Doctoral Thesis

Development of Microbial Fuel Cells Using Organic Wastes, Peat and Plants for Bioelectricity

有機系廃棄物・泥炭・植物を用いたバイオ発電のための微生物燃料電池の開発

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ABSTRACT

Population and industry growth as well as the usage of non-renewable energy resources are the main causes of greenhouse gases released into the earth's atmosphere and climate change. Also, finite, depleting supplies and the impact on the environment of fossil fuels make them unsustainable for energy production. Today, the world is facing a major problem of eutrophication and energy crisis at the same time. Hence the development of multifunctional hybrid devices is the need of the hour which can serve the dual purpose of environmental cleaning as well as the generation of efficient, sustainable and cost-effective electricity. Microbial Fuel Cell (MFC) is a device that converts chemical energy to electrical energy by the action of microorganisms in which electrochemical cells are constructed using either a bio-anode and/or a bio-cathode. In the past years and up to now, MFC has been widely studied. It does not appear only as a gifted technique for energy generation but also is an eco-friendly approach for generating electricity. MFC is an electrochemical technique in which organic substrates are oxidized through the action of microorganisms acting as a catalyst to produce electricity. MFC upholds the trait of sustainable technology it generates the electricity without requirement of any energy input. Soil-based microbial fuel cells adhere to the basic principles of MFC where soil functions as a nutrient-rich anodic medium, inoculant, and proton exchange membrane. The anode is located at a specific depth in the soil, and the cathode is placed on the top of the soil. Microbes from organic matter rich soils and peat soil have been proved to be effective as a source of alternative energy in SMFCs. SMFCs are the power sources for the environmental sensors and bioremediation which can be developed at low cost with minimal or no impact to the environment.

The first study surveyed the impact of the use of different cathode materials and the presence of iron wire in the anode on plant microbial fuel cells. Compared with carbon fiber, the voltage and electricity of the PMFC of the activated bamboo charcoal is greater. The highest voltage reached in the PMFC experiments was 0.85 V. Voltage generation of PMFCs increased as a result of the presence of iron wire in the anode. Based on the paddy plant MFC system, the electricity generation in paddy fields, as high as 69 mW/m^2 has been demonstrated and evidenced that rhizosphere microbes preferentially utilize organic exudates from rice roots for generating electricity.

The second study investigated bioelectricity production using bamboo powder, leaf mould and rice bran in the presence of fulvic acid. In view of developing a cost-effective MFC to generate electric power for a longer period of time, the present contribution was attempted. This study uses various organic wastes（fallen leaves，bamboo waste，leaf mould，rice bran as substrate materials and their admixtures to make SMFCs，the purpose is to investigate a performance of SMFC to generate electricity in accordance with the metabolism of microorganisms in composting of organic wastes. Soil microbial fuel cell using less expensive and easily available organic admixtures was developed. The efficiency of voltage and electric power of SMFC was measured and discussed. Based on the soil MFC system, it has been proved that the power generation in organic waste is as high as 1071 mW/m^2.The SMFC discharged organic waste was successful as compost for plant's growth. Characterization studies（SEM，FTIR，Raman and BET）for the fresh and SMFC used bamboo carbon anodes were carried out and detailed in this paper. The characterization studies such as SEM (with EDS), FTIR, Raman and BET studies corroborated the changes caused to the surface of the bamboo carbon anode.

The third study is committed to the development of peat MFC. The performance of peat MFCs as a function of bamboo waste, fulvic acid, iron winding and surface area of the BC anode has been discussed in this work. The synergistic effect of organic decomposition by microbes and Fe complexation with humic substances has been detailed to be responsible for the cause of electric power in Peat MFCs. The power output for Peat MFC with an iron winding was measured about 35 times higher (1440.5 mW/m^2) than that without iron winding (41.7 mW/m^2) after a day. The presence of iron might play a significant role towards the enhancement of power supply in Peat MFCs. On adding Bamboo waste and fulvic acid to peat, the generated power was raised to 1371 mW/m^2 and 1488 mW/m^2 for an output voltage of 0.80±0.01V after a day.

The fourth study combines the performance of the plant MFC with the soil MFC. Combines soil MFCs and peat MFCs with plants (paddy plants, sweet potatoes, potatoes) to form PMFCs that do not affect plant growth and can continue to generate electricity. The efficiency of voltage and electric power of MFC was measured and discussed. The maximum power of the unit area of the MFC system after combining SMFC can reach 543 mW/m^2.

Finally, the application of MFC as a power supply was studied. MFCs are not suitable for large-scale power generation because their output is lower than existing power generation methods, but it has sufficient power to drive small LED lights and sensors. The purpose is to develop an MFC as a power supply to drive the sensor and is expected to contribute to environmental monitoring. Peat soil based MFCs, the first of its kind among MFCs are explored to generate voltage as high as 3.3V when six MFCs connected, thereby driving a small soil moisture sensor. It is a method of organic waste with power generation effects.

Keywords: Microbial Fuel Cell , Paddy plant microbial fuel cell, Activated bamboo charcoal, Carbon fiber, Fertilizer, Soil Microbial Fuel Cell, Bamboo powder, Leaf mould, Fulvic acid, Power generation, Peat soil, Bioelectricity, MOSFET, Carbon bar, Small soil moisture sensors

CONTENTS

1. Introduction

1.1 Background

1.1.1 The origin and development process of microbial fuel cells

Energy is an important material basis for developing the national economy and improving people's living standards, and it is also an important constraint that directly affects economic development. The development and utilization of energy has brought great progress to humans. With the development of society, human demand for energy has grown rapidly. Coal, petroleum and natural gas are the main energy sources in the world and are unable to renewable energy. They provide about four-fifths of the world's energy. At present, it will continue to grow at a range of 3 % each year. It is expected that it will increase by nearly 3 by 2025 double; however, the problem of environmental pollution caused by this type of energy seriously threatened human health. Finding green energy has become a topic that must be solved in the development of human society. For decades, society has always depended on the power generation of fossil fuel. However, with the exhaustion of fossil fuel, the demand for energy consumption has increased new renewable energy. Although these energy sources have solved environmental problems and supported the industrialization and economic growth of some countries, there are still problems of energy scarcity and environmental pollution. For example, due to changes in land use, the sustainability of biomass energy technology and food and feed production, as well as high-carbon dioxide emissions competition is doubtful (Helder, Chen, etc., 2013). To deal with environmental pollution, the demand for global warming and scarcity of energy leads to the search for sustainable energy production and new environmental protection methods in the world.

In the next few decades, energy problems will greatly affect the economic development of society and the way of human lifestyle. One of the ways to solve energy problems is to increase the research and development of renewable energy, and use the microorganism metabolism process and electrical electrode the research and development of microbial fuel fuel cells combined with reactions provides a new way for the production and waste treatment. Therefore, the research of microorganisms in the pond has become a source of concern for governance and eliminating environmental pollution, and the development of new energy researchers' attention.

In 1911, British botanist Potter put yeast or E. coli in a custody of glucose and perform anaerobic medium. Its product can display a 0.3-0.5V opening voltage and 0.2mA current on the platinum electrode. (Potter MC, Lond.B, 1911). This is regarded as the beginning of the research of microbial fuel cells. In 1912, Potter proposed the concept of chemical can be converted to power by using biofilm as a catalyst. However, due to poor results, further research was stopped. More than 40 years later, American space scientific research has led to the development of microbial fuel cells, which has made great progress in the research of microbial fuel cells. The goal of research at the time was to develop a microbial fuel cell used in space aircraft and the astronaut life waste. First use microbial fermentation to generate hydrogen or other substances that can be used as fuel, and then pass these substances into fuel cells. These fuel cells become indirect microbial fuel cells. During this period, the research of microbial fuel cells was fully developed, and there were also various types of fuel cells. After entering the 1980s, the study of microbial fuel cells was active, and the research of microbial fuel cells that used oxidized and restored media was fully carried out. The widespread application of oxidation and restore media has greatly improved the output power density of microbial fuel cells, showing the possibility of as a small power density power supply. However, because the media is expensive and partially toxic, it hinders the further development of microbial fuel cells. Until 1990, microbial fuel cells (MFC) seemed to be alternative, which was a response to the demand for no net carbon dioxide launch energy (Trapero, Horcajada, LinaRes and Lobato, & Lobato, 2017). In the wastewater treatment plant, chemistry stored in wastewater can be converted into electricity. Since then, a lot of progress has been made, and it has been applied to technology that is now called sediments microbial fuel cell (SMFC).

At the same time as the separation of electric bacteria, there are also many scholars who are committed to the research on microbial molecular ecology of mixed bacteria unable microbial fuel fuel cells. From 1960 to the decades of microorganisms that can be directly transferred to electrons in recent years, people have always believed that adding exogenous electron transmission intermediates are necessary steps to generate electricity in microbial fuel fuel cells. Kelvin and other found that the presence of certain microorganisms can be transmitted to electronics without exterior electron transmission intermediates. This has made the traditional microorganized fuel cells be possible for the high potential substance as a low potential substance as a microbial electron transmission intermediate, which is possible (Kelvin B Gregory, Daniel R Bond, Derek R Lovley, 2004). The results of this research have once again promoted the rapid development of microbial fuel cells.

In the past ten years, by selecting and modifying the progress of the electrode material, the progress of fuel cell configuration, and the use of high-conductive efficiency efficiency, a cheap proton exchange membrane (Shentan Li, Hailiang Song, Xianning Li and Fei Yang, in 2013), MFCS's performance was obtained enhancement. Although a considerable enhancement function has been carried out to improve the SMFC of power generation, the continuous supply of organic matter is still a challenge to maintain long term operation. Strik first introduced sustainable alternative to providing organic matter to SMFC. Strik et al. (2008) plants using photosynthesis to provide organic materials through photosynthesis. This new fixes of SMFC are called plant microbial fuel cells (PMFC). Considering that PMFCS uses photosynthesis to provide organic materials for the system, and sunlight is infinite energy, and develop self-maintained microbial fuel fuel cells. These microbial fuel fuel cells depend on light rather than organic substances (Rosenbaum, HE &Angence, 2010).

Now it seems that the raw material range of microorganisms fuel cells has been greatly broaden. From the initial use of pure substances such as glucose, sodium acetate, methanol, ethanol, etc., to the domestic sewage, food processing wastewater, starch plant water out of water, landfill garbage filtration solution Wastes such as livestock and poultry wastewater are fuel. Early microbial fuel cells have very low power density, only 0.1mW/m^2. Recent research results show that in the microbial fuel cell with oxygen as the final electronic receptor, the maximum power density has reached 1500mW/m^2 or more: When using iron cyanide, it can even reach 4.31W/m^2 (Zhaozhi Pan, Dongjie Niu, 2010).

1.1.2 The working principle of microbial fuel cells

MFC technology is based on the principle of redox reactions. The bacteria oxidize the organic matter to produce carbon dioxide (CO_2), electrons, and protons. The natural metabolism of the microbes is utilized to generate electricity. The substrates are converted into electrons by bacteria. Figure 1.1 shows the two-chambered MFC that illustrates the working of MFC technology. It consists of an anode, cathode, exchange membrane, or salt bridge. Where the anode chamber is an aerobic and the cathode chamber is aerobic. The exchange membrane is either a cation exchange membrane or proton exchange membrane, joining the two chambers and only protons are allowed to diffuse. The MFC consists of anode and cathode chambers, and they are separated by a proton exchange membrane (PEM) as shown in the figure above. At the anode, the microbes or microorganisms oxidize the fuel/substrate to generate protons, electrons, and CO_2. While the protons moved to the cathode chamber through the exchange membrane. The electrons are transferred from anode chamber to cathode chamber employing an external electrical circuit to generate electrical energy. By using an air cathode or by bubbling water, the oxygen is provided in the cathode chamber. The redox potential of oxygen is more than any other electron acceptors. Hence, it is considered a better cathodic electron receiver. The contact failure of electrodes with the oxygen, reduction of oxygen at a slow rate on the carbon electrode are the drawbacks that lead to the limited utilization of oxygen in microbial fuel cell technology. Even though the reaction of the cathodic chamber can be improved by using electrodes coated with catalysts. Since the catalysts are rare metals and expensive.

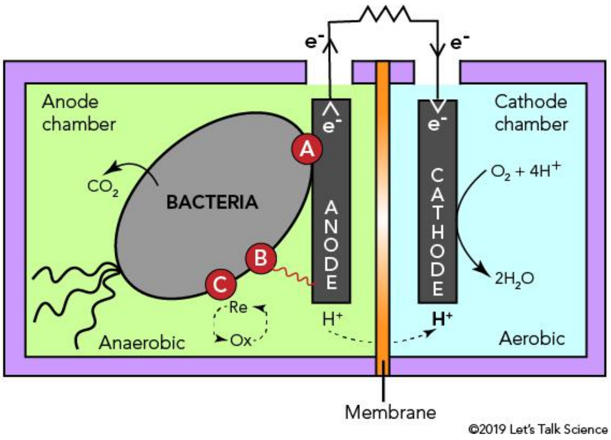

Fig.1.1 Microbial Fuel Cell Diagram

(https://letstalkscience.ca/educational-resources/stem-in-context/microbial-fuel-cells)

1.2 Objective and thesis structure

This thesis mainly consists of three parts as shown in Figure 1.2. Part I includes Chapter 2, Chapter 3 and Chapter 4, and study the development of microbial fuel cells based on paddy plants, organic waste and peat soil. Part II includes Chapter 5, and study combines the performance of the soil MFCs and peat MFCs with plants (paddy plants, sweet potatoes, potatoes). Part III includes Chapter 6, and study the application of soil MFCs and peat MFCs as a power supply to drive a small soil moisture sensor.

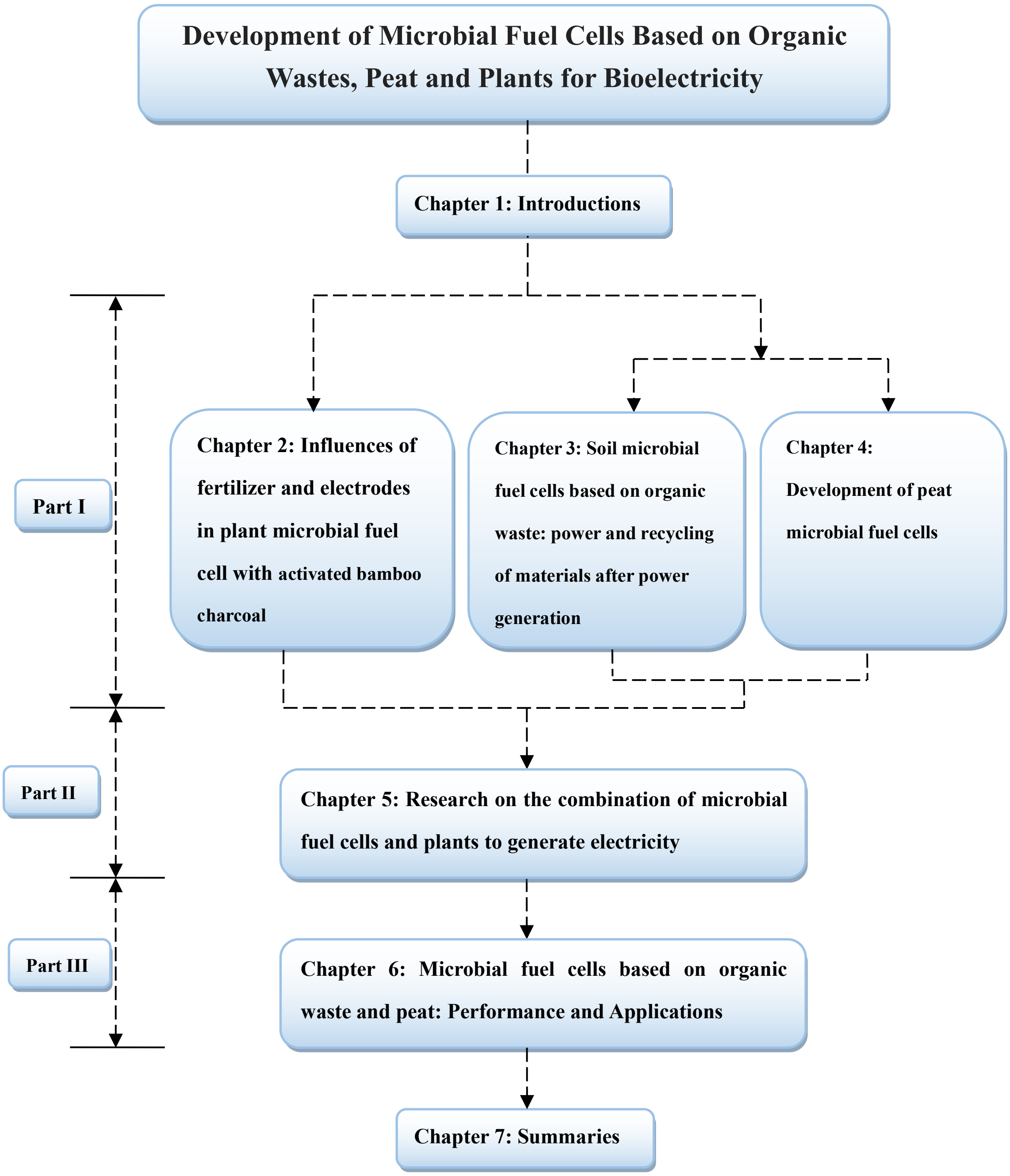

Fig.1.2 The structure of this thesis

Chapter 1 gives a brief introduction of the background, the objective and the structure of this thesis.

Chapter 2 surveyed the impact of the use of different cathode materials and the presence of iron wire in the anode on plant microbial fuel cells. Compared with carbon fiber, the voltage and electricity of the PMFC of the activated bamboo charcoal is greater. Voltage generation of PMFCs increased as a result of the presence of iron wire in the anode.

Chapter 3 developed soil microbial fuel cells that use various organic wastes （fallen leaves，bamboo waste，leaf mould，rice bran） as substrate materials and their admixtures. The anode and cathode materials were bamboo carbon (with iron winding) and granular activated carbon respectively. The study explored the possibilities of generating power due to the microbial degradation of chosen organic wastes and their admixtures. The polarization curves were plotted with the current-voltage and current-power characteristics for the influence of organic wastes and the admixtures in the presence of fulvic acid. The SMFC with different admixtures corroborated the microbial degradation of organic compounds and the subsequent power generation with respect to days. The admixture used in the SMFC was proved very effective as compost in growing Komatsuna seeds with a scope for recycling and zero disposal. The Electrochemical Impedance Spectroscopy study corroborated the influence of admixture compositions in the variation of resistance values. The characterization studies such as SEM (with EDS), FTIR, Raman and BET studies corroborated the changes caused to the surface of the bamboo carbon anode. The cost analysis confirmed that the fabrication of SMFC unit is inexpensive thanks to the consumables from sustainable sources.

Chapter 4 is committed to developing peat MFCs. The performance of peat MFCs as a function of bamboo waste, fulvic acid, iron winding and surface area of the BC anode has been discussed in this work. The synergistic effect of organic decomposition by microbes and Fe complexation with humic substances has been detailed to be responsible for the cause of electric power in Peat MFCs. The presence of iron might play a significant role towards the enhancement of power supply in Peat MFCs. The carbon potency of peat soil is well tapped which ultimately facilitated an appreciable power output through microbial degradation process. The power generation as a function of anodic surface area has been explored.

Chapter 5 combined the performance of the soil MFCs and peat MFCs with plants (paddy plants, sweet potatoes, potatoes). The efficiency of voltage and electric power of MFC was measured and discussed. Compared with soil MFCs, the voltage and electricity of the peat MFCs with plants is greater.

Chapter 6 studied the application of soil MFCs and peat MFCs as a power supply to drive a small soil moisture sensor. The practicability in lighting an LED using series connected soil MFCs have been attempted and succeeded in the present work. The practicability in driving a small soil moisture sensor connecting six peat MFCs have been attempted and succeeded in the present work. It is a method of organic waste with power generation effects.

Chapter 7 summarizes the main conclusions of this thesis.

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2. Influences of fertilizer and electrodes in plant microbial fuel cell with activated bamboo charcoal

2.1 Introduction

Due to the polluting side-effects, the depletion of fossil fuel sources and the continuing rise in energy demand, there is a significant need for renewable energy sources. The mainstream technologies include solar, wind, hydro, geothermal, and bioenergy, but emerging technologies are growing in interest. One of these emerging technologies originates in bioelectrochemistry (A. Hussain, S.M. Arif, M. Aslam, 2017). Bioelectrochemical systems are technologies that use enzymes or microorganisms as catalysts in a redox reaction (T. Zheng, J. Li, Y. Ji et al., 2020), often in the form of the conversion of chemical energy into (bio)electricity. These current producing systems are used in various applications ranging from environmental sensing and bioremediation to mere electricity harvesting (D. Pant, A. Singh, G. Van Bogaert et al., 2012).Energy demand of entire world is increasing rapidly with the increase in technological development (Nepal et al., 2021). Conventional and non-renewable sources of energy like fossil fuel and coal reserves are being utilized extensively to fulfill the energy needs (Mishra et al., 2020, Prabha et al., 2021). Hence, there is high demand of new renewable sources of energy which will be environment friendly, affordable, and globally feasible (Ananthi et al., 2021, Kumar et al., 2020a). The pursuit for alternate clean and green energy technologies to fulfill future energy requirements is a foremost challenge in view of the rising greenhouse gases (GHGs) level in the environment and socioeconomic instability (Kumar et al., 2021a, Mishra et al., 2021), along with several other challenges associated with development and adoption of new technologies for the generation of clean and green bioenergy. (Kumar et al., 2020b, Nie et al., 2020). In this latter case, the system is called a microbial fuel cell (MFC) (B.E. Logan, B. Hamelers, R. Rozendal, U, 2006). A plant microbial fuel cell, as described by Strik et al., in 2008 (D.P.B.T.B. Strik, H.V.M. Hamelers et al., 2008), consists of a combination of a living plant and an MFC and is characterized by the remarkable feature that it converts light absorbed by the plants into electricity via several intermediate bioelectrochemical steps.

One of the significant factors responsible for rise in global warming is rising carbon dioxide concentration in atmosphere (Letcher, 2020, Kumar et al., 2019). This rise in carbon dioxide concentration in environment in the whole world is consistent in last fifty years since industrial revolution. As per the recent statistics, the rise in the carbon dioxide proportion in environment in this period is from 320 to 390 ppmv (parts per million volume) (Rae et al., 2021). In 2018, the concentration of atmospheric carbon dioxide was 409.23 ppmv (Misra et al., 2019) and it is predicted that it could be 800 ppmv by the year 2100 (da Silva et al., 2020). High carbon dioxide concentration and climate change affects the growth of plant and its development significantly owing to photosynthetic carbon assimilation (Wang et al., 2020). Chemical reduction of carbon is occurred in plant due to absorption of atmospheric carbon dioxide and resultantly storage of chemical energy in plant. In addition to this, photosynthesis is also responsible for providing carbon skeleton for the organic molecules that makes the vegetal structure (Vanlerberghe et al., 2020). Hence selection of plant with appropriate photosynthetic pathway is significant in the assessment of performance of PMFC. Various studies on crop plants like Saccharum officinarum L and Sorghum bi-color L revealed that, in higher environmental concentration of carbon dioxide, the photosynthesis rates were increased significantly (Verma et al., 2020).The rate of photosynthesis is affected greatly by the atmospheric carbon dioxide concentration and hence it resultantly affects the performance of PMFC. It should be recommended that concentration of atmospheric carbon dioxide should be monitored and analyzed to interpret the expected performance of PMFC.

