from catalytic activity of organic substrate, and then electrogenic bacteria can convert organic substrate to green energy [15]. Unfortunately, produced potential green energy by sediment microbial fuel cell is usually low. For example, up to 70% wastewater treatment efficiencies were obtained from constructed wetland couple with sediment microbial fuel cell device, only 198.8 mW/m^2 power density was produced by the SMFC device [16]. Although this phenomenon is an acceptable level of organic treatment from wastewater, the power density obtained from SMFC significantly limits the usage network of SMFC to generate bioelectricity for real scale application. Furthermore, power generation with organic wastes released from plant roots to the environment in plant sediment microbial fuel cells was recorded as 1 mWatt [17]. In this respect, the obtained low power from SMFC limits use of this type device for practical on-site application for bioelectricity production (i.e. landscape lighting). Consequently, innovative approaches or technological designs are necessary to how to increase power from SMFC while the wastewater treated more efficient and more economical.

In this study, a solar energy assists sediment microbial fuel cell (S-SMFC) was tested to generated bioelectricity from liquid organic waste. Briefly, the purpose of the current study was to: (i) design a solar assist sediment microbial fuel cell to generate bioelectricity from liquid organic waste; (ii) investigate electricity production by electrogenic bacteria and solar energy in the same systems at the first time in the literature; (iii) discuss electricity production mechanism of this hybrid system and compare produced green energy from control.

2. MATERIAL AND METHODS

2.1. Sampling and Bacteria Culture

Sediment sample was collected a wetland habitat (depth of 60cm) in Turkey, and then the sample was mixed with an anaerobic culture that collected from an active sludge reactor. The mixture was transferred into a plastic container inoculated for one month. Nitrogen gas (80%) was applied into the mixture 20 minutes once a day in order to removed oxygen and created anaerobic environment for electrogenic bacteria. Supported culture was prepared, and Proteobacteria composition was enriched in the culture [18]. Accordingly, 15mM sodium acetate was used as carbon sources, 7.1 mM NH_4Cl d for nitrogen sources, and 3mM BES solution for methanogenic inhibitor in the culture. Furthermore, sterilized mineral solution was also added into the culture solution in order to supported to bacterial growth. Correspondingly, 1mL mineral solution is contained per liter: 5.6 g $(NH_4)_2SO_4$, 2 g $MgSO_4 \cdot 7H_2O$, 200 mg $MnSO_4 \cdot H_2O$, 3 mg H_3BO_3, 2.4 mg $CoCl_2 \cdot 6H_2O$, 1 mg $CuCl_2 \cdot 2H_2O$, 2 mg $NiCl_2 \cdot 6H_2O$, 5 mg $ZnCl_2$, 10 mg $FeCl_3 \cdot 6H2O$, and 0.4 mg $Na_2MoO_4 \cdot 2H_2O$).

2.2. Experimental Design

Rectangular polyester containers (13x13 cm) with volume of 500 mL were selected as treatment and control reactor in order to obtained sediment microbial fuel cell (SMFC) environment. Volume of anode chamber in each reactor was 150 mL, and the anode and cathode chamber was separated by glass wool and clay layer (1mm). The anode electrode of each SMFC reactor was a horizontal rectangular graphite plate (100 mm X 100 mm and 60 mm thickness), and cathode electrodes were graphite felt with a diameter of 130 mm. Zeolite mineral was selected as supporting media, and the anode chamber of the reactors was filled with this material. Graphite electrode was buried into the mixing and peat sample with contains 3% NaCl was added on the separator (glass wool and clay layer) and creating a salt bridge in each reactor matrixes. The cathode electrodes for each reactor were placed on the peat, and they were connected by anodes with high anti-corrosion and good electrical conductivity of 0.8 mm titanium wire. The external resistance was selected as 25 Ω in order to obtain a current and increase population of electrogenic bacteria in the reactor matrix. The designed SMFC reactors both treatment and control was cultivated for one month in thermostatically controlled chamber at 35.8 °C. After cultivation period, 2V 20 mA solar panel was connected in parallel with treatment reactor, and this hybrid system was powered by sediment microbial fuel cell and solar energy, and so the hybrid system was named as S-SMFC (Figure 1). Conversely, the control reactor was only powered by sediment microbial cell that namely as C-SMFC. The reactors were located at the window that directly meet sunlight, and the average temperature was measured as 25°C. An acid-based catalyzer was added into cathode chamber in order to increase open circuit voltage of the reactor.