Photosynthetic active radiation (PAR) is to be reported 150 W/m^2 in the Western Europe, and it is estimated that it can be 10 times high in the equatorial region (Martínez et al., 2020). Electromagnetic radiations in the waveband of 400-700 are considered as PAR (Dou and Niu, 2020). The incidence of sunlight radiation on the portion of plant canopy is arrived in two ways, as direct flux manner and diffuse fluxes manner or both.

There are certain criteria which are generally followed by the earlier researchers to select the plant species for PMFC applications and the preference should be given to plants which have excellent ability to survive and grow in water-logged condition to avoid oxygen interruption in anode chamber and resultantly maintain the redox potential gradient (Shaikh et al., 2020). Plants with high biomass production capacity and more rate of photosynthesis are recommended for PMFC applications (Apollon et al., 2021). There are various plants which are explored till date by different researchers along the globe for power generation using PMFC (Table 2.1) and their efficiency in power generation is also discussed in various earlier articles (Azri et al., 2018, Sarma and Mohanty, 2018). Nevertheless, this review showing a sincere attempt to focus on criteria adopted for the selection of plant species in PMFC application. Specific discussion on plant names and their performance in different designs and configuration is deliberately minimized. There are many factors which influence the power generation by each plant in different circumstances like the maximum power reported using S. anglica was 222 mW/m^2 which was nearly twice of the power obtained with same plant earlier (Nitisoravut and Regmi, 2017). So, it is necessary to consider aspects like light intensity, plant species, plant health, and concentration of atmospheric carbon present at particular location. In addition to this, the type of microbial communities and its interaction with plant roots in the rhizosphere is equally significant. Selection of plant species is also dependent on the type of application like power generation. It might be expected to have other applications like heavy metal removal and phytoremediation in “Constructed wetland MFC” (CW-MFC) or sewage treatment plant (Teoh et al., 2020). There are some studies in which plant species are grown in cathode chamber as the plant provides oxygen as a product of photosynthesis in the cathode chamber which will react with electrons received through the circuit of MFC to form water (Kadam et al., 2018).

In this study, a performance of paddy plant microbial fuel cell (PMFC) is evaluated by experiments using container of bucket. Two types of electrodes, namely carbon fiber and activated bamboo charcoal, are used on paddy PMFC. Influences of electrode material and existence of iron wire attached to anode on voltage generation are investigated. The efficiency of voltage and electric power of PMFC as a function of organic wastes either in a separate form or as admixtures was measured and discussed.

Table 2.1 Selected references for plant species used in plant microbial fuel cell (PMFC).

Name of Plant Species	**Fuel Cell Type**	**Duration of operation**	**Highest Power Density (PD) recorded and reported**	**Reference**
Canna indica	CW-MFC	140 Days	18 mW/m^2	(Lu et al., 2015)
Canna indica	CW-MFC	N/A	320.08 mW/m^3	(Srivastava et al., 2015)
Typha latifolia	CW-MFC	N/A	6.12 mW/m^2	(Oon et al., 2015)
Physcomitrella patens	BryoMFC	70 Days	6.7 ± 0.6 mW/m^2	(Bombelli et al., 2016)
Lolium perennee	PMFC	70 Days	55 mA/m^2	(Ueoka et al., 2016)
Oryza sativa	RPF-MFCs	N/A	140 mA/m^2	(Ueoka et al., 2016)
Sporobolas arabicus	PMFC	2 Months (60 Days)	120 mW/m^2	(Gilani et al., 2016)
Typha latifolia	CW-MFC	228 Days	93 mW/m^3	(Oon et al., 2016)
Elodea nuttallii	CW-MFC	276 Days	184.8 ± 7.5 mW/m^3	(Oon et al., 2017)
Canna indica	CW-MFC	90 Days	5.11 mW/m^3	(Wang et al., 2017)
Phragmites australis	CW-MFC	3 months (90 Days)	0.15 mW/m^3	(Song et al., 2017)
Phragmites australis	CW-MFC	160 Days	22 mW/m^2	(Wetser et al., 2017)
Spartina anglica	CW-MFC	160 Days	82 mW/m^2	(Wetser et al., 2017)
Cyperus involucratus R.	PMFC	5 Days	5.99 mW/m^2	(Nitisoravut and Regmi, 2017)
Brassica juncea	PMFC	30 Days	69.32 mW/m^2	(Sophia and

				Sreeja, 2017)
Trigonella foeumgraecum	PMFC	30 Days	80.26 mW/m^2	(Sophia and Sreeja, 2017)
Canna stuttgart	PMFC	30 Days	222.54 mW/m^2	(Sophia and Sreeja, 2017)
Sedum album	PMFC	360 Days	0.0024 μW/m^2	(Tapia et al., 2017)
Sedum sexangulare	PMFC	360 Days	0.0084 μW/m^2	(Tapia et al., 2017)
Sedum rupestre	PMFC	360 Days	0.0155 μW/m^2	(Tapia et al., 2017)
Sedum hybridum	PMFC	360 Days	0.092 μW/m^2	(Tapia et al., 2017)
Sedum reflexum	PMFC	360 Days	>0.001 μW/m^2	(Tapia et al., 2017)
Sedum kamtschaticum	PMFC	360 Days	>0.001 μW/m^2	(Tapia et al., 2017)
Sedum spurium	PMFC	360 Days	>0.001 μW/m^2	(Tapia et al., 2017)
Acorus tatarinowii	PSMFCs	51 Days	21 mW/m^2	(Liu et al., 2018)
Vetiveria zizaniodes Nash	PMFC	N/A	242 ± 10.5 mA/m^2	(Regmi et al., 2018)
Puccinellia distans	PMFC	114 Days	83.7 mW/m^2	(Md Khudzari et al., 2018)
Chlorophytum comosu*m*	DPPFC	100 Days	18 mW/m^2	(Md Khudzari et al., 2018)
Epipremnum aureum	PMFC	60 Days	15.38 mW/m^2	(Sarma and Mohanty, 2018)
Dracaena braunii	PMFC	60 Days	12.78 mW/m^2	(Sarma and Mohanty, 2018)
Chasmanthe floribunda	PMFC	100 Days	0.21 mW/m^2	(Azri et al., 2018)
Papyrus cyperus	PMFC	100 Days	1.083 mW/m^2	(Azri et al., 2018)

Chlorophytum comosum	PMFC	100 Days	18 mW/m^2	(Azri et al., 2018)
Aglaonema commutatum	PMFC	55 Days	0.38 V	(Zhao et al., 2019)
Spartina anglica	pSMFC	105 Days	1.04 mW/m2	(Sudirjo et al., 2019a)
Cordyline fruticosa	PMFC	02 Days	3.5 mW cm − 2	(de La Rosa et al., 2019)
Pennisetumal opecuroides	CW-MFC	22 Days	162.47 mV	(Guan et al., 2019)
Phragmites communis	CW-MFC	22 days	128.01 mV	(Guan et al., 2019)
Vigna radiata	PMFC	30 Days	0.35 mW/m^2	(Pamintuan and Sanchez, 2019)
Oryza sativa	PMFC	115 Days	321.7 mV	(V et al., 2020)
Iris pseudacorus	CW-MFC	94 Days	25.14 mW/m^2	(Yang et al., 2020)
Phragmites australis	CW-MFC	94 Days	25.14 mW/m^2	(Yang et al., 2020)
Hyacinth pink	CW-MFC	94 Days	25.14 mW/m^2	(Yang et al., 2020)
Scirpus validus	CW-MFC	180 Days	19.5 mW/m^2	(Di et al., 2020)
Typha orientalis	CW-MFC	180 Days	19.5 mW/m^2	(Di et al., 2020)
Iris pseudacorus	CW-MFC	180 days	19.5 mW/m^2	(Di et al., 2020)
Wachendorfia thyrsiflora	PMFC	54 Days	1036 ± 59 mW/m^3	(Gulamhussein and Randall, 2020)
Cyperus papyrus nanus	PMFC	54 Days	510 ± 92 mW/m^3	(Gulamhussein and Randall, 2020)
Pennisetum alopecuroides	PMFC	120 Days	667.94 ± 128.65 mV	(Guan and Yu, 2021)
Typha angustifolia	PMFC	120 Days	451.12 ± 94.37 mV	(Guan and Yu, 2021)

Amaranthus viridis	PMFC	180 Days	185.23 ± 15.10 mA/m^2	(Arulmani et al., 2021)
Triticum aestivum	PMFC	180 Days	291.23 ± 7.50 mA/m^2	(Arulmani et al., 2021)

Note: N/A-not available, pSMFC-Plant sediment microbial fuel cell, RMFC-Rhizosphere MFC, CW-MFC-Constructed wetland microbial fuel cell, BryoMFC-Bryophyte microbial fuel cell, DPPFC-Direct photosynthetic plant fuel cell, PMFC-Photosynthetic plant fuel cell and RPF-MFCs-Rice paddy field microbial fuel cells.

2.2 Experimental Study

Electrode material used for anode in PMFC should be conductive, biocompatible, chemically stable, and affordable for the application (Sonawane et al., 2020). Metal anodes made up to non-corrosive stainless steel are recommended but copper is not used due to its toxic effect on bacteria. Different forms of electrodes of carbon like compact graphite plates, cloth made up of fibrous material, granules or rods of different dimensions, foam shaped objects and paper felt are advisable as anode for MFC application (Salehmin et al., 2021). Electrodes with higher surface area are recommended as it can provide more sites for bacterial attachment and formation of bio film. But it is essential to maintain the porous nature to allow the protons to reach ion exchange membrane and cross it resulting into completion of the circuit and maintenance of redox gradient in the system (Li et al., 2021). The choice of electrode material to be used in PMFC is dependent on its resistance. Generally, those materials which provide least resistance are preferred for PMFC application. But use of highly efficient electrodes like platinum electrodes or platinum coated electrodes is not feasible due to high economic price. Resistance of the anode contributes to the overall resistance of PMFC and hence it hampers its performance (Li et al., 2020). Two types of electrodes were used on the PMFC. Carbon fiber, which do not have any negative effect on the growth of paddy roots (Moqsud, 2015). However, it is considered that carbon fiber is not suitable for the anode, because the roots of paddy are closely attached with the carbon fiber; thus, making it difficult to be removed. In this study, carbon fiber and activated bamboo charcoal was used as the cathode. Activated bamboo charcoal (KPCCo., Ltd.,Shiga Prefecture, Japan) was used as anode or cathode. These electrodes are good at conducting electricity with an electrical resistance of 5 ohm. Figure 2.1 shows electrode materials of cathode and anode. The activated bamboo charcoal in sizes of around 120 x 50 mm and the carbon fiber in mass of 10 g are connected to stainless wire. It was confirmed that power generation of soil microbial fuel cell (SMFC) using organic waste increases by connecting iron wire with anode of the activated bamboo charcoal (Moqsud, 2013). To investigate the effect to generation of PMFC, the activated bamboo charcoal with iron wire was also used.

Schematic diagram on experimental device of the PMFC using bucket of 13L is illustrated in Figure 2.2. Test conditions of the PMFC are shown in Table 2.2. The soil was prepared by mixing clayey soil, sandy soil, culture soil and leaf mold. 7 buckets were prepared for the PMFCs. Bucket No.1 was not planted for comparing the electricity generation with or without plant. There was no fertilizer mixed in this bucket. Bucket No.2 was prepared by mixing chemical fertilizer of 5g into the soil. Buckets No.3~No.7 were prepared by mixing organic fertilizer of 30g. The carbon fiber was used for buckets No.1~No.4 as cathode. The activated bamboo charcoal was used for buckets No.1~No.7. The activated bamboo charcoal with iron wire was used for buckets No.4 and No.6 for a purpose of increasing a performance of the PMFC. Additionally bucket No.7 with organic fertilizer and without electrode was prepared. The rice plants were planted in the soil in each bucket except for bucket No.1. Black rice (ancient rice) was selected, because the black rice is resistant to disease and easy to grow. Paddy plant MFCs were performed during the rice cropping season (from June to August) in the Nagasaki University Bunkyo-machi campus, Japan. The weather condition during the study period was good for growing paddy plants.

Three anodes made of the activated bamboo charcoal in size of 120 x 50 mm were inserted into the soil and three cathodes made of the carbon fiber in mass of 10 g were placed on a surface of the soil. The anode area covers around 0.006 m^2 inside the soil of the PMFC. The anode was set approximately 50mm below the surface of the soil, while the cathode was placed immediately above the soil surface, but under the water. These electrodes were connected via lead wires. Both the anode and cathode were connected to a data logger. The data logger is set to measure the voltage in every 5 minutes' interval.

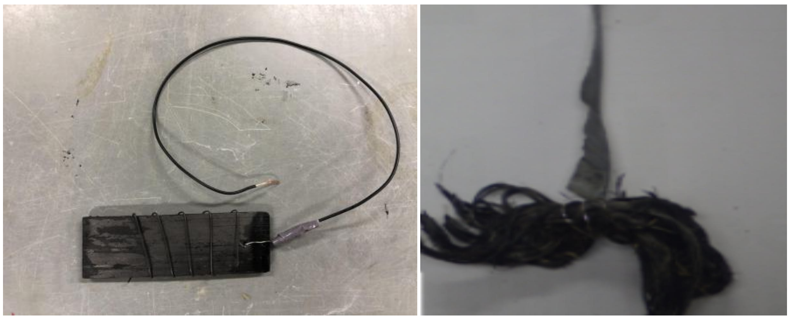

Fig.2.1 Electrode materials of cathode and anode

（Activated bamboo charcoal (120x50); Carbon fiber (cathode)）

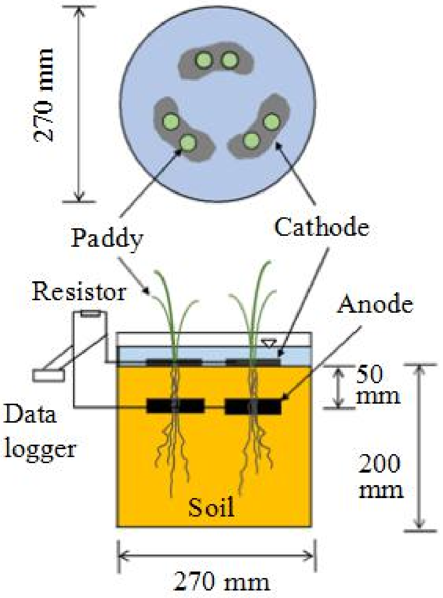

Fig.2.2 Cross section of the experimental device using bucket of 13 L.

Table 2.2 Test conditions on paddy plant MFC using bucket.

No.	**Plant**	**Fertilizer**	**Cathode**	**Anode**
1	Without	Without	Carbon fiber	Activated bamboo charcoal
2	Paddy	Chemical	Carbon fiber	Activated bamboo charcoal
3	Paddy	Organic	Carbon fiber	Activated bamboo charcoal
4	Paddy	Organic	Carbon fiber	Activated bamboo charcoal with iron wire
5	Paddy	Organic	Activated bamboo charcoal	Activated bamboo charcoal
6	Paddy	Organic	Activated bamboo charcoal	Activated bamboo charcoal with iron wire
7	Paddy	Organic	none	none

2.3 Results and discussion

2.3.1 Experiment using bucket of 13 L with carbon fiber and activated bamboo charcoals electrodes

Figure 2.3 illustrates the variation of voltage generation with time in rice PMFCs in different buckets. The voltage generation on the case of without paddy plant (No.1) increased gradually and reached to 0.2 V. After that, the value increased and decreased. It was observed that algae grew in the bucket. This might have occurred due to the presence of nutrients in the culture soil. The result suggests that the voltage of bucket No.1 was generated due to the presence of algae. The voltage generation for the case of bucket No.2with chemical fertilizer reached to 0.5 V initially and then the value decreases gradually. This occurred as a result of the chemical fertilizer which works quickly, but the effect does not continue for long term. The voltage generation for bucket No.3 increased up to 0.68 V, but after that it dropped down. Maximum voltage for bucket No.4 reached at 0.85V. Power generation increases during the day, so the voltage of all buckets showed clear peak value in daytime.

Figure 2.4 shows the growth of paddy plant with time in different buckets. The growth of the plant for all buckets increased gradually and the length became more than 800 mm. Growing speed of buckets No.3~No.7 with organic fertilizer is relatively high comparing that of bucket No.2 with chemical fertilizer. It was also observed that the growth of bucket No.4 with iron wire is enhanced. It may be considered that iron was supplied to the plant as nutrition. Figure 2.5 shows growth of paddy plant in different buckets. Additionally, paddy seedling was planted to bucket No.7 with organic fertilizer and without electrodes. It was found that the electrodes do not influence the growth of paddy plant.

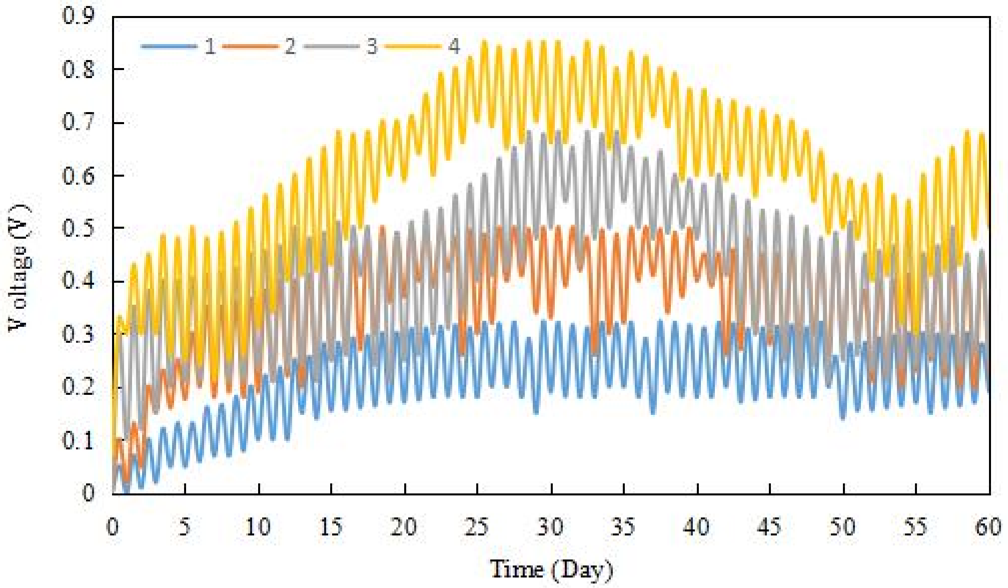

Fig.2.3 The variation of voltage generation with time in PMFCs in different buckets

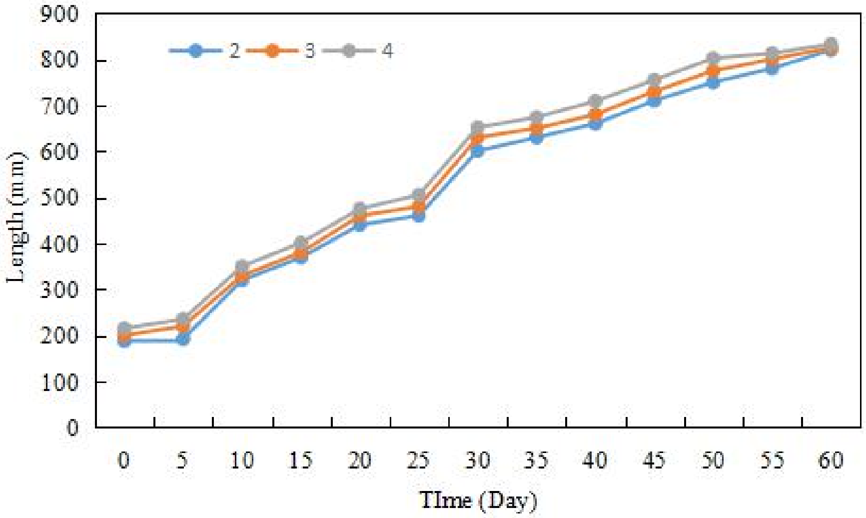

Fig.2.4 Length of paddy plant with time in different buckets

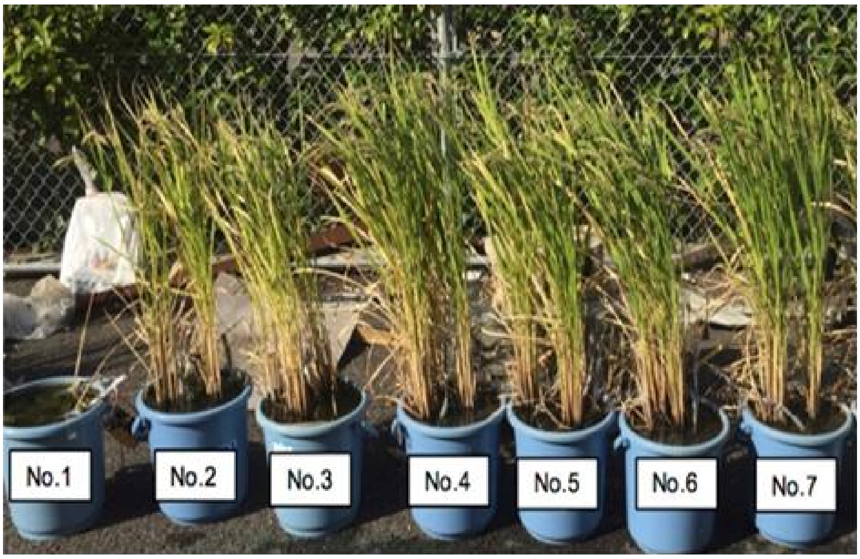

Fig.2.5 Growth of paddy plant in different buckets

2.3.2 Experiment using bucket of 13 L with activated bamboo charcoals electrodes and activated bamboo charcoals electrodes

Figure 2.6 illustrates the variation of voltage generation with time in rice PMFCs in bucket No.5 and bucket No.6. The voltage of bucket No.5 and bucket No.6 clearly changes in day and night. Power generation increases during the day and hardly generates at night. The voltage generation for bucket No.5 increased up to 0.72 V, but after that it dropped down. Maximum voltage for bucket No.6 reached at 0.9V. It was the highest so far in PMFCs research.

Electrode output is measured in volts (V) against time. The current I in Amperes (A) is calculated using Ohm's law, $I= V/R$, where V is the measured voltage in volts (V) and R is the known value of the external load resistor in Ohms. From this it is possible to calculate the electric power output P in watts (W) of PMFCs by taking the product of the voltage and current i.e. *P= I x V*. For obtaining a maximum power of PMFCs, the values of voltage are measured using different resistances.

Figure 2.7 shows the relationship between voltage and current in the PMFCs of bucket No.5 and bucket No.6.It was found that the relationship was almost linear. The intercept and inclination of the line represents electromotive force and internal resistance for the MFCs respectively. It represents that the PMFCs with a good performance indicates high electromotive force. Maximum electric power is calculated from the linear relationship between voltage and current. The test results obtained from Figure 2.7 are given in Table 2.3. The electromotive force of bucket No.6 for the time of 24 h was 500mV. The internal resistance of PMFCs was relatively high. The maximum power per anode area is 69 mW/m^2 for the PMFC with iron wire.