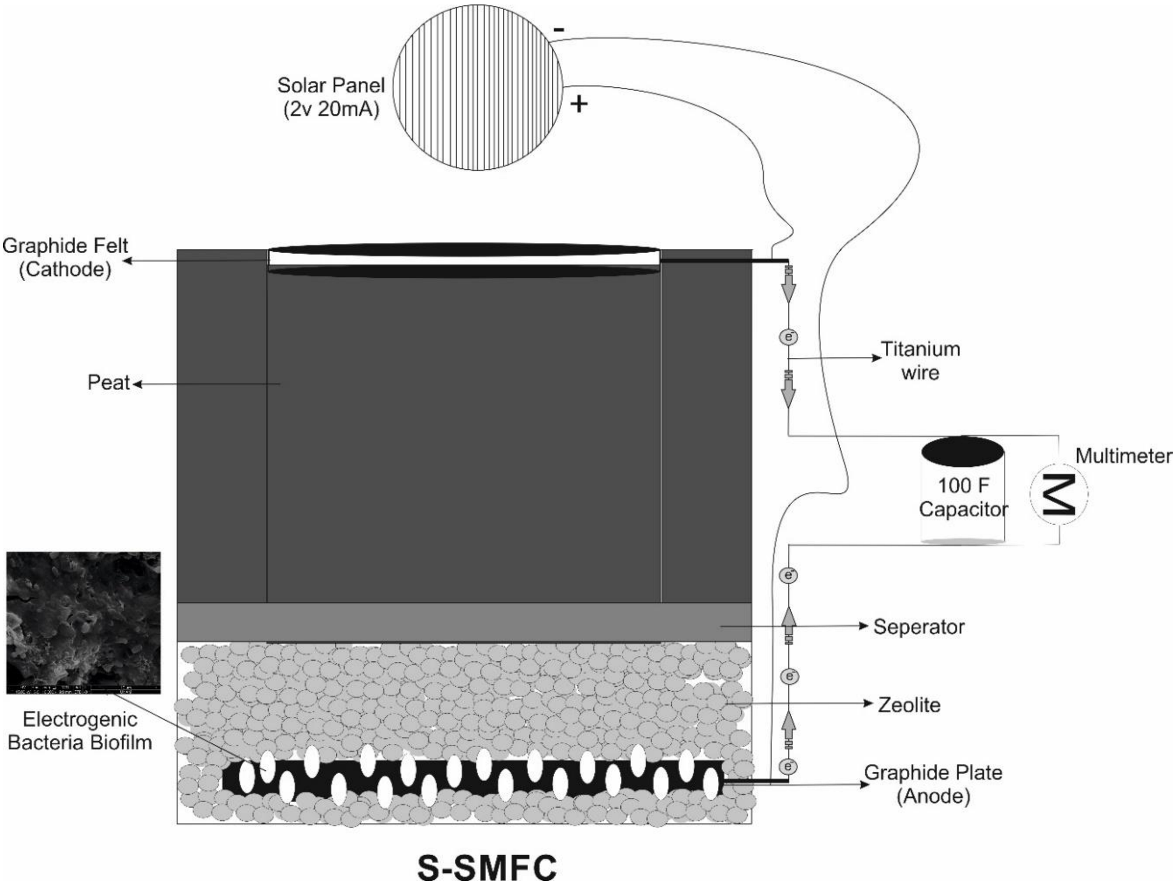


Figure 1. Schematic demonstration of Solar assist sediment microbial fuel cell (S-SMFC)