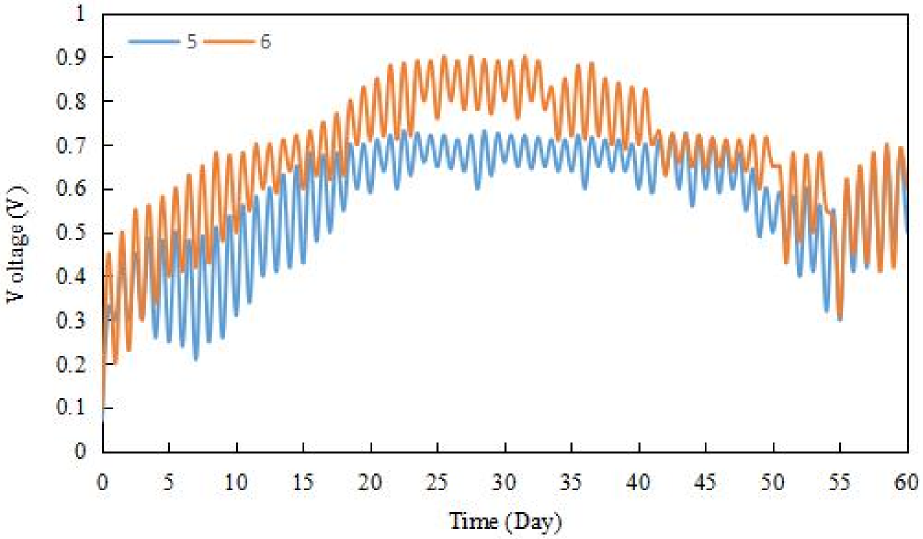

Fig.2.6 The variation of voltage generation with time in PMFCs in different buckets

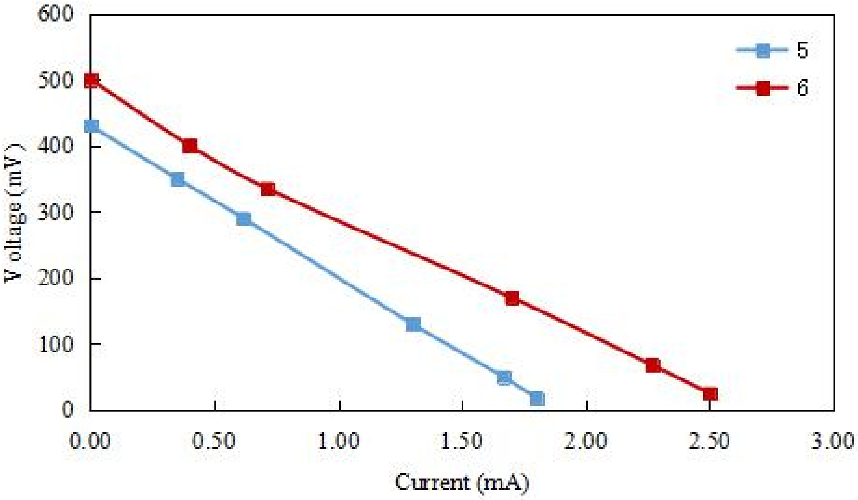

Fig.2.7 The relationship between voltage and current in the PMFCs of bucket No.5 and bucket No.6 for the time of 24 h

Table 2.3 Test results on PMFCs for the time of 24 h

No	**Maximum Voltage (V)**	**Internal resistance (Ω)**	**Maximum power per area of anode (mW/m^2)**
5	0.43	239	40
6	0.5	200	69

2.4 Conclusions

The following conclusions were obtained from this study.

(1) The result suggests that the voltage of the case without plant was generated due to the presence of algae. The voltage generation of the case with chemical fertilizer increased fast and reached to 0.5V. It is considered that chemical fertilizer works quickly, but the effect does not continue for long.

(2) The voltage of the case with organic fertilizer increased gradually and maximum voltage reached was 0.68V. The voltage of the case with organic fertilizer and using anode with iron wire increased gradually and maximum voltage reached was 0.85V. It was observed that the voltage of this case is more stable compared with that of the case without iron wire. However, the voltage on the PMFCs depends on sunlight.

(3) It was found that the electrodes in PMFCs do not influence the growth of paddy plant. It was also observed that the growth of paddy plant is promoted when iron wire is used. This suggests that iron was supplied to the plant as nutrition.

(4) Compared with carbon fiber, the voltage and electricity of the PMFC of the activated bamboo charcoal is greater.

(5) The maximum power per anode area of 69 mW/m^2 was obtained on the PMFCs with activated bamboo charcoals electrodes and activated bamboo charcoals electrodes (with iron wire).

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3. Soil microbial fuel cells based on organic waste: power and recycling of materials after power generation

3.1 Introduction

Today, the world is facing a major problem of eutrophication and energy crisis at the same time. Hence the development of multifunctional hybrid devices is the need of the hour which can serve the dual purpose of environmental cleaning as well as the generation of efficient, sustainable and cost-effective electricity (Kumar et al., 2018). The global energy crisis and heavy metal pollution are the common problems of the world. At this juncture, the development of microbial fuel cells (MFCs) is a promising technique for sustainable energy production and it is simultaneously coupled with the remediation of heavy metals from water and soil (Fang and Achal, 2019). The idea of using microbes to produce electricity was conceived in the early twentieth century by Michael Cressé Potter who initiated the subject in 1911 (Potter, 2019). Later in 1931, Barnett Cohen created microbial half fuel cells, when connected in series, were capable of producing over 35 volts with only a current of 2 milliamps (Cohen, 1931). Thus, an MFC is a device that converts chemical energy to electrical energy by the action of microorganisms (Allen and Bennetto, 1993). These electrochemical cells are constructed using either a bio-anode and/or a bio-cathode. Most MFCs contain a membrane to separate the compartments of the anode and the cathode. The electrons produced during oxidation are transferred directly to an electrode or, to a redox mediator species. The electron flux is moved to the cathode. The charge balance of the system is compensated by ionic movement inside the cell, usually across an ionic membrane. Most MFCs use an organic electron donor (from natural resources) that is oxidized to produce CO2, protons and electrons such that the technology itself gains its prominence among others especially towards renewable energy production. Microbial electrolysis cells have been demonstrated to produce hydrogen (Heidrich et al., 2012). Microbes from organic matter rich soils and sediments have been proved to be effective as a source of alternative energy in MFCs. MFCs have been generated at low cost, sustained for long periods of time with minimal impact on the environment (Rinaldi et al., 2008) and can be used as power sources for environmental sensors and environmental bioremediation. MFCs can be elegantly opted for the biomass-based energy production, but many technical challenges must be overcome before they can be applied to renewable energy production. The integrated method of sustainable energy production along with the treatment of wastewater has attracted and increased the attention of researchers across the globe (Logan and Regan, 2012).

MFC systems can be applied to the generation of electricity at water/sediment interfaces in the environment such as bay areas, wetlands and rice paddy fields. Using these systems, the electricity generation in paddy fields, as high as 80 mW/m^2 (based on the projected anode area) has been demonstrated and evidences that rhizosphere microbes preferentially utilize organic exudates from rice roots for generating electricity (Kousuma et al., 2014). Integrating the SMFC in rice paddy soil offers a promising way to mitigate the arsenic (As) accumulation in rice tissue and reduces the dietary arsenic exposure, while simultaneously producing electricity (Williamson et al., 2019).

Because soil-based microbial fuel cells adhere to the basic principles of MFC, soil functions as a nutrient-rich anodic medium, inoculant, and proton exchange membrane (PEM). The anode is located at a specific depth in the soil, and the cathode is placed on the top of the soil and exposed to air. The soil is naturally mixed with a variety of microorganisms including the electrogenic bacteria required for MFC, and is full of complex sugars and other nutrients accumulated from the decay of plant and animal materials. The tendency by the electrogenic bacteria in the oxygen-deficient condition in transferring the excess electrons to the extracellular acceptors during the metabolic process generates electricity (Huan et al., 2014). Sediment microbial fuel cells are applied to wastewater treatment. Simple deposited microbial fuel cells can generate energy while decontaminating wastewater (Xu et al., 2015).

Soil has been used to generate electricity in microbial fuel cells and has shown several potential applications. Jiang et al (2015) reported that the generated electrical signals by soil microorganisms are in linear relationship with the Cd 2+ toxicity in the soil. An insertion-type SMFC was inserted into waterlogged soil to enhance the biodegradation of phenol and simultaneously the generation of the highest power density of 29.45 mW/m^2. Thus it is advantageous that the removal of organic pollutants and COD in waterlogged soils could be enhanced by a soil MFC system coupled with electricity generation. Unfortunately, this method has significant implications for soil remediation because it may accelerate the transformation or degradation of some toxic organic pollutants under anoxic conditions (Huang et al., 2011). Arends and his coworkers (2014) explored the reduction in methane emissions in paddy soils and sediments while operating with sediment MFCs. MFC upholds the trait of sustainable technology albeit it generates a small amount of electricity without requirement of any energy input. Mulyadi and Rika (2018) generated the maximum power of 98.2 mW from soil microbial fuel cells and recommended the same for the remote areas in the North Kalimantan Province of Indonesia. There are certain factors which govern the performance of soil based MFCs which include the soil organic carbon, mineralization rates and bacterial community structure. Notably, the performance of soil MFC using an agricultural soil was higher of about 17 folds than the soil procured from the forest (Sara et al., 2012).

In view of developing a cost-effective SMFC to generate electric power for a longer period of time, the present contribution was attempted. The utilization of various organic wastes as substrate materials and their admixtures was focused. The efficiency of voltage and electric power of SMFC as a function of organic wastes either in a separate form or as admixtures was measured and discussed. Characterization studies for the fresh and performed anodes were carried out and detailed in this paper.

3.2 Development of soil microbial fuel cells that can compost and generate power

3.2.1 Organic waste and SMFC assembly

The organic wastes chosen for the present SMFC study such as crushed fallen leaves (FL), bamboo waste (BW), leaf mould (LM) and rice bran (RB) were procured from the local sources at Nagasaki, Japan. Initially the procured FL and BW were crushed and made into a powder to improve the contact area with the electrodes. LM is a product of slowly decomposed deciduous shrubs and tree leaves as well as known compost which is retentive of water and fertilizer (K. Omine, V. Sivasankar, S.D. Chicas, 2018). Rice bran is one among the used organic materials in the admixture, rich in vitamins and minerals and serves (S.A.S.C. Faria, P.Z. Bassinello, M.V.C. Penteado,2012) as a good fermenting ingredient under aerobic and anaerobic conditions. Fulvic acid (FA) is one of the organic acids originally found in forests and soils, and plays a role in supplementing plants with minerals. The organic materials were crushed into a powder and analyzed for carbon, nitrogen, potassium and phosphorus contents. The analysis of phosphorus and potassium was performed by standard methods using Atomic Absorption Spectrometer (Model ContrAA800F). The total nitrogen and total carbon were analyzed by an elemental analyzer (EA; EA1112, Thermo Fischer Scientific, MA, USA) with the weighed amount of organic matter (1.0 ± 0.1 mg) by dry combustion method (M.A. Tabatabi and J. M. Bremner, Automated, 2003).

Solid phase MFC assembly was fabricated with a dimension of $14 \times 7 \times 5.5$ cm^3 using a plastic container as shown in Figure 3.1. The packing of the MFC container was done with the organic mixture (FA, BW and LM) between the anode and the cathode. The FL is good with organic nutrients and they get decomposed by the addition of LM which acts as a vital source for microorganisms. Simultaneously, the BW contained with lactic acid grows enormous bacterial organisms under anaerobic condition can possibly decompose the fallen leaves along with the LM. The bamboo carbon anode (Akaneya Tikutan Corporation, Japan) with a dimension of $12 \times 3.5 \times 0.5$ cm^3 is surrounded by an iron wire (1 mm) of length of 4.5 cm. The carbon anode (unit area is equal to 0.0042 m^2) was placed on the packed bed of organic waste or admixture of 1 cm height and the packing was continued above the anode for the height of 3 cm to facilitate the perfect anaerobic condition. On the other hand, granular activated carbon, GAC (1.4 cm height) which serves as the cathode, was evenly distributed at the top of the organic waste or admixture with a stainless steel (SS, 0.1 cm) mesh inserted exactly at the center of the GAC layers. In order to facilitate a perfect operation in MFC, the device was covered with a wrap to prevent the sample from coming into contact with air and also to maintain an anaerobic environment.

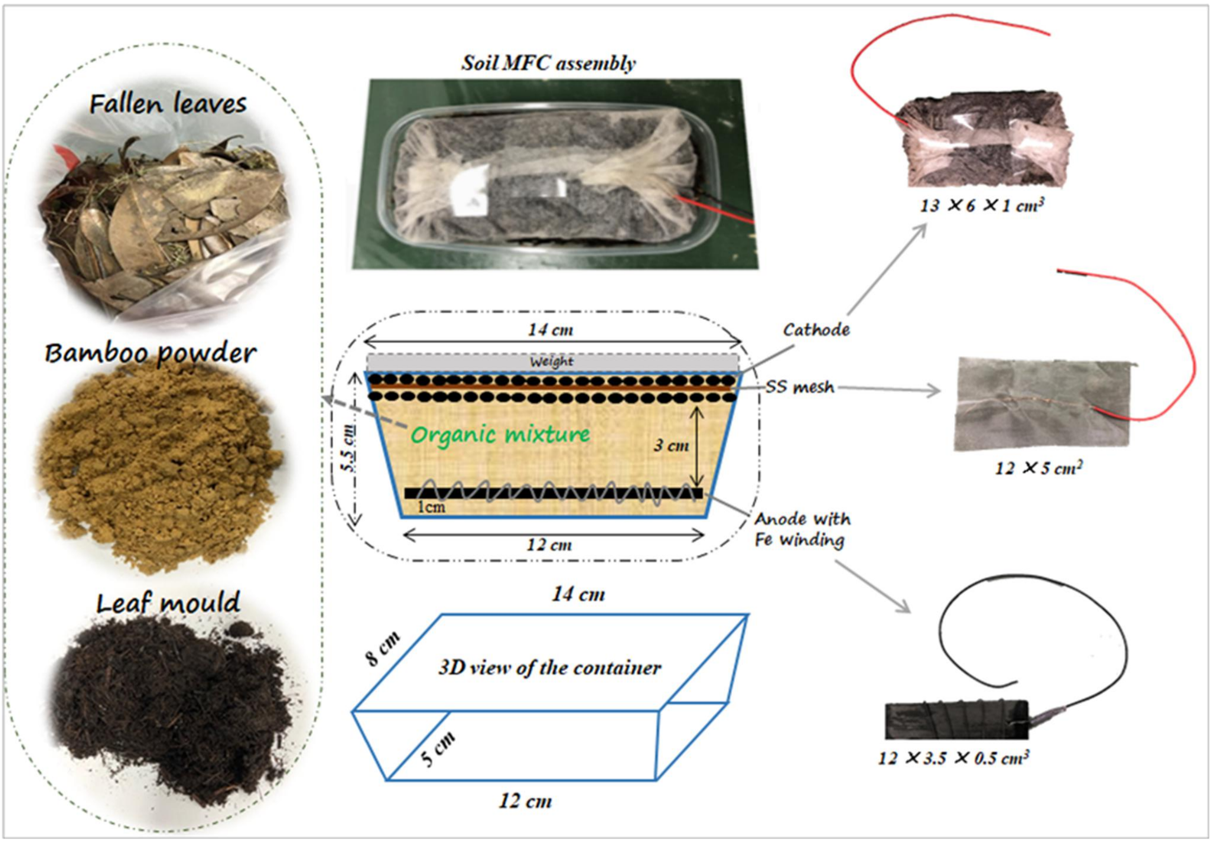


Fig. 3.1 Soil MFC assembly and the sketch, electrodes (bamboo carbon anode with Fe winding and granular charcoal cathode) and electrode materials

3.2.2 SMFC operations and influential factors

The influence of organic waste, the admixture composition, volume and fulvic acid (Interman Corporation, Japan) on the output voltage was measured. The SMFC was operated by initiating the connection between the cathode and the anode via an external resistor (1000 Ω, 500 Ω, 100 Ω, 50 Ω and 10Ω) and a voltage (V) across the resistor was measured using a data logger (Model: MCR-4 V). The calculation of internal resistance was done from the external resistance, recorded voltage and the current ($I = V/R$). The maximum power was derived from the polarization curve of current versus power ($P = I \times V$). The measurements were made at 5 min intervals using the data logger with a precise resolution of 10 µV of measureable range from ±300 mV to ±24 V during the operation of SMFC.

The details on the SMFC experimental studies conducted through different systems are shown in Table 3.1. The polarization curves were drawn by plotting the current-voltage (*I*-*V*) and current-power characteristics for different resistance values on the circuit. The pH and the electrical conductivity of the SMFC sample were measured with a pH-meter (Hanna model HI8424) and a conductivity meter (Hanna model HI2315-01) respectively.

Table 3.1 Details of SMFC operations: Organic materials, admixture and compositions

System No.	**FL (g)**	**BW (g)**	**LM (g)**	**RB (g)**	**FA(mL) (0.01% in water)**	**H_2O (mL)**
1-1	150	0	0	0	0	150
1-2	150	0	0	0	150	0
1-3	0	150	0	0	0	150
1-4	0	150	0	0	150	0
1-5	0	0	150	0	0	150
1-6	0	0	150	0	150	0
2-1	0	75	75	0	112.5	0
2-2	0	75	75	0	150	0
2-3	0	75	75	0	180	0
3-1	0	75	75	0	180	0
3-2	0	50	100	0	180	0
3-3	0	100	50	0	180	0
4-1	0	75	75	15	180	0
4-2	0	0	150	15	100	0
4-3	0	120	0	12	150	0
4-4	0	75	75	0	180	0

FL-Fallen Leaves; BW-Bamboo Waste; LM-Leaf Mould; RB-Rice Bran; FA-Fulvic Acid The units for FA and H_2O are expressed in ‘ mL’ whereas the remaining others are expressed in ‘g’

3.2.3 MFC waste as compost for crop production: germination test

The crop cultivation analysis is essential to understand and evaluate the degree of decomposition of organic matter in the compost. If the composting is insufficient, the application may cause hindrance to the growth of crops due to intermediate metabolites and gaseous decomposition which would ultimately lead to abnormal germination and root growth of crops. Prior to the application of the compost, the germination test is indispensable and performed in accordance with the standard procedure (S. Fujiwara, 1997) as follows:

An Erlenmeyer flask of 200 mL capacity was taken with 10 g of SPMFC (discarded) waste and 100 mL of boiling water (to promote the extraction and to have a bacterial effect) and stirred for 1 h and then the solution was left undisturbed until it reaches the room temperature. Then the solution was filtered with two layers of gauze. Simultaneously, the water extract of bamboo was prepared as a control as given for SPMFC (discarded) waste. The water extracts of SPMFC and bamboo were poured onto 30 Komatsuna seeds distributed in the separate dishes and in addition another control using water in a Petri dish with 30 seeds was also taken. Then the seeds were maintained at ambient temperature of 298 K for 3–6 days and then observed for their germination through hair root formation.

3.2.4 Electrochemical Impedance study and Characterization of anode-bamboo carbon with iron winding

Electrochemical Impedance Spectroscopy (EIS) was performed to study the electrochemical behavior of SMFCs performed with different admixture compositions after 24 h using potentiostat (Model: Potentio-Galvanostat, VSP-300, Bio-Logic Science Instruments). The real and imaginary impedance measurements were obtained at a scan rate of time about 4 h between the frequency range of 1 mHz and 1 MHz. A small AC signal of 10.18 mV was applied during the measurement to simulate the current response from the SMFCs without affecting its regular performance. The equivalent circuit model consisting of ohmic resistance connected in series to two parallel circuits, charge transfer resistance and mass transfer resistance. Constant Phase Elements (CPEs) are capacitors which are used to adjust the system response to the equivalent circuit model. The obtained experimental data was fit to the equivalent circuit using the ZView R Software.

The characterizations of anode samples were performed by Scanning Electron Microscopy after a carbon coating of the samples (SEM; Jeol JSM-7500 FAM) and Energy Dispersive Spectroscopy (EDS; Jeol EDS JSM-7500). The functional group identification was done by Fourier transform infrared spectroscopy (FTIR) using JASCO Corporation IRT-5200 FT-IR being equipped with the Attenuated Total Reflectance (ATR) spectrophotometer method with diamond window. Raman spectroscopic measurements were done with a confocal Raman microscope Horiba XproRA using 532 nm lasers in the range of 150–5000 cm−1. The physical and structural characteristics were determined by nitrogen adsorption/desorption at 77.5 K using Micromeritics ASAP 2020 surface area and porosity size analyzer.

3.3 Results and discussion

3.3.1 Individual influence of FL, BW and LM in power generation

The basic physical properties such as bulk density, moisture content and pH for the organic materials and the chemical analysis which includes the total nitrogen, total phosphorus, total potassium and total carbon for FL, BW, LM and RB are given in Table 3.2.The analyzed amount of total carbon (53.6%) and total nitrogen (7.24%) in LM was higher than the other three organic materials. The amount of carbon content in the other three materials follows the order: FL > RB > BW. However, the total nitrogen content of 3.2% in RB was higher than FL and BW of 0.84% and 0.1% respectively. The C/N ratio is reported to affect the performance and the power generation in MFCs using organic materials thanks to the influence of microbial metabolism. The C/N ratio for FL, BW, LM and RB are 55.5, 280, 7.4 and 10.5 respectively. Due to the presence of very less total nitrogen content, the C/N ratio in FL and BW was high than that of LM and RB materials with high good nitrogen contents.

The influence of each organic material in combination with water and FA (0.01%) was studied using SMFC. The maximum power generated for 24 h of elapsed time in SMFC based on the polarization (*I*–*V*) curves is shown in Figure 3.2 (A and B) where the internal resistance (Ω) and the emf (V) can be calculated from the slope and the intercept respectively. The maximum power (per m^2) generated in SMFC due to the packed FL, BW and LM in combination with water was 119 mW, 119 mW and 226 mW respectively. LM in combination with water generated electricity (226 mW/m^2) about 1.9 times higher than FL and BW. While replacing the FA instead of water, the power generation (Table 3.3) from the organic wastes was increased from 2.39 to 2.80 times in SMFC.

The high power output due to the addition of FA attributed the increase in the population of microorganisms during the decomposition of FA which is a suitable substrate with good solubility in water and prone for the microbial attack than the other compounds of humus nature (Grunda, 1970; Kunc et al., 1976; Machado et al., 2020). The microbial degradation of FA under anaerobic condition at anode is shown in Eq. (3.1).

$$\boldsymbol{C_{14}H_{12}O_8 + 20H_2O \rightarrow 14CO_2 + 52H^+ + 52e^-} \tag{3.1}$$

Conspicuously, the LM-FA combination was remarkable due to the effective participation of both in driving the power unlike the other combinations. Thus the influence of organic materials in the power generation can be determined as follows.

LM > BW > FL (in combination with FA) and LM > BW = FL (in combination with water). In view of the above observation, LM and BW were used in the SMFC construction for the subsequent experiments.