2.3. Waste Dosage, Measurement, and Analysis

A wide speared liquid organic waste (10% juice waste + 90% deionized water or 10% sugary tea waste + 90% deionized water) produced in household environment was selected for waste in this experiment, and 15 ml waste was added into each reactor in a day. In this case, approximately 110 mL liquid waste was assessed and controlled on the side by reactors in one week, and the waste was converted to electricity by electrogenic bacteria in the SMFC reactors. Produced electricity from each reactor was recorded daily by a multimeter, and then stored 100 F capacitor. After 60 days of operation, the graphite anodes were collected from the reactors and a field-emission scanning microscope was used to determine the biofilm settled on the graphite electrodes. Furthermore, anodic biofilm on the electrodes were separately collected from both S-SMFC and C-SMFC, and metagenomics analysis was evaluated. The temperature of experiment condition was continually measured by a digital thermometer. Furthermore, the charged capacitor from the reactors were serially connected each treatment day, and the Ni-Cd based battery (1.2 V 800 mAh) was charged these capacitors.

3. RESULTS AND DISCUSSIONS

3.1. Voltage Output and Electricity Generation Assessment

The electricity production performance of the reactors both S-SMFC and C-SMFC were shown in Figure 2a. Correspondingly, the S-SMFC was generated open circuit potential between 1542 and 1919 mV for 10% juice waste, and between 1442 and 1978 mV for 10% sugary Tea waste during the experiment period. This results indicated that the SMFC and solar energy were together produced open circuit potential while the waste broke to pieces, and thus this kind of hybrid system can be used as generated clean energy. On the other hand, the generated electricity from C-SMFC was relatively lower than S-SMFC and output open circuit voltage was ranged from 979 and 1428 mV during the experiment period. Moreover, statistical analysis was also suggested that generated voltage from S-SMFC higher than C-SMFC *($p<0.05$)*, and thus it can be concluded that high voltage can be generated for a SMFC when it hybridizing with solar energy. The mentioned from material and method section that solar energy was produced from 2V mini solar panel and it can be emphasized that the panel adequate power and current for assisting density population on the anode surface.

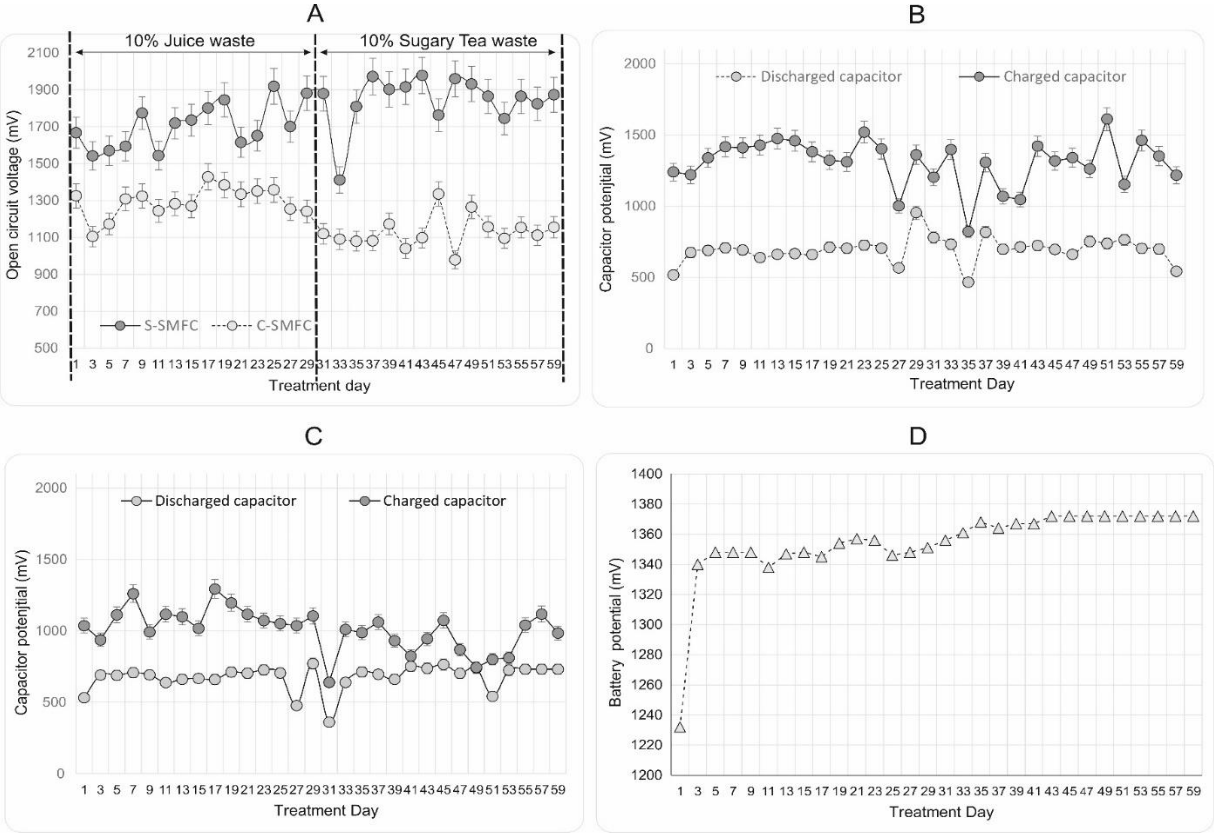


Figure 2. Open circuit voltage of S-SMFC and C-SMFC according to different liquid organic waste (a), Charged and discharged capacitor potential of S-SMFC (b), Charged and discharged capacitor potential of C-SMFC (c), and Battery potential that charged by serially connected capacitors in the experiment period (d).

The generated electricity from reactors were storage in capacitors, and the charged and discharged potential of capacitors were shown in Figure 2b, 2c. In parallel with output voltage in the reactors, the capacitor potential increased with generated electricity from S-SMFC, and the electricity was ranged from 821 to 1621 mV in the experiment period. Furthermore, capacitor potential which connected in C-SMFC also increased with produced electricity, and ranged from 639 to 1294 mV during the treatment days. These results indicated that the reactors produced storing form of electricity from the waste and solar energy, and stored electricity from S-SMFC was higher than C-SMFC. The statistical analysis suggested that capacitor potential for S-SMFC significantly higher than capacitor for C-SMFC ($p<0.05$). The battery potential result was also confirmed that the reactors generated to storing form of electricity during the experiment period, and thus the potential was increased from 1232 to 1372 mV in the experiment period (Figure 2d).

3.2. Waste Disposal Analysis

The average waste (10% juice waste and 10% sugary tea waste) disposal both in S-SMFC and C-SMFC during the experiment period are shown in Figure 3a. Correspondingly, 840 mL liquid organic waste was used as fuel to generate electricity in S-SMFC, whereas C-SMFC was used 830 mL liquid organic waste in order to produced bioelectricity in the same operational condition during the experiment period. These results indicated that organic compounds in the S-SMFC converted faster to electricity by microbial metabolism compare to C-SMFC. Thus, it can be hypothesized that solar energy increased current in the S-SMFC matrix, and more current led to increasing bacterial density in the graphite electrode. In this case, the increasing bacterial density in the electrode of S-SMFC converted more waste to bioelectricity compare to electrode of C-SMFC in the experiment period. The SEM images from the graphite electrodes were confirmed to this phenomenon that high bacterial density can be seen on the graphite electrode that obtained by S-SMFC (Figure 4a). Similar evidences were also reported by various researchers who indicated that increased current on the graphite led to increasing bacterial population on the electrodes. Accordingly, Kim et al. [19] was found that the bioelectricity current increased when the external resistance (below 100 Ω) connected by parallel in a MFC. Same researcher was reported that high current flow on the graphite electrode due to high external resistance increased electrogenic bacteria population. On the other hand, Commoult et al. [18] also reported that high current flow and low anodic potential (-400 m V) on the electrode increased electrogenic bacteria population in the culture.