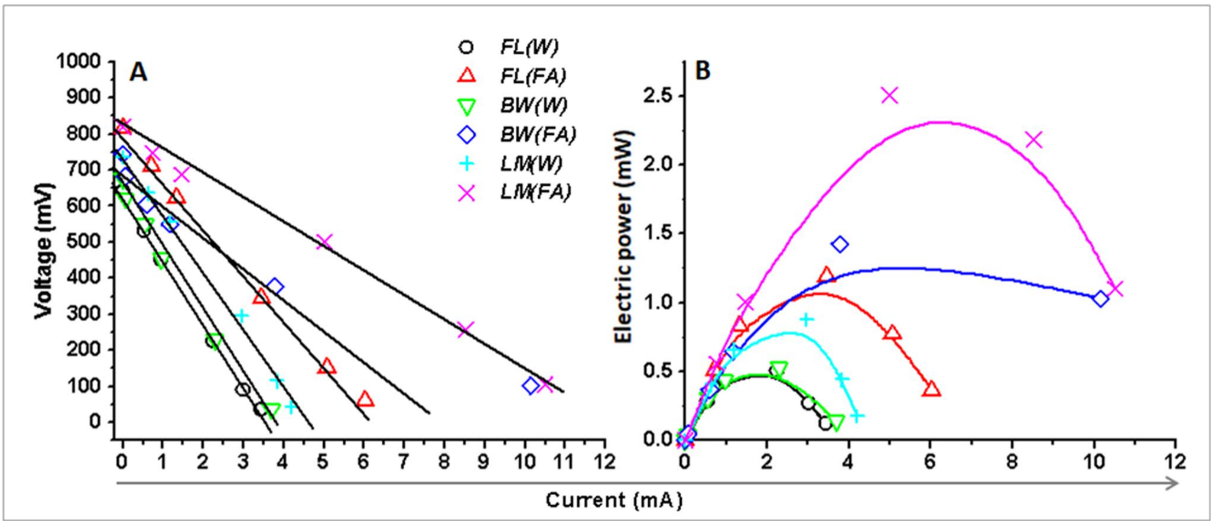


Fig.3.2 SMFC operation using different organic waste materials for the time of 24 h: Curves of Current Versus Voltage (A) Current Versus Electric power (B)

Table 3.2 Physical and chemical analyses of the organic waste materials

Parameters	Organic material			
	FL	BW	LM	RB
Bulk density (kgm^{-3})	78.5	250.1	337.6	502.5
Moisture content (%)	12.4	50.3	215.1	7.5
pH	4.7	7.1	6.2	6.5
Total N (g/kg)	8.4	1.0	72.4	32.1
Total P (g/kg)	2.7	0.5	10.5	66.8
Total K (g/kg)	2.6	1.0	6.7	15.1
Total C (g/kg)	466	280	536	337
C/N ratio	55.5	280	7.40	10.5

3.3.2 Influence of different volumes of 0.01% fulvic acid along with BW and LM

The maximum power of SMFC was directly proportional to the volume of added FA to the organic (1:1) admixture of BW and LM as represented in Figure 3.3 (A and B). The generated power was found to increase from 580 mW/m^2 to 833 mW/m^2 after 24 h (Table 3.3). Accordingly, for a decrease in the internal resistance by 4.9 Ω (57.85-52.94 Ω), there was an increase in the output voltage of 0.09 V (0.81-0.90 V). It is thus inferred that the increase in the amount of FA facilitated the growth of microorganisms leading to increasing decomposition of organic admixture and the ejection of more electrons resulting with high output power (Eq.3.1). Interestingly, the power generation of 709 mW/m^2 by the 1:1 admixture in SMFC was 2.13 folds and 1.19 folds higher than that of the individual organic materials BM and LM respectively. Thus the potentiality of LM and FA could be realized to be more significant than that of the combined BW in the admixture.

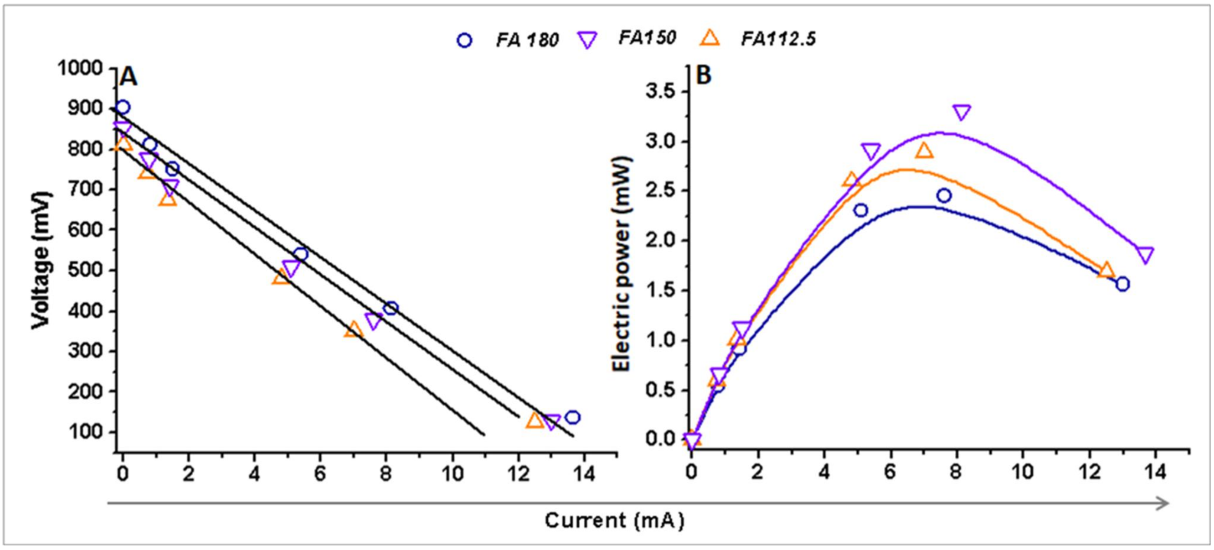


Fig.3.3 SMFC operation using different volumes (ml) of fulvic acid (0.01%) taken with BW– LM admixture for the time of 24 h: Curves of Current Versus Voltage (A) and Current Versus Electric power (B)

Table 3.3 Internal Resistance, Maximum Voltage and Maximum Power measured in the SMFC systems

System No.	Internal Resistance (Ω)	Maximum Voltage (V)	Maximum Power (mWm^{-2})
1–1	183	0.61	119
1–2	136	0.80	285
1–3	183	0.68	119
1–4	73	0.75	333
1–5	182	0.75	226
1–6	79	0.83	595
2–1	58	0.81	580
2–2	57	0.85	709
2–3	53	0.90	833
3–1	48	0.81	833
3–2	51	0.77	714
3–3	58	0.75	595
4–1	21	0.71	1071
4–2	20	0.69	476
4–3	93	0.69	238
4–4	22	0.69	833

3.3.3 Influence of the admixture (BW and LM) ratio in generating electric power

The SMFC containing the 1:1 admixture (50% BW and 50% LM) with 0.01% of FA was able to generate 833 mW/m^2 after the time of 24 h (Figure 3.4A and 4B). However, on increasing the amounts of LM and BW to 66.7% (by keeping the other material with 33.3%), the maximum power was dropped to 14.3% (714 mW/m^2) and 28.6% (595 mW/m^2) respectively. From the studies, it is apparent that the power generation of 595 mW/m^2 in SMFC developed with BW and LM in the ratio of 2:1 with 180 mL (0.01%) FA becomes equal to the SMFC with 150 g LM with 150 mL (0.01%) fulvic acid. In a similar way, almost the equal power of 709 mWm-2generated from the SMFC with the 1:1 organic admixture of BW and LM and FA (0.01% of 150 mL) can be a suitable alternate for the SMFC (714 mW/m^2) with 1:2 organic admixture and FA (0.01% of 180 mL). Evidently, it can be sought for an alternate composition in the organic admixture and FA to generate the equal power or almost closer.

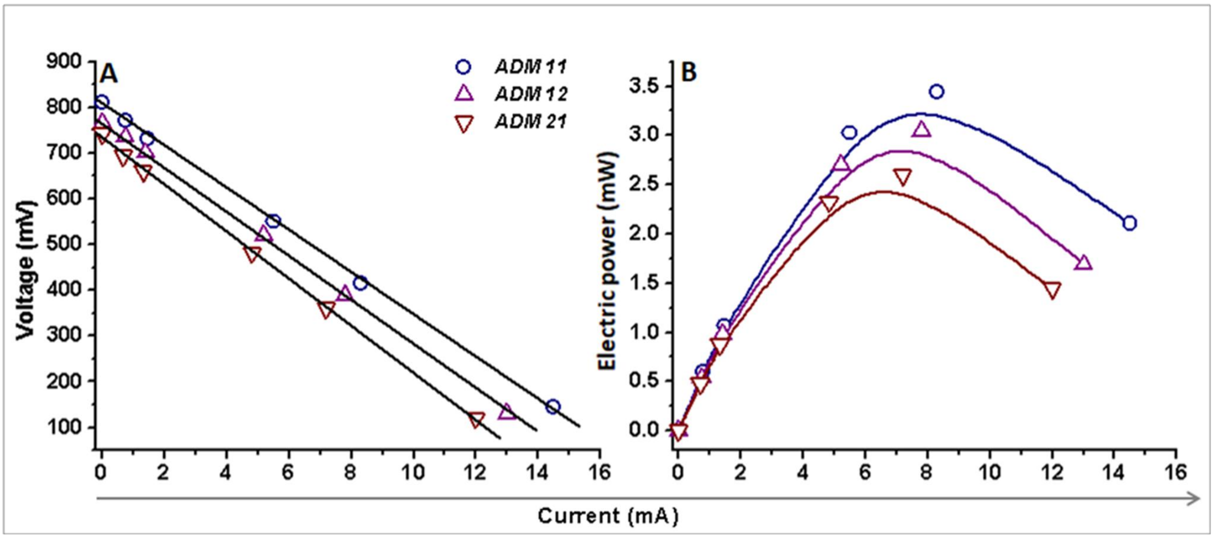


Fig. 3.4 SMFC operation using different organic admixture ratios for the time of 24 h: Polarization curves of Current Versus Voltage (A) and Current Versus Electric power (B)

3.3.4 Influence of admixture combinations in generating electricity

The highest output power measured in SMFC was 1071 mW/m^2 for the admixture containing BW, LM, RB and FA (System 4–1). However, the generated electric power drops to 833 mW/m^2 (System 4–4) when RB was removed from the organic admixture. The enhancement of additional electric power of 238 mW/m^2 in the system 4-1 can be attributed to the increased degradation of organic compounds (especially the polysaccharides) present in RB due to sufficiently grown microorganisms. Moreover, taking the systems 4–1 and 4–4 into consideration, the total amount of nitrogen (5.745 ± 0.24 g) was able to decompose the total amount of carbon (63.73 ± 2.53 g) present in the admixtures and generates a good output power. Nevertheless, the decrease in the amount of carbon (5.06 g) and nitrogen (0.48 g) due to the absence of RB in the system 4-4 leads to a decreased power generation.

The electrical power generated by SMFC (system No. 4-1) in the present work is about 65 times higher than the SMFC studied by Yoshimura et al. (2018) and about three times higher than the SMFC-W (rice bran with water) and about 2.1 times higher than SMFC-M (rice bran with mineral solution) as reported by Takahashi et al. (2016). The SMFC constructed as per the system No. 4-3 could generate only the minimum electric power of 238mW/m^2. It is because of the limited oxidative degradation of organic compounds in the admixture of SMFC due to the lesser growth of microorganisms as a consequence of insufficient supply of nutrients in the absence of LM. In addition, it can also be well attributed to the poor nitrogen content of 0.505 g to decompose 37.64 g of carbon in the admixture in the system 4-3. It is pertinent to explain that the depletion of nitrogen will take place before the completion of decomposition. Also, the generation of microorganisms would decrease as a consequence of depleted nitrogen in the admixture. Thus, it can be inferred that the lesser oxidative degradation ejects the minimum release of electrons to generate less electrical power, nonetheless, it is about 14 times greater than the SMFC reported by Yoshimura et al (2018). The superfluity of nutrients in the SMFC system (No. 4-2) is evident from LM and FA for the enhanced microbial growth albeit the inadequacy of organic compounds (due to the absence of BW) and subsequent degradation was less effective to generate the maximum electric power of 476 mW/m^2 (Table 3.3) than the other systems (No. 4-1 and No. 4-4). Based on the amounts of carbon and nitrogen in the admixture (4–2), the total nitrogen content seems to be almost doubled (11.34 g) as compared to 4–1 and 4–4 whereas the amount of carbon (85.46 g) is not proportionate for the process of decomposition which ultimately leads to the lessening of electric power. However, the generated electricity was about 29 times higher than the reported output of Yoshimura et al (2018). In pertinent to systems 4–1 and 4-3, the generation of electric power was about 27.3 and 6.1 times higher than that of the power generated using kitchen and yard wastes. Similarly, on comparing the study of Moqsud et al., the generated power for 4–1 and 4-3 systems is found to be higher by about 17.9 and 4 times respectively. The recent developments on solid-phase MFCs are reported by Budihardjo et al.by exploring the electric power generations using different wastes and electrodes. The corresponding polarization curves are shown in Figure 3.5 (A and B). The calculated values of C/N in admixtures for systems 4–1, 4–2, 4–3 and 4-4 are 11.07, 7.54, 74.53 and 11.12 respectively (Fig.3.6).

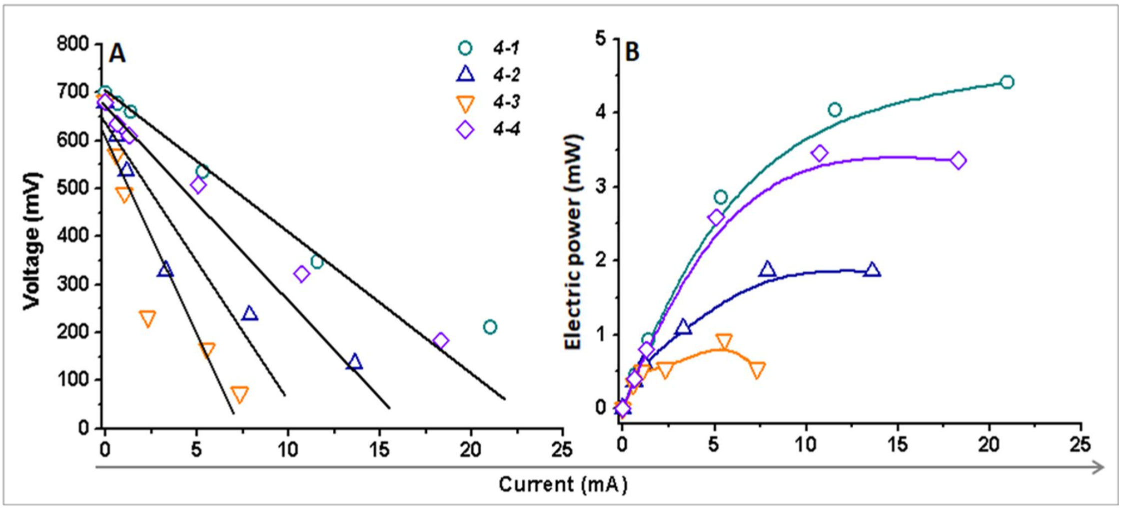


Fig. 3.5 SMFC operation using different organic admixture combinations for the time of 24 h: Polarization curves of Current Versus Voltage (A) and Current Versus Electric power (B)

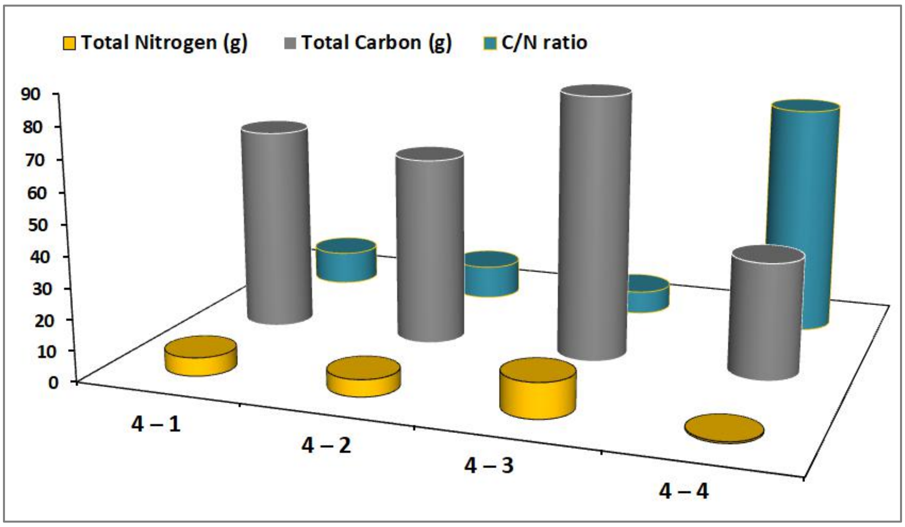


Fig.3.6 The amount of total carbon, total nitrogen and the C/N ratio in the admixtures for the systems 4-1 to 4-4

(Total Nitrogen and Total Carbon are measured in g and C/N ratio has no unit expression)

3.3.5 Electricity generation using different admixtures in SMFC

The variation of voltage with time in SMFC for four different organic admixtures is shown in Figure 3.7.In the SMFC system 4-1, subsequent to an initial drop till 6h due to lack of microbial degradation, the potential rises gradually up to 0.72 V for an elapsed time of three days. At this stage, the gradual microbial degradation of macromolecular biopolymers such as cellulose and hemicellulose present in BW, LM and RB takes place and converted to low molecular weight compounds on the anode. Likewise in the SMFC system 4-2, the potential increase and fall was observed due to the early fluctuation in bacterial growth. Then the potential rise was steep up to 0.79 V for the elapsed time of 30 h (1¼ days) and remains constant till 54 h (2¼ days). After a slight descending trend, the voltage was 0.77 V at 72 h (3 days) but very immediately, a jump in voltage was recorded with a maximum of 0.83 V till 130 h (5½ days). The first peak value of0.79 V attributed the degradation of low molecular weight compounds such as sugars and amino acids whereas the second peak (0.83 V) corroborated the degradation products of oligosaccharides, proteins and amino acids present in the organic admixture (Yoshimura et al. 2018). In contrary to the above SMFC systems (4-1 and 4-2), the 4-3 system was found with an initial rise in the potential from 0.69 V to 0.725 V till the 9th hour. It is pertinent to the easily degrading compounds especially of low molecular weight by the supply of sufficient nutrients sufficiently from RB and FA. In continuation to this, the polarization curve pattern had a dip and rise and measured with a voltage of 0.70 V after 45 h (1¾ days) and retained the constancy till 79 h (3¼ days). As a consequence of the degradation of macromolecular compounds present in the organic admixture, there was a tremendous rise to 0.81 V at the 89th hour which remains almost the same till 124 h (5¼ days). The SMFC system 4-4 recorded the initial potential of 0.68 V followed by constancy at 0.78 V for an elapsed time of 36 h (1½ days). However, the voltage declined to a value of 0.1 V which remains constant after 42 h (1¾ days). The poor electrical power generation could be associated to the lack of effective degradation by microorganisms due to absence of RB in the admixture.

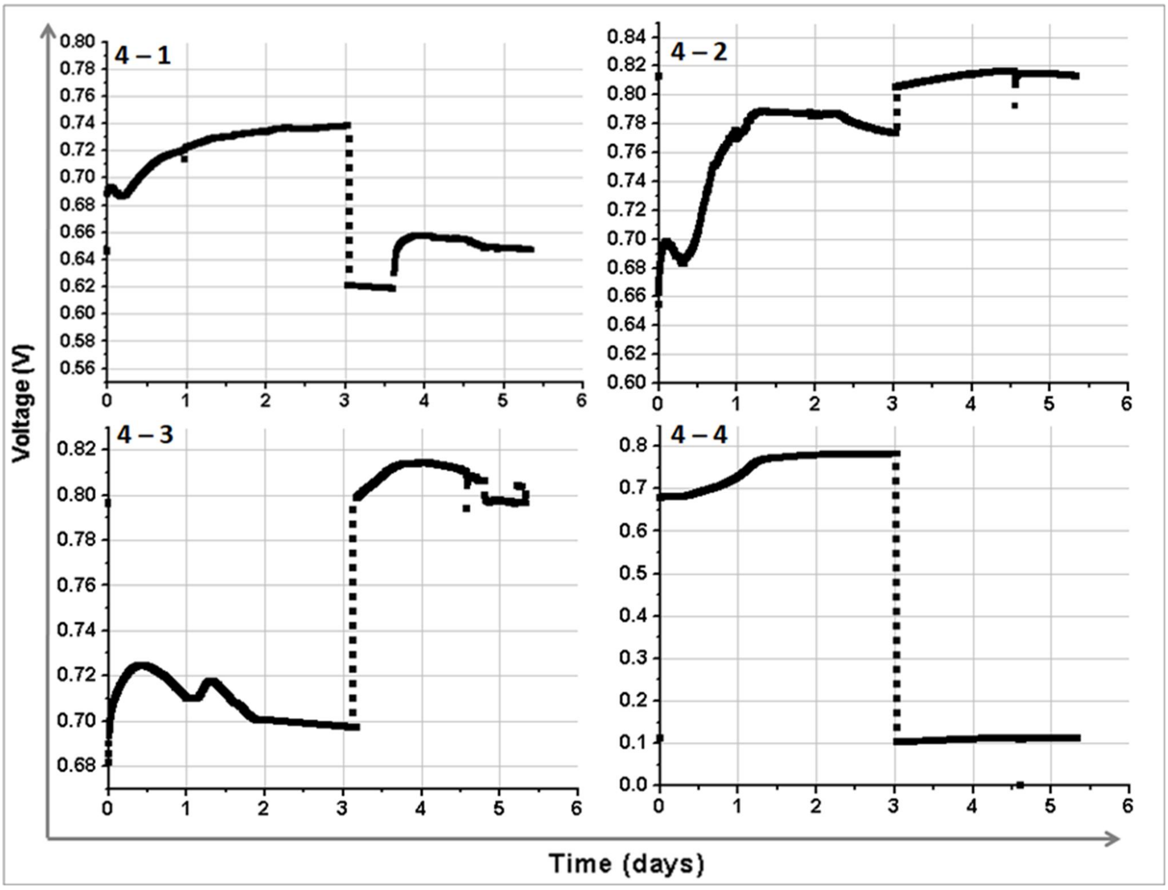


Fig. 3.7 Variation of potential in SMFC operated using different systems [4-1 to 4-4] with respect to time

3.3.6 Interpretation of the Nyquist plot for SMFC systems

The Nyquist plots for the SMFC systems are shown in Figure 3.8. The ohmic resistance (R_{ohm}) calculated through the high frequency intersection of Nyquist plot across the Z' axis for the SMFC systems 4–1, 4–2 and 4–4 is almost closer in the range of 20 ± 2 Ω cm^{-2}. Especially, in these SMFCs, the LM with the moisture content of 215.1% played a significant role along with FA and conspicuously in the SMFC system 4–2 where the R_{ohm} was decreased to 18 Ω cm^{-2} on doubling the amount of LM. Conversely, the absence of LM in the system 4-3 correspondingly shifted the R_{ohm} value of 99 Ω cm−2 to about five times (to the average value obtained for 4–1, 4–2 and 4-4 SMFCs) due to the significant reduction in moisture. In agreement with the present study, Li et al. reported a sharp decrease R_{ohm} with respect to the increase in the moisture content of soils in China. The charge transfer resistance, for the SMFCs 4–2 and 4–4 with similarity in semi-circle portions at the high frequency region was determined to be in the range of 79 ± 1 Ω cm^{-2}, however, R_{ct} of system 4-3 (500 Ω cm^{-2}) was 6–10 times greater than the other three SMFC systems. The influence of admixture on the charge transfer properties of SMFCs systems could be observed. In particular, the absence of RB increased the R_{ct} by 30 Ω cm^{-2} in the system 4–4 than that in system 4–1 (50 Ω cm^{-2}) for the similar admixture compositions (Table 4). The mass transfer resistance, R_{mt} in SMFC system 4–2 was lesser (34 Ω cm^{-2}) than that in 4–1. The decrease in R_{mt} could be attributed to the doubled quantity of LM accompanied with increased moisture and lessened diffusion resistance of oxygen species. The role of Warburg impedance (W) in SMFCs 4–3 and 4-4 demonstrated the electrolytic diffusion from diagonal lines with the slope of 45° in the low frequency region. The measured internal resistance (Table 3.3) for the SMFC (4–1 to 4-3) systems agree well to those measured by Electrochemical Impedance Spectroscopy as shown in Table 3.4, Table 3.5.

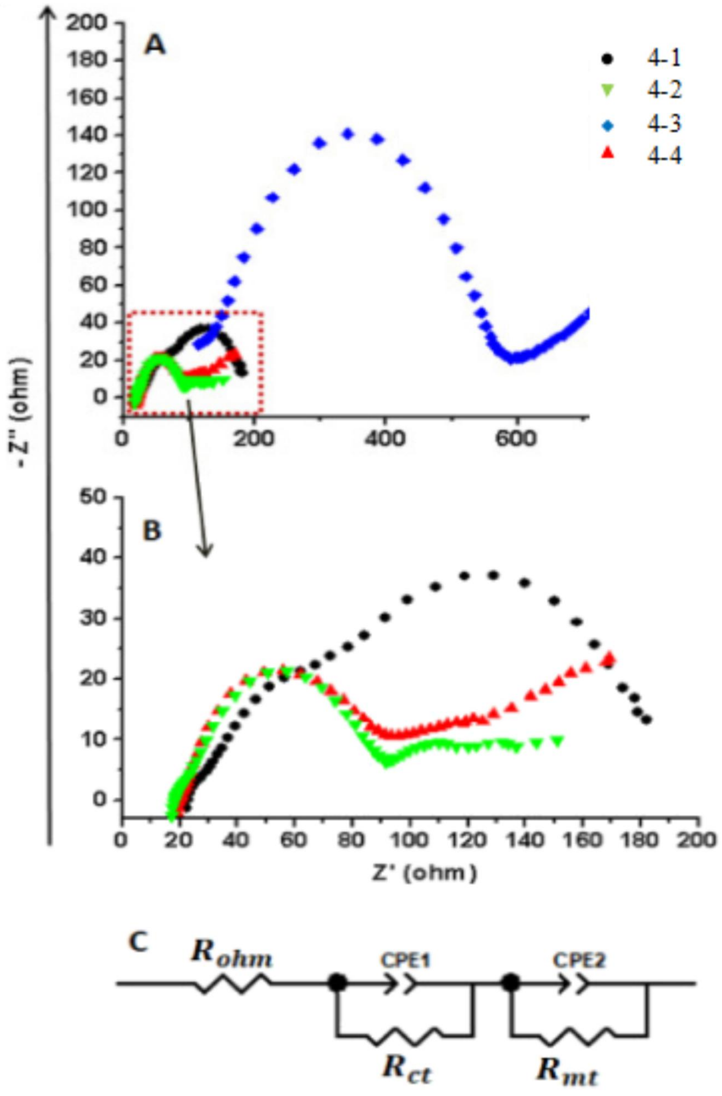


Fig.3.8 Electrochemical Impedance spectroscopy (EIS) of Soil microbial fuel cell systems: Nyquist plots (A and B) Equivalent circuit representation of SMFC (C)

Table 3.4 The measured resistance data of R_{ohm}, R_{ct} and R_{mt} of the SMFC systems. (Resistances are measured in Ω cm^{-2}.)

SMFC system	R_{ohm}	R_{ct}	R_{mt}
4–1	22	50	128
4–2	18	78	34
4–3	99	500	Not observed
4–4	20	80	Not observed

Table 3.5 Textural properties for the fresh and SMFC used bamboo carbon anodes.

Parameters	**Fresh**	**SMFC used**
V_p - Pore volume (cm^3g^{-1})	0.000554	0.001734
d_p - Pore diameter (nm)	1.1903	1.7231
Surface area (m^2g^{-1})	11.094	2.1366
Average diameter (nm)	1.9966	3.2458
Middle diameter (nm)	3.7202	2.7657

3.3.7 Characterization studies of bamboo carbon anode

The surface morphology for the fresh bamboo carbon before its application as an anode in MFC is shown in Figure 3.9 (A, B and C) in view of locations marked in Figure 3.10C. The amounts of C and O in the different locations of carbon anode are represented (Table 3.6 and Figure 3.11). The surface morphology in the locations A and B appears highly rough with cracks and pits all over however, the surface was observed sealed and smooth with very limited cracks and pits in the location C. Contrary to this, the surface morphology was observed with grains and distortions in the case of carbon anode as evident from the images represented in Figure 3.9 (1-5). The surface of carbon anode becomes attached to the microorganisms during the operation of an MFC which can be observed on the surface of images 1 to 5 in Figure 3.9. The heterogeneous attachment of microorganisms on the surface of anodic carbon perhaps due to the variation in the specific surface area in the chosen locations (1-5) which can offer space to hold microorganisms. Manickam et al (2013) reported that the active colonization of the carbon anode by microorganisms was enhanced by the porous structure of carbon and plays a vital role in the electron transfer process to generate more power with minimum electricity loss (Kumar et al. 2015). The potentiality and the number of microorganisms are proportional to the electron transfer and hence the output power (Kalathil and Pant, 2016). In agreement with the surface morphology of the carbon anode, Zhang et al (2014) reported the rough surface of bamboo carbon with cracks which would increase the number of electrochemically active sites to favour the process of electron transfer from the microorganisms to the anode. The coloured SEM pictures illustrate the variation in the mass percentages for carbon (red) for the fresh and MFC applied anodic carbon which may be attributed that the meager difference in the carbon is the amount of carbon consumed from the surface as a nutritious food for the growing microorganisms (Figure 3.11). The amount of carbon expected to be consumed by microorganisms was estimated in the range of 0.672 g to 5.1396 g (Figure 3.10A) as calculated from the EDS results. Furthermore, the amount of Fe in the carbon anode after the operation of MFC based on EDS results was calculated from 0.614 g to 16.595 g (Figure 3.10B). The elemental Iron (Fe) is prone for oxidation which also signifies the generation of voltage from the MF cell as given in Eq. (3.2).

$$\boldsymbol{Fe^{2+}(aq) + 2e^{-} \leftrightharpoons Fe\,(s); E^{0} =- \; 0.44\,V\,at\,298\,K} \qquad \textbf{(3.2)}$$

The contribution of Fe winding facilitates the release of Fe (II) ions along with the ejection of electrons which results in feeding the Fe (II) nutrient to the growing microorganisms and the potential increase due to the electron loss (Omine et al 2018). The amount of oxygen content was found higher (0.614 g-6.958 g) in the carbon anode after its application in the MFC than the unused carbon anode (Figure 10B). This may be pertinent to the fact of oxygen diffusion which takes place towards the anode where it gets reduced to oxide by accepting electrons from the anode (Eq. 3.3 and Eq. 3.4).

$$\boldsymbol{mO_2 + (4n+4)e^{-} \rightarrow 2mO^{n-}(m = 1, 2, 3, \ldots\ldots\ldots and\; n = 0, 1, 2, \ldots\ldots\ldots)} \qquad \textbf{(3.3)}$$

$$\boldsymbol{O_2(g) + \; 4H^{+}(aq) + \; 4e^{-} \; \rightleftharpoons \; 2H_2O\,(l); E^{0} =+ \, 1.23\,V\,at\,298\,K} \qquad \textbf{(3.4)}$$

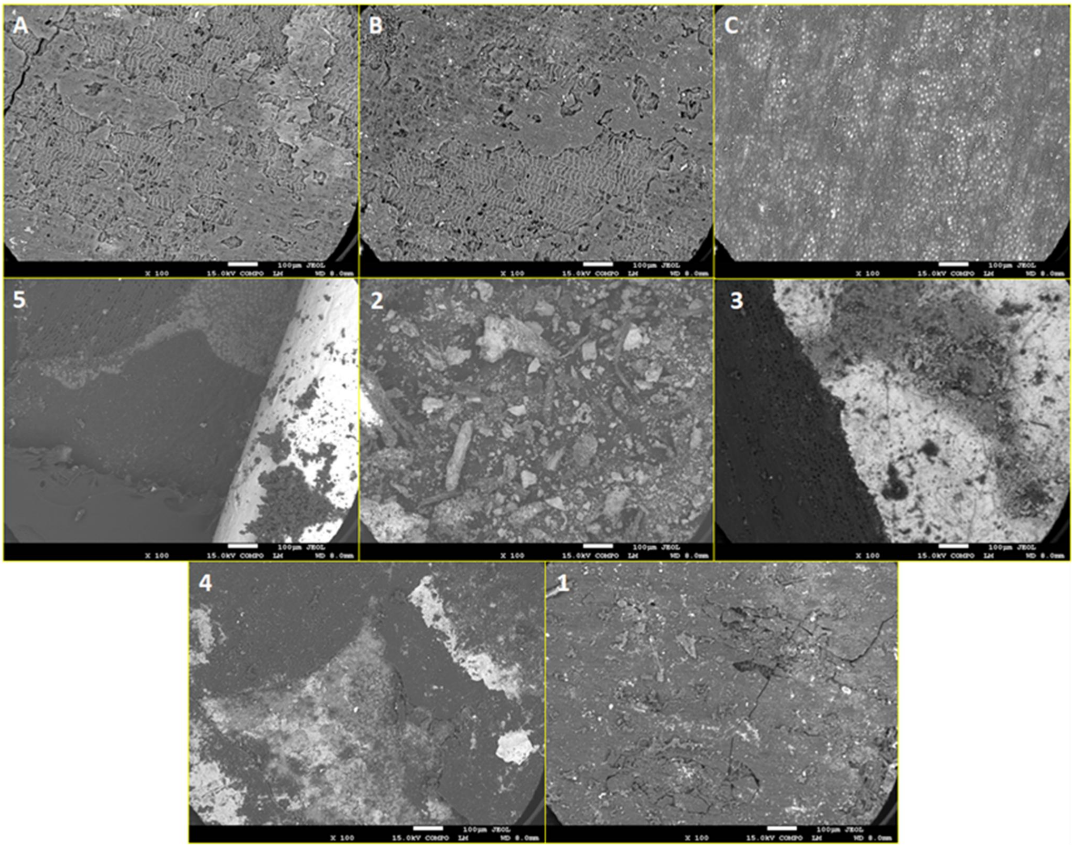


Fig. 3.9 Scanning electron micrographs for the fresh bamboo carbon-Anode for locations A, B and C; Used bamboo carbon-Anode for locations 1, 2, 3, 4 and 5

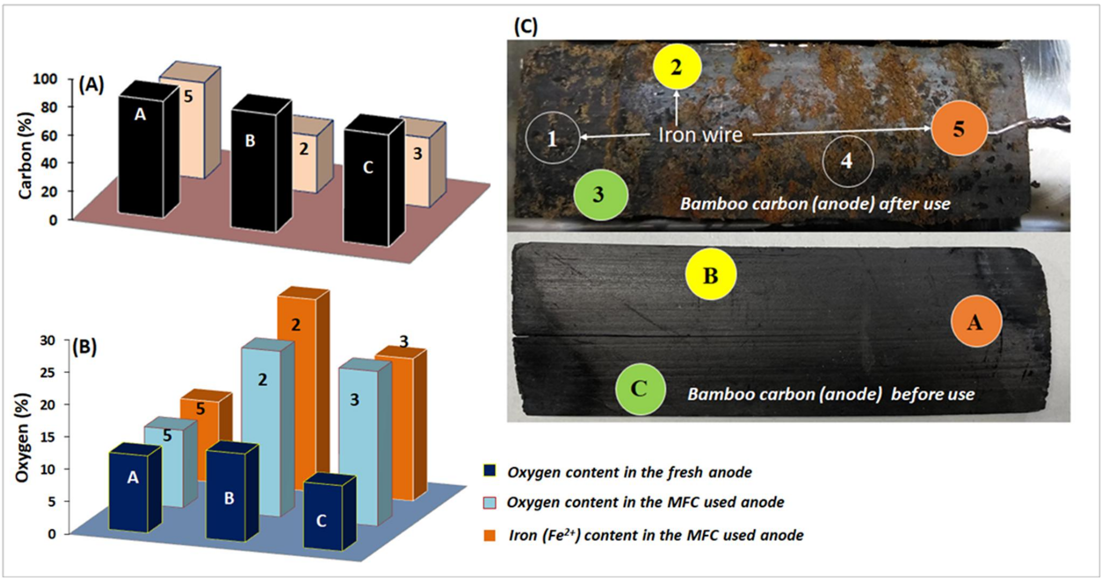


Fig. 3.10 Percentage of carbon (A) and oxygen (B) in the bamboo carbon-Anode; Image of the anode material used and the spots of samples for the analysis of elements

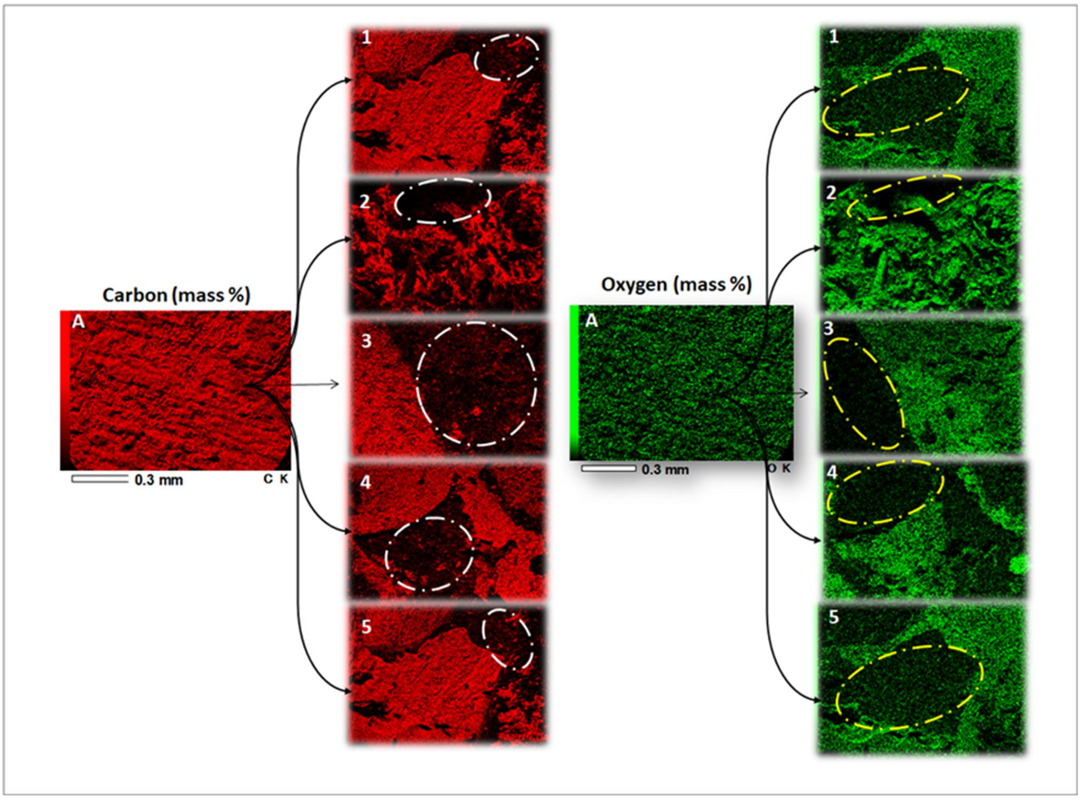


Fig. 3.11 The mass percentages of carbon and oxygen in the fresh (A) and used carbon anode material (1-5)

Table 3.6 Details of carbon and oxygen amounts calculated from EDS

Spot No.	**Amount of carbon loss**		**Calculated CO_2**	**Oxygen gained**	
	Mass (%)	**Mass (g)**		**Mass (%)**	**Mass (g)**
5 and A	14.79	1.775	6.508	0.10	0.016
2 and B	42.83	5.139	18.845	11.99	1.918
3 and C	30.19	3.623	13.284	13.77	2.203
1 and A	5.60	0.672	2.464	9.01	1.442
1 and B	9.08	1.089	3.995	7.30	1.168
1 and C	9.55	1.146	4.202	10.78	1.725
4 and A	14.04	1.685	6.178	10.45	1.672
4 and B	17.52	2.102	7.709	8.74	1.398
4 and C	17.99	2.159	7.916	12.22	1.955

The FTIR analysis (Figure 3.12A) corroborated certain changes between the fresh and the SMFC used bamboo carbon anodes. The stretching vibration (υ_{O-H}) assigned to the surface hydroxyl (– OH) groups (due to cellulose and lignin) for the fresh and the used bamboo carbons were located at about 3250 cm^{-1} and 3450 cm^{-1} respectively. The vibrational shift of about 200 cm^{-1} along with the decreased intensity could be attributed to the reduction of hydroxyl groups into corresponding oxides during the electrochemical reactions governed by the microorganisms generated from the organic admixtures. This is further supported by the EDS analysis with increased oxygen content in the used bamboo carbon anode. The present finding is in agreement with the observations of Li et al.. In a similar way, the vibrational stretch (υ_{C-O} of cellulose) at 1080 cm^{-1} for the fresh carbon anode was shifted to 1000 cm^{-1} for the SMFC used carbon anode with increased band intensity. This may be pertinent to the diffusion of oxygen towards the anode with subsequent reduction into oxide on the electrode's surface as supported by EDS results. The vibrational band for the carbonyl stretching was observed at about 1740 cm^{-1}. The stretching and bending frequencies for the methylene C–H groups were identified at about 2920 cm^{-1} and 1380 cm^{-1} respectively. The band attributing the bending vibration of N–H group in amino groups appeared at about 1460 cm^{-1}. The sharp peaks around 2363 cm^{-1} and 3100 cm^{-1} belong to the respective stretching vibrations of C≡C (alkynes) and = C–H (alkenes) bonds. The bending vibration of C–H in polycyclic compounds was recorded in the low frequency region at around 720 cm^{-1}

The Raman spectra as shown in Figure 3.12B represented the D – band and G – band peaks at 1339 cm^{-1} and 1586 cm^{-1} reflect the C–C bond stretching due to E_{2g} and A_{1g} vibrational modes respectively. The alteration in the shape of the E_{2g} (G) peak at 1586 cm−1 attributes the significance of interferences that take place on the surface of bamboo carbon. The surface changes on the SMFC used carbon as a consequence of microbially controlled electrochemical reactions lessened the intensity of G – band and the disorderliness of sp^2 – carbon as well. In light of the present observation, Ray and McCreery reported the pertinence between the integrated intensity (D to E_{2g}) and the disorderliness of carbon atoms due to the associated sorption and electrochemical reactions. The signature of degraded organic compounds on the surface of SMFC used carbon anode could be explored from the Raman stretching of C–H (phenyl ring) and N–H (amino compounds) at about 3044 cm^{-1} and 3466 cm^{-1} respectively.

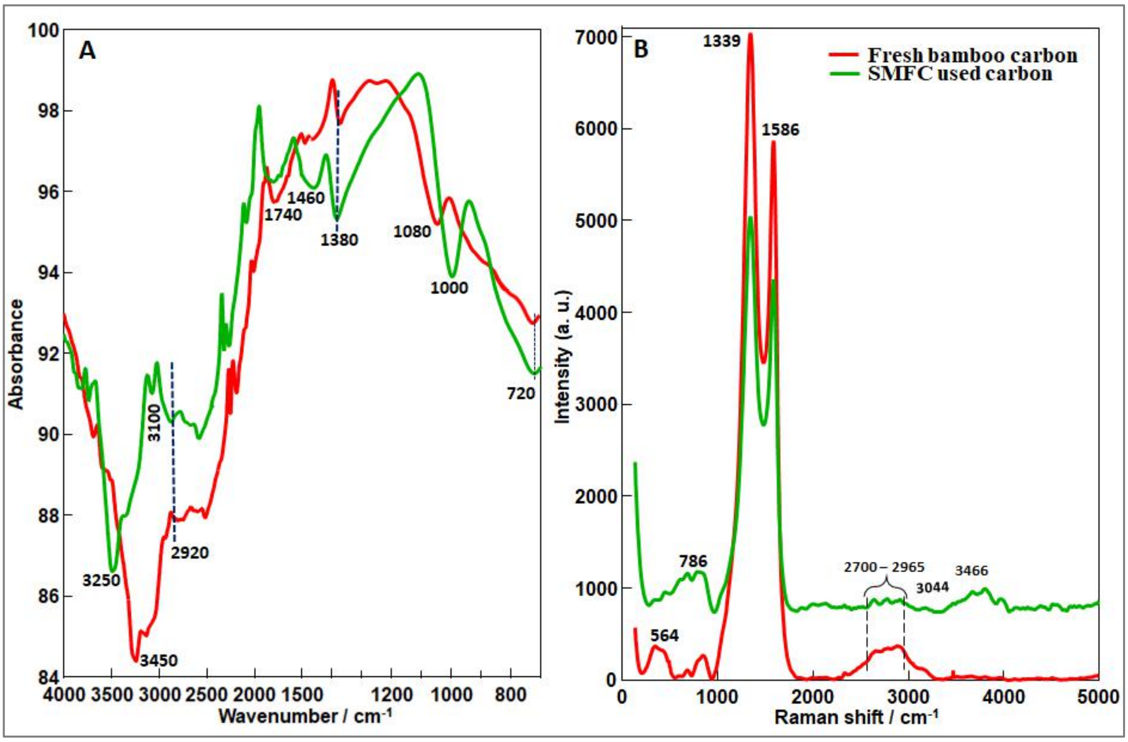


Fig.3.12 FT Infrared and Raman Spectra for the fresh and SMFC used bamboo carbon anode

The adsorption isotherm for nitrogen in graphical form is displayed for nitrogen adsorption versus the equilibrium relative pressure (p/p0) as shown in Figure 3.13A. The anodic material, bamboo carbon exhibited the type H4 hysteresis which is quite established to contain the micro and mesoporous carbons. However, the H4 loop advocates the dominance of microporosity along with noticeable mesoporous carbons as it is the hybrid of type I isotherm with narrow slit – like pores. The adsorption amount of nitrogen at the maximum relative pressure (p/p0) was measured with 7.763 cm^{3}g^{-1} and1.662 cm^{3}g^{-1} for the fresh and SMFC used carbon anodes respectively (Table 3.5). Hence it is logical to observe the decrease of nitrogen adsorption and the specific surface area (11.094 m^{2}g^{-1} to 2.137 m^{2}g^{-1}) in the SMFC used carbon because the filling of pores takes place on the anodic surface during the bio-based electrochemical activity. As a matter of fact, the roughness of surface with distinct cracks is able to provide high specific surface area to enhance the attaching sites for biofilm formation leading to commendable electron transfer process to the anodic carbon. In the present work, the bamboo carbon anodes were characterized with nanopores as micropores (dp ≤ 2 nm) and mesopores (dp = 2 – 50 nm) (Figure 3.13B) which could generate the power density

(1071 mW/m^2) of about 55 times higher than that of a cloth carbon. In light of this fact, it is corroborated that the entrapment of endogenous mediators leads to the expedited electron transfer in SMFC.