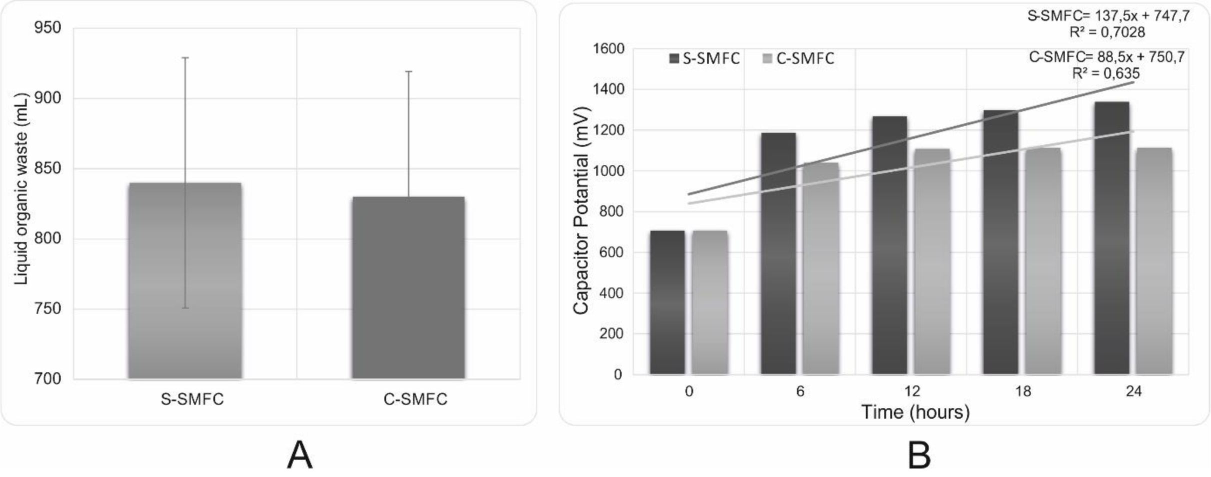


Figure 3. Disposal liquid organic waste volume in S-SMFC and C-SMFC in the experiment period (A), and Charged kinetics of capacitor from the reactors according to time (B).