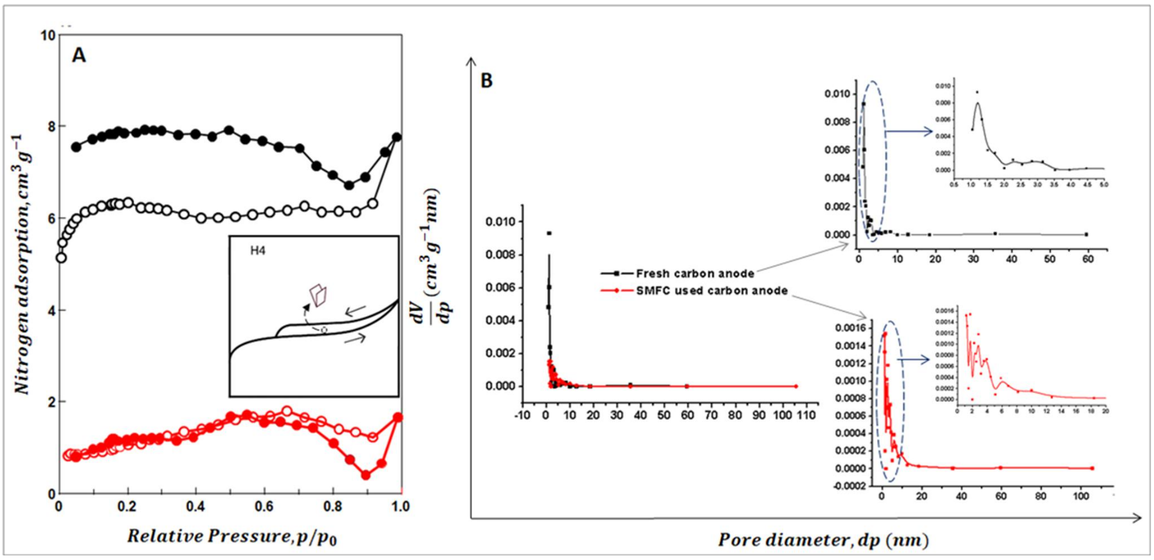


Fig.3.13 Nitrogen adsorption/desorption isotherms (A) and pore size distribution for the fresh and SMFC used carbon anodes (B)

3.3.8 Results of germination analysis and suitability for crop growth

In spite of technical advancements in energy storage devices, the need of the hour mainly depends on its proper disposal without harming the environment. In view of curtailing the disposal problems, the organic solid which was left after the power generation in SMFC was focused for a successful application as compost for the crop growth. The results of Komatsuna germination test revealed that the SMFC used organic admixture was able to germinate 93% of the seeds with high rate of germination as compared to the rate in water (86%)and bamboo waste (27%) as shown in Figure 3.14A. The pH and electrical conductivity (EC) of the compost on the first day and after two months revealed that the growth of microorganisms has control over these essential parameters (Figure 3.14B). The pH and EC of the SMFC compost after two months was 6.4 and 1.5 mmho/cm respectively and confirmed the suitability for the crop production. On the basis of crop growth and phytotoxicity, the EC measured for the used compost from SMFC was less than the range of 2-4 mmho/cm suggested for compost (Turan, 2008; Yang et al., 2015; Zhang and Sun 2016). The increased pH from 5.2 (on the first day) to 6.4 after two months indicated the enhanced rate of microorganism activity due to ammonification and mineralization of organic nitrogen (Eklind and Kirchmann, 2000; Onwosi et al., 2017; Kim et al., 2018).It is substantiated that the SMFC waste contains many beneficial microorganisms which were able to facilitate the growth of crops. These results made an emphasis towards the recycling of resources by targeting zero waste ultimately.

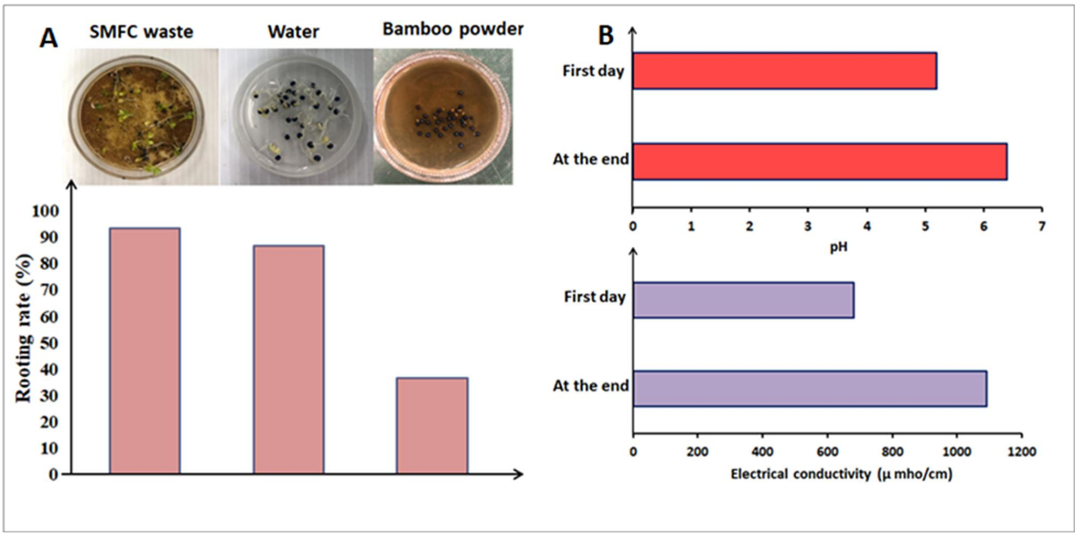
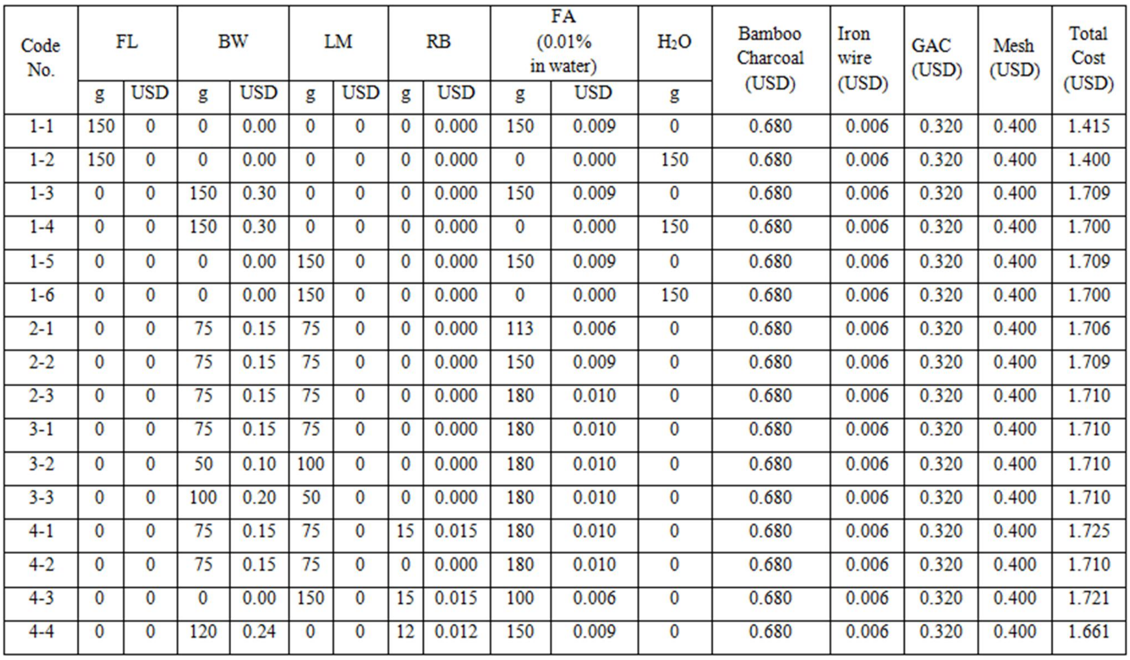


Fig. 3.14 Germination test for SMFC waste (A) pH and EC of SMFC waste

3.3.9 Cost analysis of the developed SMFCs

The components, which are said to be non-consumable, used for a single unit of SMFC are bamboo carbon anode, GAC cathode and SS mesh. The estimated cost of anode, cathode and SS mesh per developed SMFC unit are \$0.68, \$0.32 and \$0.40 respectively. More than 80% of the total cost per SMFC unit (\$1.1-\$1.4) belongs to the non-consumable components which last for a long period and can be reused for the SMFC application (Table 3.7). Owing to the reusability of such components, it is apparent that the total cost depends upon the remaining 20% or less from the consumable items such as organic waste materials (BW- \$0.3, LM-\$0.3 and RB- \$0.015), Iron winding (\$0.006) and fulvic acid (\$0.009). The cost of such consumables for the development of SMFC was estimated in the range of \$0.26 to \$0.34 per unit. As a mark of sustainable development, the development of SMFC is significant and deemed to remain state-of-the-art. Upon taking the consumable cost into consideration (<\$1), the developed SMFC is similar in its cost albeit the generated power density is higher by about 28 times (M. Behera, P.S. Jana, M.M. Ghangrekar,2010) and10 times (Y. Zhang, J. Sun, Y. Hu, S. Li, Q. Xu,2012) to the fabricated MFCs.

Table 3.7 Estimated cost for the developed SMFCs



Code No.	FL		BW		LM		RB		FA (0.01% in water)		H_2O	Bamboo Charcoal (USD)	Iron wire (USD)	GAC (USD)	Mesh (USD)	Total Cost (USD)
	g	USD	g	USD	g	USD	g	USD	g	USD	g					
1-1	150	0	0	0.00	0	0	0	0.000	150	0.009	0	0.680	0.006	0.320	0.400	1.415
1-2	150	0	0	0.00	0	0	0	0.000	0	0.000	150	0.680	0.006	0.320	0.400	1.400
1-3	0	0	150	0.30	0	0	0	0.000	150	0.009	0	0.680	0.006	0.320	0.400	1.709
1-4	0	0	150	0.30	0	0	0	0.000	0	0.000	150	0.680	0.006	0.320	0.400	1.700
1-5	0	0	0	0.00	150	0	0	0.000	150	0.009	0	0.680	0.006	0.320	0.400	1.709
1-6	0	0	0	0.00	150	0	0	0.000	0	0.000	150	0.680	0.006	0.320	0.400	1.700
2-1	0	0	75	0.15	75	0	0	0.000	113	0.006	0	0.680	0.006	0.320	0.400	1.706
2-2	0	0	75	0.15	75	0	0	0.000	150	0.009	0	0.680	0.006	0.320	0.400	1.709
2-3	0	0	75	0.15	75	0	0	0.000	180	0.010	0	0.680	0.006	0.320	0.400	1.710
3-1	0	0	75	0.15	75	0	0	0.000	180	0.010	0	0.680	0.006	0.320	0.400	1.710
3-2	0	0	50	0.10	100	0	0	0.000	180	0.010	0	0.680	0.006	0.320	0.400	1.710
3-3	0	0	100	0.20	50	0	0	0.000	180	0.010	0	0.680	0.006	0.320	0.400	1.710
4-1	0	0	75	0.15	75	0	15	0.015	180	0.010	0	0.680	0.006	0.320	0.400	1.725
4-2	0	0	75	0.15	75	0	0	0.000	180	0.010	0	0.680	0.006	0.320	0.400	1.710
4-3	0	0	0	0.00	150	0	15	0.015	100	0.006	0	0.680	0.006	0.320	0.400	1.721
4-4	0	0	120	0.24	0	0	12	0.012	150	0.009	0	0.680	0.006	0.320	0.400	1.661

3.4 Conclusions

In the present research, an inexpensive SMFC was designed using organic wastes/admixtures using bamboo carbon anode with iron windings and granular charcoal as cathode for the generation of electric power. The following conclusions were obtained from this study.

(1) The influence of leaf mould both in fulvic acid and water generated more electric power than that of bamboo waste and fulvic acid materials.

(2) The variation in the ratio of the admixture in the presence of fulvic acid influenced the generation of voltage and electrical power, especially the SMFC containing bamboo waste: leaf mould in the ratio 1:1 measured the maximum output power.

(3) The measured electric power of 1071 mW/m^2 for the admixture (bamboo waste +leaf mould+ rice bran+ fulvic acid) was the highest whereas the lowest power generation of 238 mW/m^2 was recorded without leaf mould (bamboo waste + rice bran+ fulvic acid).

(4) The EIS study inferred the influence of admixture composition and its moisture content in altering the resistance values. The role of total nitrogen in admixtures of systems 4–1 (bamboo waste +leaf mould+ rice bran+ fulvic acid) and 4-4 (bamboo waste +leaf mould+ fulvic acid) played significantly in the decomposition process of SMFCs. The variation of potential with respect to time (in days) corroborated the generation of power in respect of the microbial degradation and supply of nutrients.

(5) Based on the pH, EC and germination analysis, the bio-waste from SMFC was found suitable for growing crops. The SEM, FTIR, Raman and BET studies corroborated the participation of surface carbon atoms leading to the modification of anodic carbon as a consequence of the bio-electrochemical activity. The presently fabricated SMFCs remain the state-of-the-art and being realized economically viable as confirmed from the cost analysis. Nevertheless, further investigations to study the effective fermentation process are required for all organic wastes in addition to rice bran.

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4. Development of peat microbial fuel cells

4.1 Introduction

MFC is one of the most recently developed bio-electrochemical devices that convert biomass-based resources into electrical power (N. Çek, 2016). A range of wastewaters have been used as effective fuel sources for MFCs, thus demonstrating not only the technology potential as a carbon-neutral and green energy source, but also its significant versatility (C. Santoro, 2017) . MFCs, which come across as a challenging but promising technology, do the job to convert biomass into electrical energy by taking advantage of the metabolic microorganisms' activities (catalysis reactions). As a result of these benefits, MFCs are defined as environmentally friendly, renewable, bio and green energy production tools MFCs, which come across as a challenging but promising technology, do the job to convert biomass into electrical energy by taking advantage of the metabolic microorganisms' activities (catalysis reactions). As a result of these benefits, MFCs are defined as environmentally friendly, renewable, bio and green energy production tools (N. Çek, 2020). Soil microbial fuel cells (SMFCs) are a special class of MFCs in which soil acts as a support matrix, a source of microorganisms, and, in a membraneless configuration, a separator between anode and cathode (PA Castresana, 2019). Therefore, the overall design of SMFC is simpler and easier to extend than traditional MFC (S.G.A. Flimban, 2019).

Furthermore, in SMFC, there is no need to provide external fuel as in other types of MFC, which further simplifies the system operation as the organic matter produced by the action of organisms present in the soil is transported to the anode by diffusion (R. Nitisoravut, 2017). Therefore, SMFCs are ideal for cost-effective power generation in remote areas where low maintenance is desirable.But the current power of SMFC is low, which is not enough to meet the requirements of power generation, and more research is needed to further improve SMFC. Unfortunately, the commercialization of MFCs is still not considered reliable due to their low power density, short durability (K. Ben Liew, 2020).

The anode chamber of MFCs must be anaerobic and rich in organic material (A. Erensoy, 2021). One of the materials that will meet these conditions is peat, which provides both anaerobic conditions and contains rich organic matter. Peat is a candidate material as used as a source of organic matter in MFCs. In this study, peat-based MFCs are designed by using peat as a substrate material in MFCs.Furthermore, this study is planned to contribute to the commercialization of MFCs by using peat.

The study is committed to the development of peat MFC. The performance of peat MFCs as a function of bamboo waste, fulvic acid, iron winding and surface area of the BC anode has been discussed in this work. The synergistic effect of organic decomposition by microbes and Fe complexation with humic substances has been detailed to be responsible for the cause of electric power in Peat MFCs. The presence of iron might play a significant role towards the enhancement of power supply in Peat MFCs. The carbon potency of peat soil is well tapped which ultimately facilitated an appreciable power output through microbial degradation process. The power generation as a function of anodic surface area has been explored.

4.2 Materials and methods

4.2.1 MFC assembly and the details of organic admixtures

A plastic container (14 × 7 × 5.5 cm^3) was used as an MFC reactor. The bamboo carbon anode with a dimension of 12 × 3.5 × 0.5 cm^3 is surrounded by an iron wire (1 mm) of length of 4.5 cm. The carbon anode (unit area is equal to 0.0042 m^2) was placed on the packed bed of organic waste or admixture of 1 cm height and the packing was continued above the anode for the height of 3 cm to facilitate the perfect anaerobic condition. On the other hand, granular activated carbon, GAC (1.4 cm height) which serves as the cathode, was evenly distributed at the top of the organic waste or admixture with a stainless steel (SS, 0.1 cm) mesh inserted exactly at the center of the GAC layers. In order to facilitate a perfect operation in MFC, the device was covered with a wrap to prevent the sample from coming into contact with air and also to maintain an anaerobic environment. All processes were completed step by step and hence the MFC was fabricated. The schematic diagram and working principle of this MFC are given in Figure 4.1.

The organic waste chosen for the present SMFC study includes bamboo powder, leaf mould and peat soil. Materials which are rich in organic nutrients such as peat soil, bamboo waste (BW) were procured from a lotus pond in a farmland at Isahaya City located in the central part of Nagasaki Prefecture in Japan. The bamboo waste was crushed in to a power and sieved for a size less than 75µm which ensures the thorough exposure of electrodes. Fulvic acid (FA, $C_{14}H_{12}O_8$, Interman Corporation, Japan) is an organic acid which plays in the supplementation of plants.

Peat soil and BW were analyzed for total carbon and total nitrogen by an elemental analyzer (EA; EA1112, Thermo Fischer Scientific, MA, USA) with the weighed amount of organic matter (1.0±0.1 mg) by dry combustion method (Cui Li et al., 2021) and, potassium and phosphorus contents performed by standard methods using Atomic Absorption Spectrometer (Model ContrAA800F). The pH of peat soil and BW samples were measured with a pH-meter (Hanna model HI8424).

4.2.2 MFC operations and influential factors

The influence of peat soil and its combination with BW and FA, anodic surface area of BC and its wounded iron wires on the output voltage was measured. The Peat MFCs were operated by initiating the connection between the GAC cathode and the BC anode via an external resistor (51 Ω, 100 Ω and 510 Ω) and a voltage (V) across the resistor was measured using a data logger (Model: MCR –

4V). The calculation of internal resistance was done from the external resistance, recorded voltage and the current ($I = V/R$). The maximum power was calculated from the polarization curve of current versus power ($P = I \times V$). The measurements were made at five minute intervals using the data logger with a precise resolution of 10 µV of measureable range from ± 300 mV to ± 24 V during the operation of SMFC. The polarization curves were drawn by plotting the current-voltage and current – power characteristics for different resistance values on the circuit.

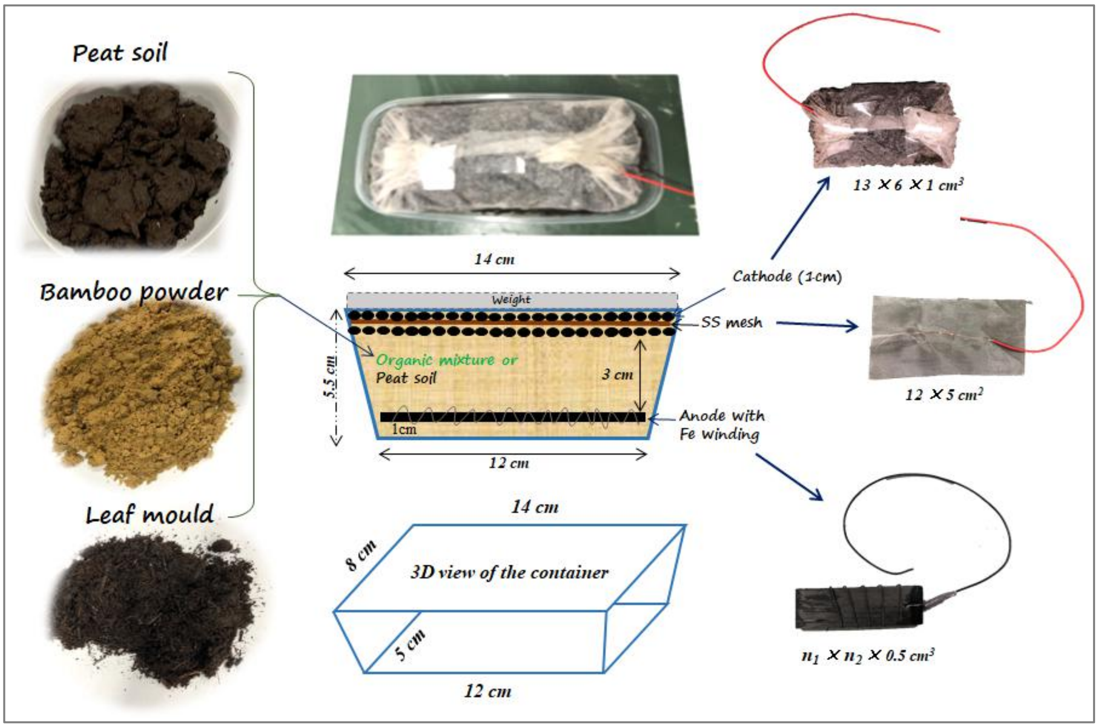

Fig. 4.1 Microbial Fuel Cell assembly, 3D view, organic admixture, peat and electrodes

4.3 Results and discussion

4.3.1 Comparison of Bamboo powder MFC and Peat MFC

The basic physical properties such as bulk density, moisture content and pH for bamboo powder, leaf mould and peat soil are given in Table 4.1. The analyzed amount of total carbon (53.6%) and total nitrogen (7.24%) in Leaf Mould was higher than the other three organic materials. The amount of carbon content in the three materials follows the order: Leaf Mould > Bamboo powder > Peat soil. However, the total nitrogen content of 0.8% in Peat soil was higher than Bamboo powder of 0.1%. The C/N ratio is reported to affect the performance and the power generation in MFCs using organic materials thanks to the influence of microbial metabolism. The C/N ratio for Bamboo powder, Leaf Mould and Peat soil are 280, 7.4 and 12.4 respectively. Due to the presence of very less total nitrogen content, the C/N ratio in Bamboo powder was high than that of Leaf Mould and Peat soil materials with high good nitrogen contents.

In the previous study, the microbial fuel cells made of bamboo powder ,leaf mould and fulvic acid had high power, but the soil had poor water retention and short continuous power generation time, so SMFC needs to be improved. Peat contains fulvic acid, so in this study, we tried to use peat to make microbial fuel cells and compared it with bamboo powder MFC.

Three bamboo powder MFC (Bamboo powder 100g + Leaf Mould 100g + Fulvic Acid 240ml) and three peat MFC (Peat 400g+ distilled water 120ml) were made under the same conditions, and different resistances were applied to them, and their voltages were measured. Figure 4.2 is the current-voltage curve and current-power curve of the bamboo powder battery. Figure 4.3 shows the current-voltage curve and the current-power curve of the peat cell. It can be seen from the curves in Figures 4.2 and 4.3 that the voltage and power of the MFCs under the same conditions are almost the same. Therefore, it can be said that the results of MFC are not abnormal, and it can be concluded that the results of MFC under the same conditions are not much different. The maximum power (per square meter) produced in the SMFC due to the combination of filled BW, LM and FA is 714 mW/m^2. The electricity generated by the combination of peat and distilled water (1428 mW/m^2) is about 2 times higher than the SMFC of BW. According to the calculation in Figure 4.2, the internal resistance of the SMFC is 21.2Ω, and according to the calculation in Figure 4.3, the internal resistance of the SMFC is 15.5Ω. In the following experiments, MFC made from peat is mainly discussed.