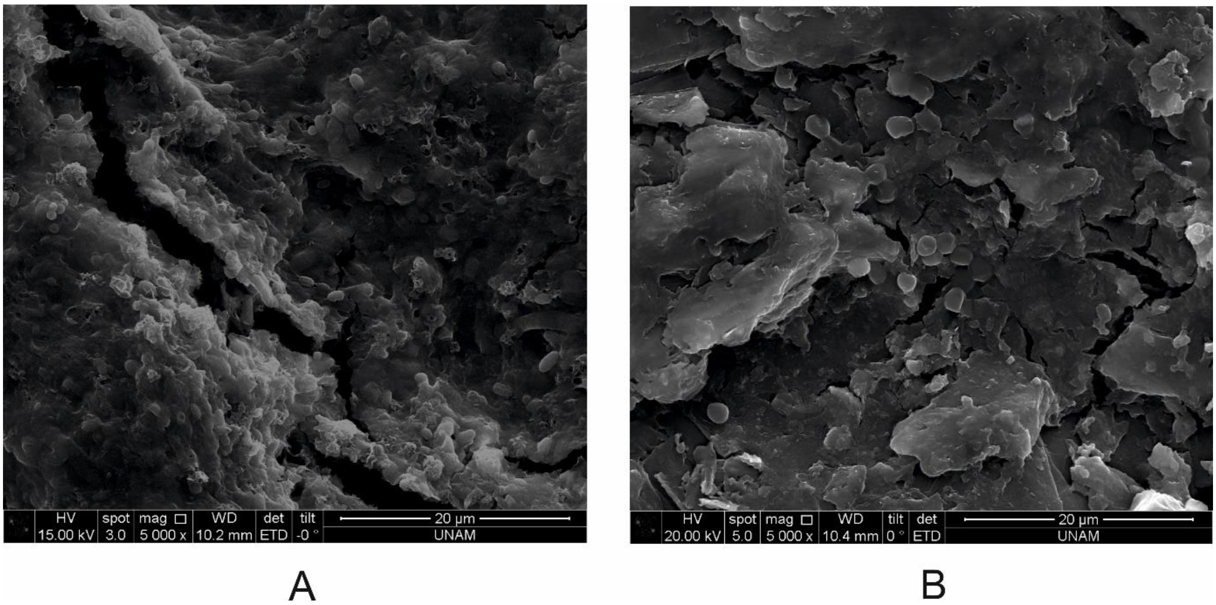
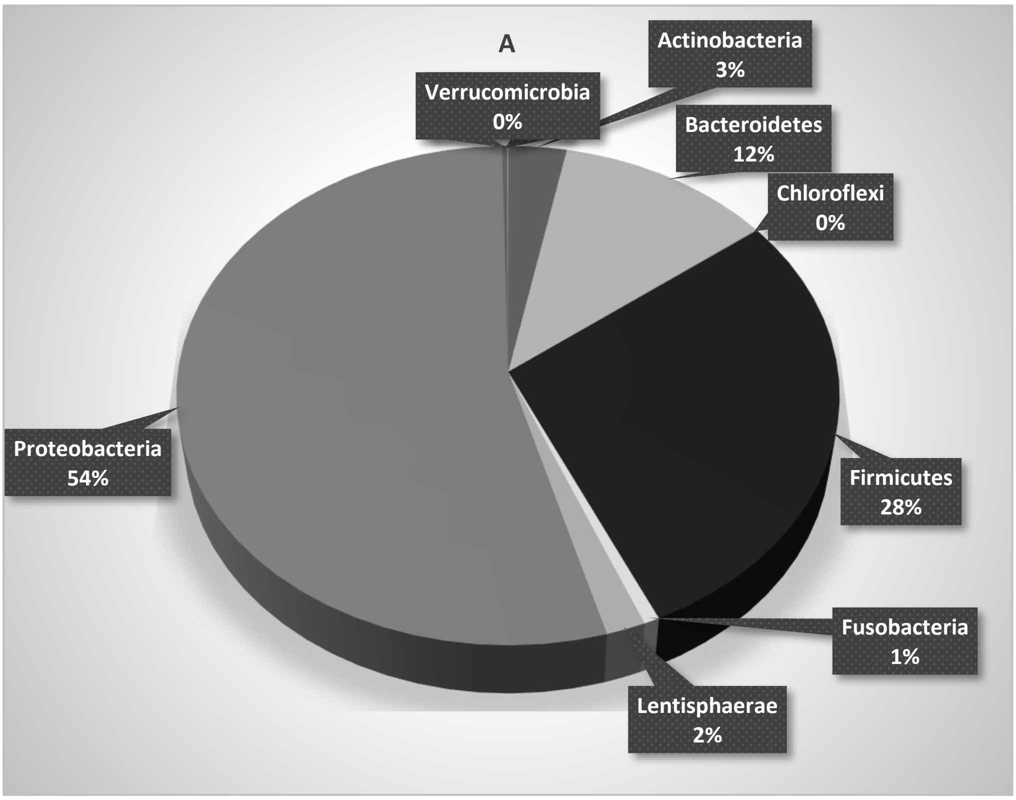


Figure 4. SEM images of biofilms on graphite electrodes of S-SMFC (A) and C-SMFC (B).