Table 4.1 Physical and chemical analyses of the organic waste materials

Parameters	**Organic material**		
	Bamboo powder	**Leaf Mould**	**Peat soil**
Moisture content (%)	50.3	215.1	433
pH	7.1	6.2	4.3
Total N (g/kg)	1.0	72.4	8
Total P (g/kg)	0.5	10.5	1.8
Total K (g/kg)	1.0	6.7	1.3
Total C (g/kg)	280	536	99
C/N ratio	280	7.40	12.4

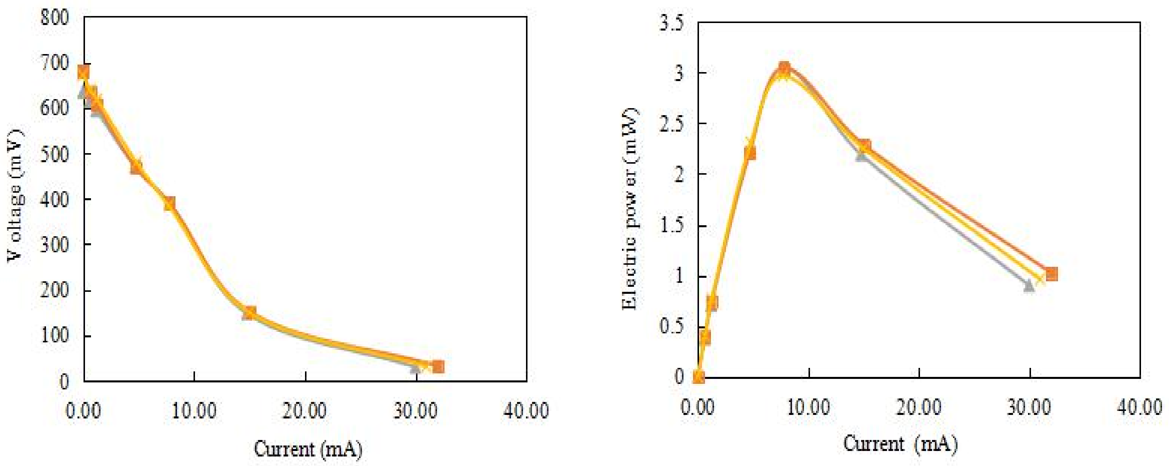

Fig.4.2 SMFC operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

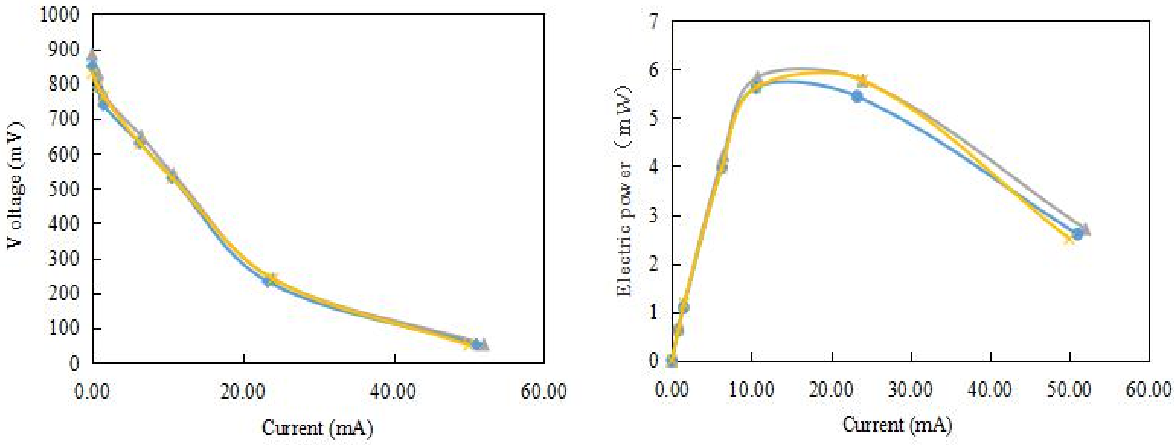

Fig .4.3 Peat MFC operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

4.3.2 Effects of Cathode Materials on Peat MFC

The same peat was used to make 6 microbial fuel cells. The cathode material of the three MFCs was bamboo carbon, and the cathode material of the three MFCs was granular activated carbon. The voltages were measured and averaged, and the curve in Figure 4.4 was obtained.

From these two figures, it can be calculated that the maximum power per unit area of the MFC with bamboo carbon as cathode is 428mW/m^2, and the maximum power per unit area of the MFC with granular activated carbon as cathode is 833mW/m^2. The current and power of the MFC with granular activated carbon are higher than those of the MFC with bamboo carbon as cathode. Therefore, in subsequent experiments, granular activated carbon was used for cathode.

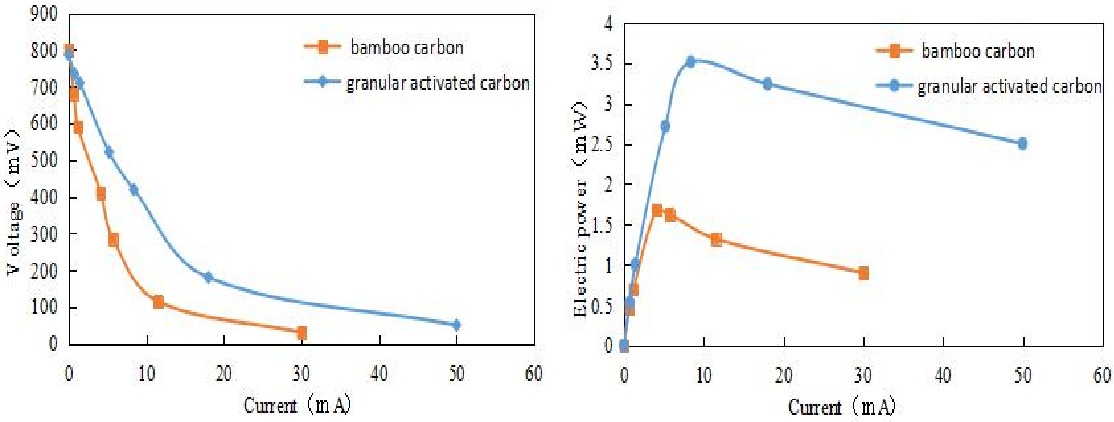

Fig.4.4 Peat MFC operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

4.3.3 Effect on adding BW and FA to peat soil in the power generation Peat MFCs

Bamboo powder and fulvic acid were added to peat to make MFC and compared to MFC with only distilled water. The details on the SMFC experimental studies conducted through different systems are shown in Table 4.2. Three MFCs were made for each system, and the voltage results were roughly the same, so one of each was chosen to plot the current-voltage and current-power diagrams. Figure 4.5 is the current-voltage curve and current-power curve of peat MFC with different materials for the time of 24 h. From the two figures, the power of MFC using distilled water is less than the power of the other two. On adding BW (Bamboo waste) and FA (Fulvic acid, 0.01% v/v) to peat, the generated power was raised to 1371 mW/m^2 (No.B) and 1488 mW/m^2 (No.C) for an output voltage of 0.80±0.01V after a day period. Figure 4.6 shows the current-voltage and current-power curves of peat MFC with different materials after one month. At the end of 30 days, an increased power of 1717 mW/m^2 and 1866 mW/m^2 was measured for No.B and No.C MFCs respectively for a constant voltage of 1.01 V. On comparison, No.B and No.C MFCs generated more power of 64.5% and 78.6% higher than No.A MFC respectively after 24 h. From the two figures, the current of the three MFCs has decreased, but the power has increased, and the maximum power of the three MFCs has no significant difference. The MFC with fulvic acid has the highest power, but the MFC with distilled water is better in terms of cost.

The treatment of BW and FA with peat generated high power of about 32.6 times and 35.4 times respectively to that water. With reference to our previous work reported on Solid Phase MFCs using BW and FA (Cui Li et al., 2021) it is commendable that the addition of peat soil to BW and water reduced the IR by 91.4% by escalating the power generation up to 11.5 times after 24 h. Similar decrement by 81.2% of IR lifted the output power 4.5 times when peat soil instead of BW was added to FA. Remarkable power generation using peat with BW and FA may be associated due to the facts as follows: (1) the growth of the microorganism such as Clostridium which lives in the structure of peat materials (Cao et al., 2019) and (2) the addition of FA, being more prone for microbial attack under anaerobic condition decomposes easily (Eq. 4.1) and facilitates the growth of microorganisms in the peat soil (Machado et al., 2020). Thus the growth of microorganisms accentuates the decomposition of organic matter resulting in the conversion of energy stored in chemical bonds. Interestingly, the presence of Fe wire oxidizes and generates electric power amidst the electrochemically active bacteria which performs the degradation process. The No.B, No.C and No.A type of MFCs produced the electric power of 1.65-1.90 folds as compared to that of a peat based MFC designed by Erensoy et al., (2022).

$$\boldsymbol{C_{14}H_{12}O_8 + 20H_2O \rightarrow 14CO_2 + 52H^+ + 52e^-} \qquad \textbf{(4.1)}$$

Table 4.2 Details of SMFC operations: Organic materials, admixture and compositions

System No.	Peat soil (g)	Bamboo powder (g)	Fulvic acid(ml) (0.01% in water)	H_2O (ml)
A	400	0	0	120
B	350	50	0	120
C	400	0	120	0

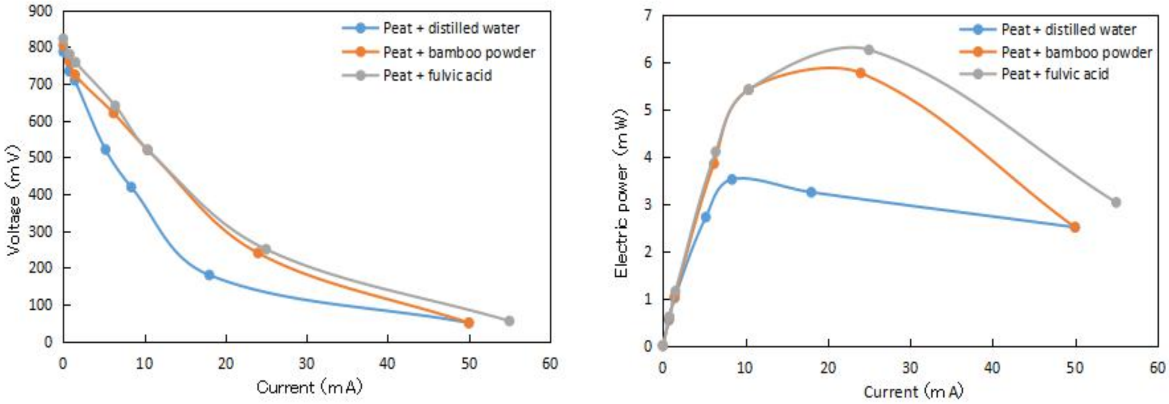

Fig .4.5 Peat MFC with different materials added operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

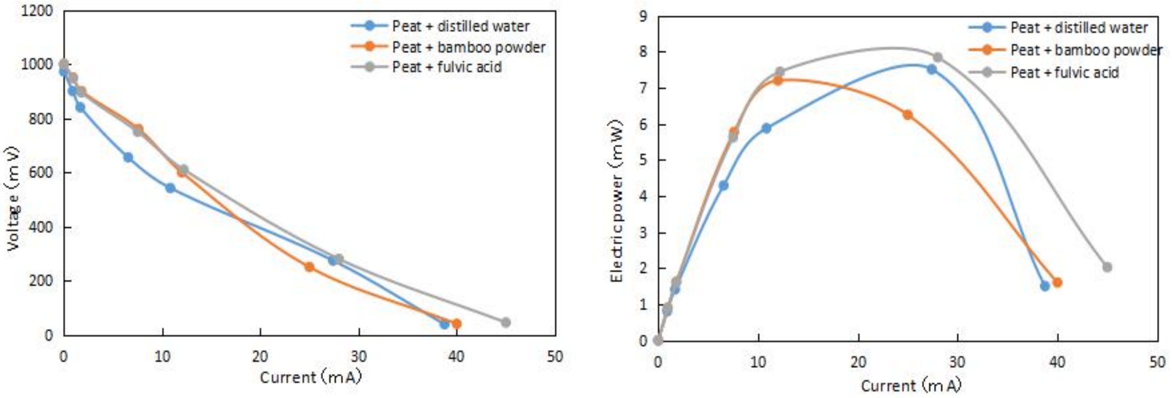

Fig .4.6 Peat MFC with different materials added operation for the time of one month: Curves of Current Versus Voltage and Current Versus Electric power

4.3.4 The effect of the number of wires wound around the anode on the power

In previous experiments, only one wire was wound around the bamboo carbon used as the anode. In order to study the influence of the iron wire on the power of the MFC, in this experiment, an MFC in which two iron wires were wound on the anode was added for comparison. Two MFCs are made from system A, one MFC with one wire is wound around the anode, and the other MFC with two wires are wound around the anode. Figure 4.7 shows the current-voltage curve and current-power curve of the two MFCs. The power (1372 mW/m^2) of the MFC with 2 wires wound on the anode is about 1.65 times higher than that of the MFC with 1 wire wound. MFC with 2 wires wound has more power.

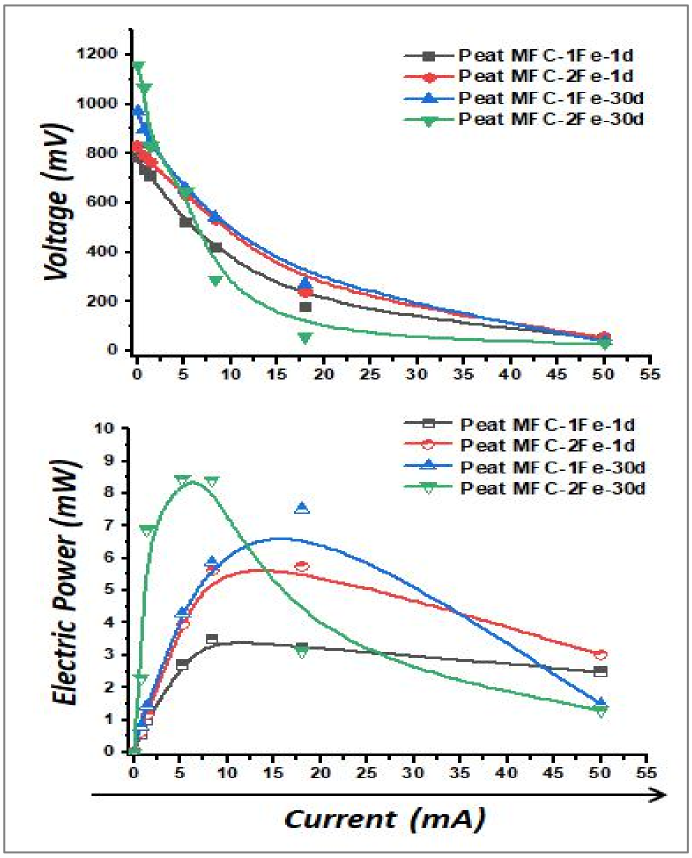

Fig. 4.7 Plots ofCurrent against Voltage and Electric power for the functioning of Peat MFC using Iron wire of 4.5 cm (1Fe) and 9 cm (Fe) at different times (1d and 30d)

4.3.5 Effect of anodic surface area in the power generation of Peat MFCs

Table 4.3 is the experimental condition of peat MFCs. In Peat MFCs, for the Vmax of 0.83 V the corresponding power generation of PDW44.5Fe9.0 after a day was 1483 mW/m^2. This trend of output gets enhanced further by increasing the Vmax up to 1.1 V with the Pmax of 2719 mW/m^2 till 10 days. Subsequently the generated power was gradually reduced to 2101 mW/m^2 (reduction of 22.7% during 11th to 20th day) and further reduction by about 30% (21-30 days) was observed with an output power supply of 1899 mW/m^2 after 30 days. Thereafter, a minimum power of 440mW/m^2

(reduction of 84% during 30 to 40 days) was generated although the open circuit voltage was consistent with 1.14 V (Figure 4.8A). Conspicuously, the maximum voltage for PDW44.5Fe9.0 was consistent between 1.01 V and 1.16 V after 10 days till the end of 40 days. The other three Peat MFCs with anodic areas of 40.3 cm^2, 44.5 cm^2 and 46.8 cm^2 generated the maximum power of 1125 mW/m^2, 1441mW/m^2 and 1250 mW/m^2 respectively for the Vmax of 0.87±0.02 V after a day. The polarization curves for the three Peat MFCs approached a minimal Pmax value after10 days albeit they ascended there after towards a maximal power output after 20 days. Thus the subsequent increase in the Pmax (after 20 days) was higher by about 95% in PDW40.3 to that of the Pmax value after 10 days. However the Peat MFCs with PDW42 and PDW46.8 were able to generate an increased power output of just 15% and 17% respectively after20 days. As shown in Figure 4.8B, the power generation was measured in decrements after 20 days and declined to 192 mW/m^2, 117 mW/m^2 and 34 mW/m^2 for PDW46.8, PDW40.3 and PDW42 respectively at the end of 40 days. The corresponding IR changes are shown in Figure 4.8C. From the above results (Table 4.4), the maximum power density delivered from PDW44.5Fe9.0 gets decreased either on increasing or decreasing the surface area of the anode. It is apparent that the power density is not linearly correlated with the anodic surface area. Accordingly, the correlation values recorded for the surface area-power density pairs were between 0.263 and 0.485 during the time period of 1-40 days. In contrast to the edge effect and mass transport of electro-active species in microelectrodes, it can be hypothesized that the influence of deposited bio film on the anodic surface on the electron transfer rate may have been the reason for the obtained observations (Lorenzo et al., 2010; De wan et al., 2008).

Table 4.3 Peat-MFC Experimental systems: Admixture and Peat compositions

Code	PEAT (g)	DW (mL)	pH	C/AREA (cm^2)	A	A/AREA (cm^2)	R (Ω)
PDW42	400	120	3.5	Granular Charcoal/98	BC/2Fe	42.0	51
PDW40.3	400	120				40.3	100
PDW46.8	400	120				46.8	510
PDW44.5	400	120				44.5	∞

BC-Bamboo Charcoal; 1Fe-Iron wire of length 1×4.5 cm; 2Fe-Iron wire (1mm thickness) of length 2×4.5 cm; DW-Distilled Water; A-Anode; C-Cathode; R-Resistance between electrodes

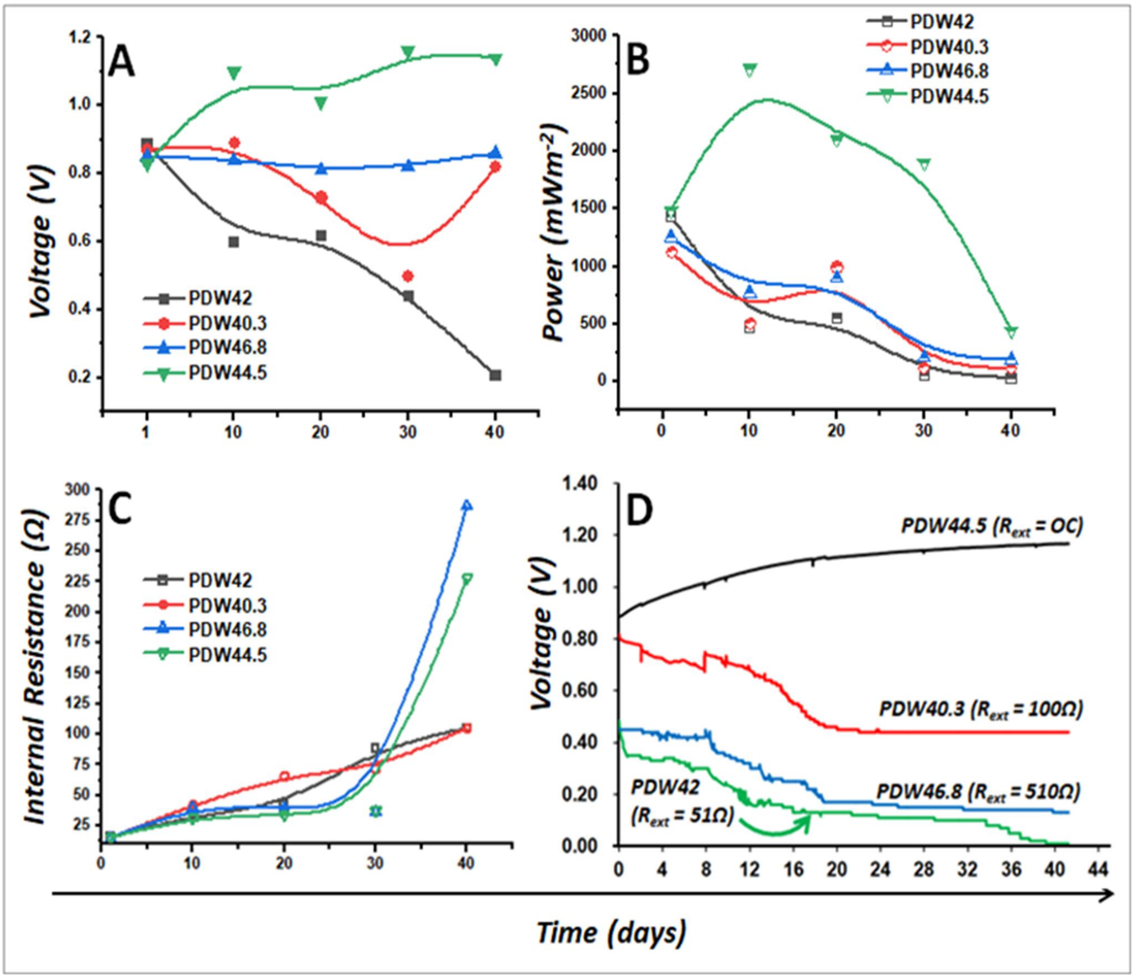

Fig. 4.8 Functioning of Peat MFC using BC anode (with Fe wire of 9 cm) of varied surface areas: Measurements of Voltage (A) Power (B) Internal Resistance (C) without external resistance; Variation of potential in volts with external resistance against time in hours (D)

Table 4.4 Microbial Fuel Cell measurements of internal resistance, maximum voltage and maximum power after time periods

Code	MFC measurement after														
	24 h			10 days			20 days			30 days			40 days		
	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}
PDW42	16	0.89	1441	33	0.60	476	41	0.62	548	88	0.44	62	105	0.21	34
PDW40.3	16	0.87	1125	42	0.89	509	66	0.73	994	72	0.5	124	293	0.82	117
PDW46.8	16	0.85	1250	40	0.84	769	40	0.81	897	37	0.82	213	287	0.86	192
PDW44.5	16	0.83	1483	31	1.10	2719	34	1.01	2101	37	1.16	1899	228	1.14	440

4.3.6 Variation of potential against time in Peat MFCs

The potential of Peat MFCs varied with time for a span of 41 days (984 h) is represented in Figure 4.8D. In the case of PDW42 MFC, the initial potential of 0.48 V gradually decreases to 0.36 V over a time period of 20h. The voltage further diminishes to 0.3 V after 162 h and remains constant till 192 h. Further decrements with 0.16 V, 0.14 V, 0.08 V and 0.02 V respectively after 288 h (12 days), 384 h (16 days), 816 h (34 days) and 930 h (38.8 days) were measured due to the depletion of degradable organic material in the anodic chamber. The diminutions were varied notably during 0-11 h, 192-288 h and 816-960 h with the decreasing slope values of 9.2 × 10-3 V h-1 ($R^2 = 0.9677$), 1.3 × 10-3 V h-1 ($R^2 = 0.9315$) and 9 × 10-4 V h-1 ($R^2 = 0.9389$) respectively. On the other hand, PDW40.3 had an initial potential of 0.42 V which on increasing the time drops to 0.25 V after 336 h (14 days) followed by a linear curve till 108 h. Later the potential gradually decreases to 0.16 V after 450 h with a slope value of 8 × 10-4 V h-1 ($R^2 = 0.9366$) and maintained constancy till 984 h. In the above two Peat MFCs, the gradual decrements observed during power generation represented the decreased electrochemical activity of the microflora which further ends up in poor degradation of organic materials. In MFCs PDW46.8 and PDW44.5 the initial potentials of 0.84 V and 0.86 V were measured. However in the former, two sudden changes occurred with 0.13V decrement (but rises upwards in no time to 0.76 V) and 0.07 V increment respectively after the elapsed time of 48 h and 192 h. These elevations in potential values attributed the increased microfloral activity enhancing a faster degradation of biochemical constancy and microstructure of organic contents (Moayedi and Nazir, 2018). Later the potential was gradually decreased to 0.44 V at 480 h due to the progressing oxidation of highly humified (sapric) peat (Zulkifley et al., 2014). The gradual fall-off in slope values during 0-192 h and 200-500 h for PDW46.8 were 6 × 10-4 V h-1 ($R^2 = 0.9657$) and 1.1 × 10-3 V h-1 ($R^2 = 0.9723$) respectively. After 480 h, the potential was stabilized at 0.44 V till 984 h. Taking the potential of PDW44.5 into consideration, there was an escalation from 0.86 V to 1.12 V during the period of 0-480 h (5 × 10-4 V h-1; $R^2 = 0.9843$). This ascending trend was followed with a slightly increased voltage of 0.04 V with a decreased slope value of 1 × 10-4 V h-1 ($R^2 = 0.9792$) till 984 h. Remarkably in PDW44.5, the degradation of peat containing organic matters occur consistently due to microfloral biofilm being exposed to high surface of BC anode. Such biofilms on the anode increase the power tremendously thanks to the direct electronic transfer to the anode (Picioreanu et al., 2007). In all the above Peat MFCs the presence of Fe wire participated in the oxidation process along with the organic matter by facilitating the generation of electric power and as a nutrient for microbial inhabitancy in peat soil as well.