On the other hand, charged kinetics of the capacitors also showed that S-SMFC charged the capacitor faster than capacitors of C-SMFC in the hours, and the charged trends of S-SMFC was more stable than C-SMFC during the experiment period (Figure 3b). Correspondingly, R^2 values were recorded as 0,7028 and 0,635 for S-SMFC and C-SMFC, respectively. More importantly, the results from capacitors potential indicated that the bioelectricity was mostly generated first 12 hours, and then they charged small amount after 12 hours both in S-SMFC and C-SMFC. Therefore, it can be hypothesized that electrogenic bacteria populations in the reactors more active when the liquid organic waste dosing into reactor matrixes, and so the waste disposal was mostly related to bacterial population density.

3.3. Bacterial Analysis

Metagenomics analysis results for S-SMFC and C-SMFC are illustrated in Figure 5. It can be seen in Figure 5 that Proteobacteria was the higher population density both in S-SMFC and C-SMFC which were 54% for S-SMFC and 52% for C-SMFC among the other bacterial group. This is important because the electrogenic bacteria are categorized in proteobacteria group, and thus this phenomenon provided crucial evidences that electrogenic bacteria found in the reactor matrixes. Furthermore, Firmucutes which contains important electrogenic bacteria were also found high percent that 28% and 11% for S-SMFC and C-SMFC, respectively. On the other hand, the results showed that density of Proteobacteria and Firmucutes in S-SMFC were higher than those of C-SMFC, so it can be hypothesized that more current flow in the S-SMFC was lead to increasing electrogenic bacteria population. Increased population provided more organic matter treatment in the S-SMFC during the experiment period. This can be explained why S-SMFC was disposed more liquid organic waste according to C-SMFC. Similarly, it can be also hypothesis that external energy income (solar energy in this study) in a sediment microbial fuel cell system may increase organic matter decomposition speed, and so the manager has high bioelectricity production and treatment efficiency in their systems. Unfortunately, there is no information in literature about a hybrid system contain SMFC, thus it is not possible to make any comparisons.



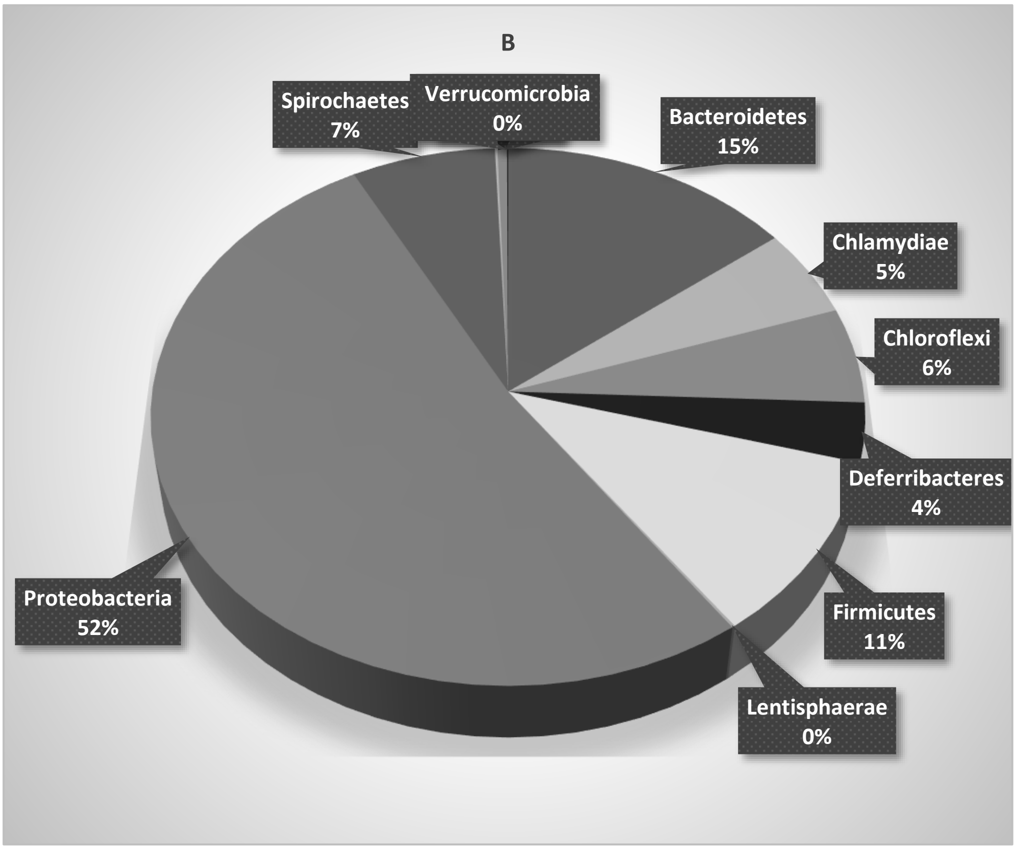


Figure 5. Metagenomics analysis results of S-SMFC (A) and C-SMFC (B)

The species composition both in S-SMFC and C-SMFC are given in Table 1. Correspondingly, *Azospirillum fermentarium* is the main species both in S-SMFC (41.26%) and C-SMFC (22.6%), and the other species ranged between 15.1% and 2.01%. *Azospirillum fermentarium* is commonly found in MFC devices and it is capable of organic matter decomposition and electron transfer. In this respect, various researchers are reported fermentation species in order to bioelectricity production by MFC devices. Chu et al. [20] reported *Azospirillum* species in a charged MFC. Yi et al. [21] found 21% *Azospirillum* content in a MFC used as biosensor. The other crucial species which determined in the present experiment were also reported in the MFC devices in order to bioelectricity production. The species is to *Clostridium sp.* [22], *Pseudomonas guangdongensis* [23], *Bacteroides sp*.[24], *Azovibrio restrictus* [25], *Levilinea saccharolytica* [26], *Seleniivibrio woodruffii* [27], *Geovibrio ferrireducens* [28].

Table 1. Species composition in S-SMFC and C-SMFC according to Metagenomics analysis results

S-SMFC		C-SMFC	
Species	**Content (%)**	**Species**	**Content (%)**
Azospirillum fermentarium	41.26	*Azospirillum fermentarium*	22.6
Clostridium saccharoperbutylacetonicum	15.1	*Pseudomonas guangdongensis*	10.37
Azospirillum thiophilum	5.85	*Sphaerochaeta associata*	6.64
Bacteroides luti	4.81	*Anoxybacillus thermarum*	6.62
Magnetospirillum gryphiswaldense	4.22	*Levilinea saccharolytica*	5.73
Parabacteroides chartae	3.07	*Lentimicrobium saccharophilum*	5.71
Clostridium arbusti	2.77	*Parachlamydia acanthamoebae*	5.34
Clostridium pasteurianum	2.15	*Parabacteroides chartae*	3.32
Caproiciproducens galactitolivorans	2.11	*Seleniivibrio woodruffi*	3.22
*Others**	18.66	*Tistrella mobilis*	2.91
		Meniscus glaucopis	2.57
		Bdellovibrio bacteriovorus	2.52
		Azonexus hydrophilus	2.18
		Sulfurisoma sediminicola	2.12
		Azovibrio restrictus	2.01
		*Others**	16.15

4. CONCLUSIONS

In this study, a solar energy assists sediment microbial fuel cell (S-SMFC) was evaluated bioelectricity production from liquid organic waste. Correspondingly, 840 mL liquid organic waste (10% juice waste and 10% sugary tea) was disposed by S-SMFC during the 60 days. The generated energy charged 100 F capacitor during the experiment period. More importantly, S-SMFC disposed more waste than control because S-SMFC has more electrogenic bacteria density (82%) compare to control (C-SMFC). Proteobacteria and Firmucutes provided crucial evidences to generate bioelectricity from liquid organic waste.

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CONFLICT OF INTEREST

The author stated that there are no conflicts of interest regarding the publication of this article.

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