4.4 Conclusions

The following conclusions were obtained from this study.

(1) The power output for Peat MFC with an iron winding of length 9 cm (PDW42Fe9.0) was measured about 35 times higher (1440.5 mW/m^2) than that without iron winding (41.7 mW/m^2) after a day.

(2) On adding BW (Bamboo waste) and FA (Fulvic acid, 0.01% v/v) to peat, the generated power was raised to 1371 mW/m^2 (No.B) and 1488 mW/m^2 (No.C) for an output voltage of 0.80±0.01V after a day period. It is commendable that the addition of peat soil to BW and water reduced the IR by 91.4% by escalating the power generation up to 11.5 times after 24 h.

(3) The power density is not linearly correlated with the anodic surface area. Accordingly, the correlation values recorded for the surface area-power density pairs were between 0.263 and 0.485 during the time period of 1-40 days.

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5. Research on the combination of microbial fuel cells and plants to generate electricity

5.1 Introduction

Environmental pollution and energy scarcity was considered as an unprecedented challenge for human society. Energy demand of entire world is increasing rapidly with the increase in technological development. Conventional and non-renewable sources of energy like fossil fuel and coal reserves are being utilized extensively to fulfill the energy needs. Hence, there is high demand of new renewable sources of energy which will be environment friendly, affordable, and globally feasible (Ananthi et al., 2021). The pursuit for alternate clean and green energy technologies to fulfill future energy requirements is a foremost challenge. These days, generation of electric energy via MFCs are gaining attention due to its greener nature and simultaneously resolving problem of waste management.With the increase in global environmental issues and depletion of conventional energy sources, there has been a compelling need for us to switch to renewable or alternate energy sources like solar, wind, geothermal energy, etc. Solar energy has been in research for a long time now, and the most popular of all the available technologies have been solar cells. Solar energy is a universally available reliable source of energy, and about 170 W/m^2 reaches the Earth's surface that is available for use (N. Sekar, R.P. Ramasamy, 2015).Plants are natural absorbers of solar energy, and they essentially require sunlight for photosynthesis. An appreciable amount of solar energy is stored in plants and released in the form of glucose (i.e., organic waste) into soil and oxygen into the atmosphere. Oxygen released from plants maintains a balance in the ecosystem and completes the oxygen cycle that is essential for the existence of life on Earth (P.G. Falkowski, L.V. Godfrey, 2008). Plant microbial fuel cells (PMFCs) are an emerging technology derived from microbial fuel cells (MFCs) that utilize organic matter excreted by plant roots to provide microbes with nutrients around the rhizosphere so as to generate electricity, as shown in Fig. 5.1 (A. Cabezas, B. Pommerenke, N. Boon, M.W. Friedrich,2015). Recent studies have not only enhanced the power output and reduced the cost (A.C. Sophia, S. Sreeja, 2017), but have also enabled the PMFCs to be integrated with various applications. For example, PMFCs have been coupled with wastewater treatment, soil remediation (C.Y. Guan, Y.H. Tseng, D.C.W. Tsang, A. Hu, C.P. Yu,2019), and reducing greenhouse gas emissions (J.B.A. Arends, J. Speeckaert, E. Blondeel, J. De Vrieze, P. Boeckx, W. Verstraete, et al.,2014). The organic waste produced released by plants into the soil acts as substrates (supplying nutrients) for the growth and reproduction of bacteria present in the soil.Microbial fuel cells make use of bacteria as catalysts and high-energy oxidants to behave as bio-electrochemical systems to produce bioenergy (A.J. Slate, K.A. Whitehead, D.A.C. Brownson, C.E. Banks,2019). Electrochemically active bacteria (EAB) oxidize the organic matter (OM) and transfer the electrons, thus produced, to the anode. These electrons then produce an electric current by transferring to the cathode in the presence of load. A similar type of bacteria (rhizobium) is expected to be present at the root nodules of the plants, and since the same kind of fuel cell is made, named Plant-microbial fuel cell (PMFC). Studies have shown that the production of sustainable power in a PMFC is 18 times higher than a conventional Sediment-type Microbial Fuel Cell (SMFC) (A. Cabezas, B. Pommerenke, N. Boon, M.W. Friedrich, 2015). PMFC applications were initially restricted to aquatic plants and indoor plants. With the help of research and development, this technology has been slowly extended to trees and soil plants (A.C. Sophia, S. Sreeja, 2017). The technology can provide practical solutions to problems like lack of rainfall, drought, and crop-related issues without disrupting food production, which is currently a matter of concern in agriculture (D.P.B.T.B. Strik, H.V.M. Hamelers, J.F.H. Snel, C.J.N. Buisman, 2008). PMFC can generate sustainable green energy and prove to be a cheap and reliable source as it completely depends on the sunlight and organic matter produced by the plants, though the type of plant also influences the energy generated (R. Pliego-Arreaga, C. Regalado, A. Amaro-Reyes, B.E. García-Almendárez,2013).PMFC utilizes root exudates and rhizodeposits secreted by plants in the rhizosphere region as a result of photosynthetic activity into bioelectricity using metabolic activities of microbial community residing in the rhizosphere region (Shaikh et al., 2020) . Plant microbial bioelectricity, as an innovative form of alternative energy, provides the production of bioelectricity without any harm to the environment, during the growth of plants in natural ecosystems or created by man. The added advantage of using PMFC as a source of renewable energy is that it can also help in reducing carbon emissions.

In this study, four PMFC systems were constructed with different plants. The main objectives were: (1) to investigate the effects of plant on electricity generation; (2) to observe and analyze different plants on PMFC performance; (3) to explore the insight into the interaction between plants and SMFCs in PMFC systems to better understand the system performance critical issues.

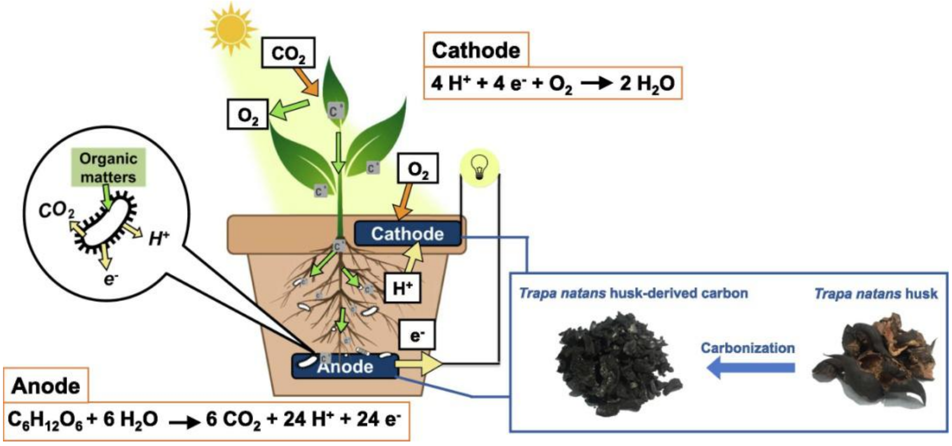

Fig.5.1 Mechanisms of plant microbial fuel cell (PMFC) with the Trapa natans husk-derived carbon electrode (https://www.sciencedirect.com/science/article/pii/S0306261922010820)

5.2 Materials and methods

5.2.1 The combination of SMFCs and plants

Recent studies have attempted several strategies to enhance the electricity production of PMFCs, such as the usage of different plant species (A.C. Sophia, S. Sreeja, 2017) and cell configurations. Several researchers have focused on the influence of electrode materials on the performance of PMFCs. Most studies used carbon-based materials as electrodes for the PMFCs. In particular, granular activated carbon, graphite felt, and activated carbon were used owing to their large surface area and acceptable conductivity. There plant species, black rice (ancient rice), sweet potato and potato were used in the experiment. These types of plants are rapid growth, high biomass, high-density of root. Because of the common advantages of these plants, they were applied to electricity production. The seedlings are cultivated in advance. Subsequently, the healthy seedlings of each species with similar sizes were selected and planted in the PMFC systems under different conditions. PMFC are generated electricity during the day and can hardly generate electricity at night, so it can be continuously generated electricity by combining SMFCs. In previous experiments, soil microbial fuel cells (SMFC) were developed using bamboo powder, leaf mould and fulvic acid. In this experiment, it was buried in three plants and developed plant MFC systems.

In the paddy-MFC study, a performance of paddy plant microbial fuel cell is evaluated by experiments using container of bucket. The soil was prepared by mixing clayey soil, sandy soil, culture soil and leaf mold. Four buckets were prepared for the PMFCs. Two types of electrodes, namely granular activated carbon and activated bamboo charcoal, are used on paddy-MFC. As shown in Figure 5.2. It also studied the height of the water level and the impact of the electrode material. Test conditions of the MFCs are shown in Table 5.1. The activated bamboo charcoal with iron wire was used for all buckets as anode. The activated bamboo charcoal was used for buckets 1-1 and 1-2. The difference between 1-1 and 1-2 lies in the level of water level. The SMFCs (with plastic boxes) in the 1-4 are buried into the soil, and the remaining three buckets directly bury SMFC into the soil.

Figure 5.3 shows a cross-sectional view of the sweet potato-MFC experimental device using a planter. The soil was prepared by mixing clayey soil, sandy soil, culture soil and leaf mold. Two planters were prepared for the sweet potato-MFCs. Two SMFCs are located inside the sweet potato-MFC. In the root of the plants, countless microorganisms are active and are responsible for supplementation. Sweet potatoes are planted in 2-1 and 2-2, but 2-3 is not planted. The SMFC of 2-1 and 2-3 are in a plastic container, and there is no plastic container in the 2-2.

Figure 5.4 shows a cross-sectional view of the potato-MFC experimental device using a planter. The soil was prepared by mixing clayey soil, sandy soil, culture soil and leaf mold. Two planters were prepared for the potato-MFCs. In the previous experiments, 2 SMFCs were used. In potato-MFC experiments, try to connect 4 SMFCs to see if it will increase electricity. Four SMFC are located inside the potato-MFC. The SMFC of 3-2 are in a plastic container, and there is no plastic container in the 3-1.

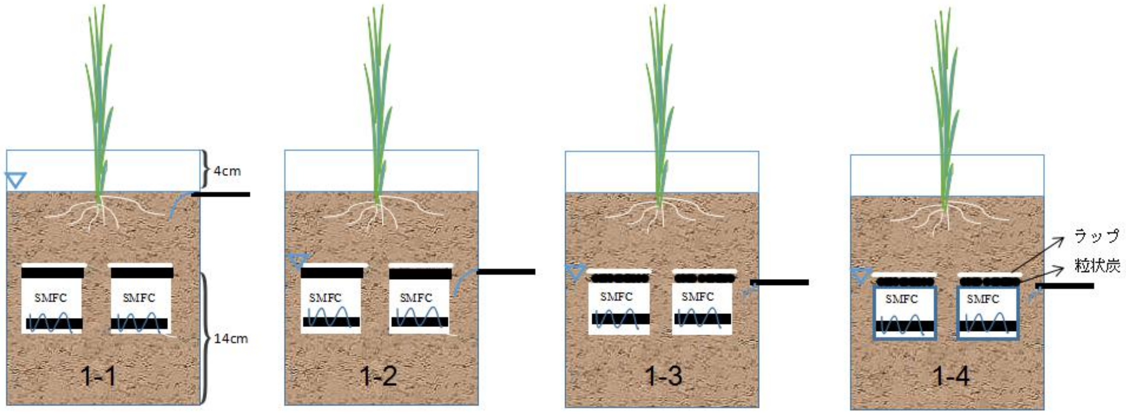

Fig.5.2 Cross section of paddy-MFC systems

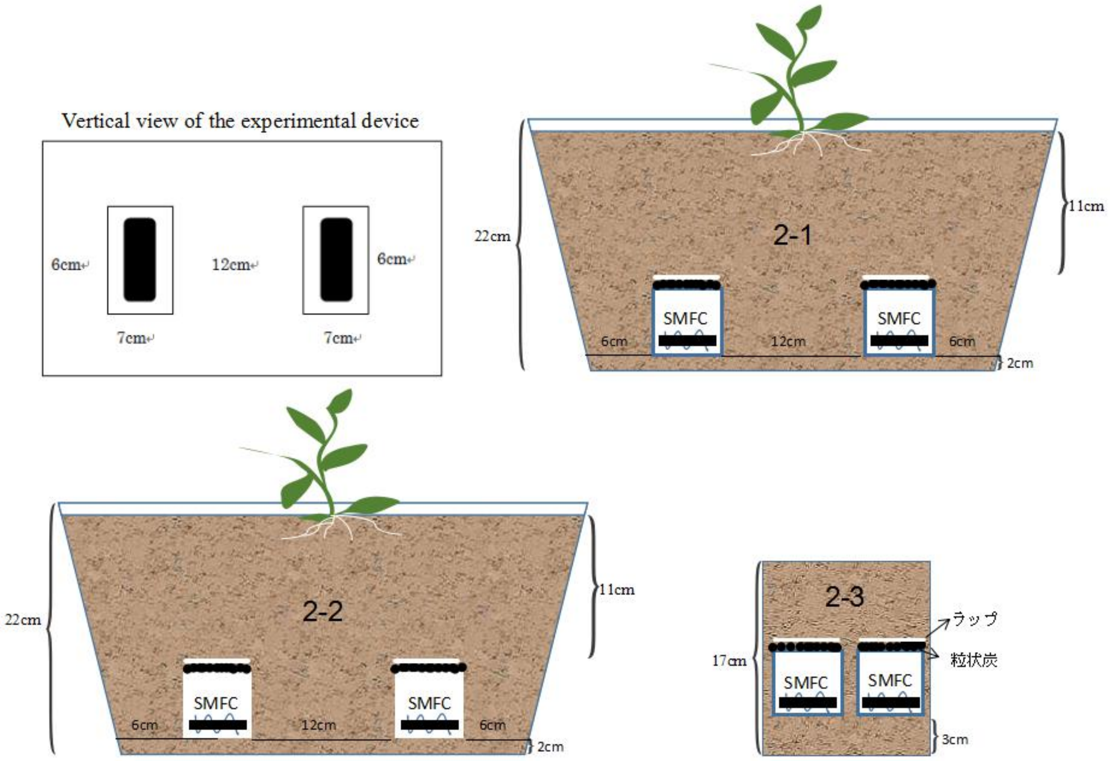

Fig.5.3 Cross section of sweet potato-MFC systems

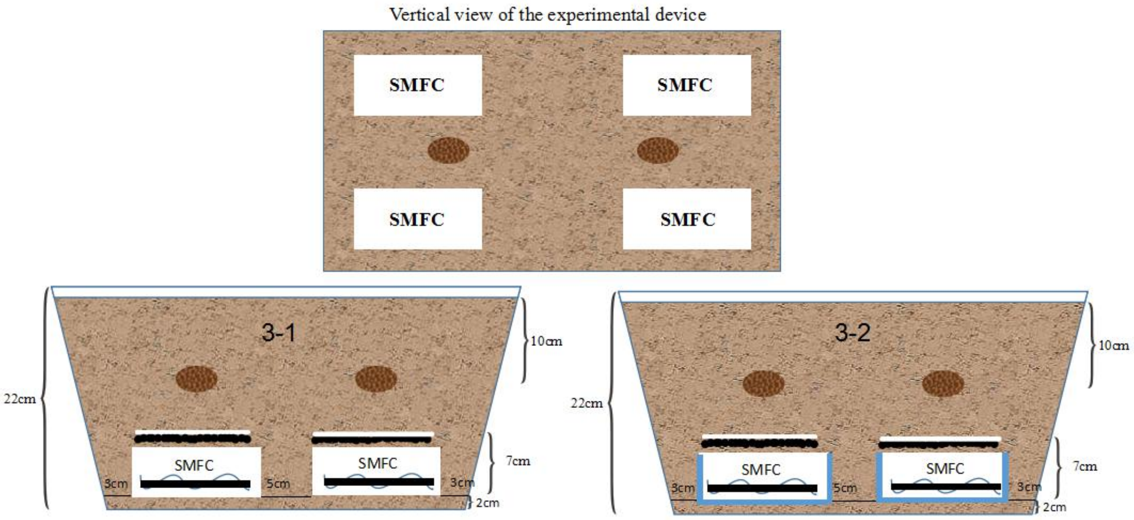

Fig.5.4 Cross section of potato-MFC systems

Table 5.1 Test conditions on plants with soil MFCs

Case	Plant	SMFC quantity	Plastic box	Cathode	Anode	Water level
1-1	Paddy	2	No	BC	BC with iron wire	High
1-2	Paddy	2	No	BC	BC with iron wire	Low
1-3	Paddy	2	No	GAC	BC with iron wire	Low
1-4	Paddy	2	Have	GAC	BC with iron wire	Low
2-1	sweet potato	2	Have	GAC	BC with iron wire	Low
2-2	sweet potato	2	No	GAC	BC with iron wire	Low
2-3	Without	2	Have	GAC	BC with iron wire	Low
3-1	Potato	4	No	GAC	BC with iron wire	Low
3-2	Potato	4	Have	GAC	BC with iron wire	Low

GAC: granular charcoal Cathode; BC: bamboo carbon

5.2.2 The combination of peat MFCs and plants

Two types of peat MFCs were used on the paddy plants. Power generation of peat MFCs using peat increases by wrapping iron wire on the activated bamboo charcoal anode.Schematic diagram on experimental device of the peat MFCs inside the paddy plant is illustrated in Figure 5.5. Test conditions of the MFCs are shown in Table 5.2. Two peat MFCs are located inside the paddy plant. The soil is ordinary soil on the grass. The peat MFCs of 4-3 and 4-4 are in plastic containers, and there are no plastic containers in the 4-1 and 4-2. 4-1~4-2 and 4-3~4-4 were prepared as replications of the same conditions, respectively.

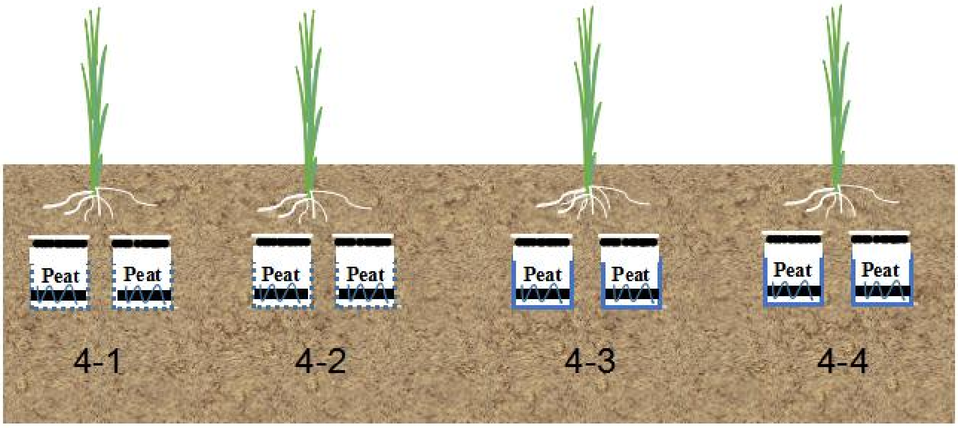

Fig.5.5 Cross section of peat MFCs with paddy plants

Table 5.2 Test conditions on paddy plant with peat MFCs

Case	**Plant**	**Fertilizer**	**SMFC**	**Plastic box**	**Resistance between electrodes (Ω)**	**Water level**
4-1	Paddy	Organic	Peat MFC*2	No	100	Low
4-2	Paddy	Organic				
4-3	Paddy	Organic		Have		
4-4	Paddy	Organic				

5.3 Results and discussion

5.3.1 Experimental results of the paddy-MFC system

Figure 5.6 is the relationship between voltage (electromotive force) and time under the condition of 470Ω external resistance. The voltage from 1-1 to 1-4 shows a slow rising trend. The voltage of 1-1 and 1-2 began to decline in about 2 weeks, and the voltage of 1-3 and 1-4 began to decline after 30 days. It can be seen from Figure 5.6 that the voltage of paddy-MFC with low water level is higher, and the voltage of the paddy-MFC of the cathode granular activated carbon is higher. The voltage of paddy-MFC with plastic boxes is higher. The maximum voltage of the 1-4 reached was 0.9V. It was the highest so far in paddy-MFCs research. Compared with activated bamboo charcoal, the voltage and electricity of the paddy-MFCs of the granular charcoal cathode is greater.

Electrode output is measured in volts (V) against time. The current I in Amperes (A) is calculated using Ohm's law, $I= V/R$, where V is the measured voltage in volts (V) and R is the known value of the external load resistor in Ohms. From this it is possible to calculate the electric power output P in watts (W) of PMFCs by taking the product of the voltage and current i.e. $P= I x V$. For obtaining a maximum power of PMFCs, the values of voltage are measured using different resistances. Figure 5.7, Figure 5.8 and Figure 5.9 show the relationship between voltage-current and voltage-electric power in the paddy MFCs on 1D, 30D and 60D, respectively. The test results obtained from Figure

5.7, Figure 5.8 and Figure 5.9 are given in Table 5.3. The electromotive force of 1-3 and 1-4 paddy-MFCs (30D) with granular charcoal cathode was about 900 mV. Maximum electric power is calculated from the linear relationship between voltage and current. The maximum power per anode area is 220mW/m^2 for the PMFC with plastic boxes. Whether it is the maximum voltage or the maximum power, 1-1 is lower than the 1-2, indicating that the large amount of water is not conducive to the power generation of SMFCs inside the paddy plants. SMFCs in combination with paddy plants generated electricity (107mW/m^2) about 1.55 times higher than PMFC (69mW/m^2). While replacing the granular charcoal cathode instead of bamboo carbon, the power generation (Table 5.3) from the SMFCs was increased from 1.55 to 2.54 times in the paddy-MFC system.

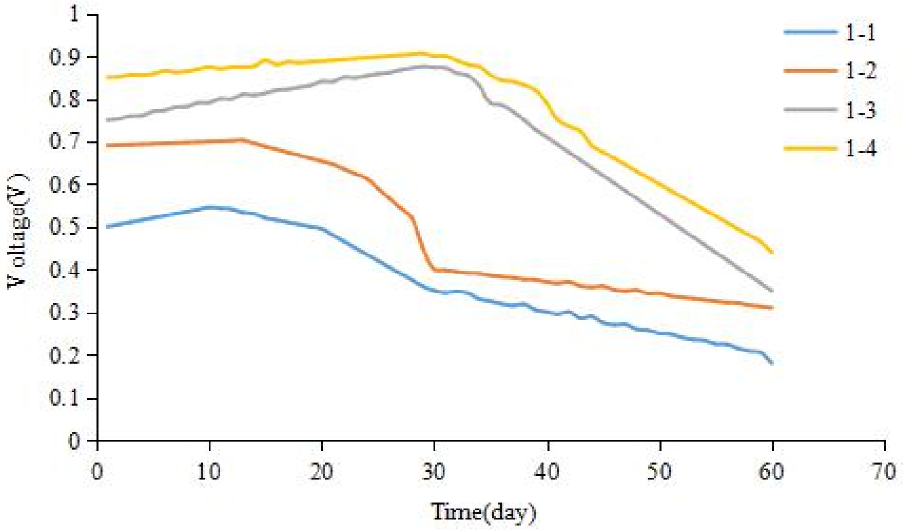

Fig.5.6 Variation of potential in paddy-MFC operated using different systems [1 to 4] with respect to time

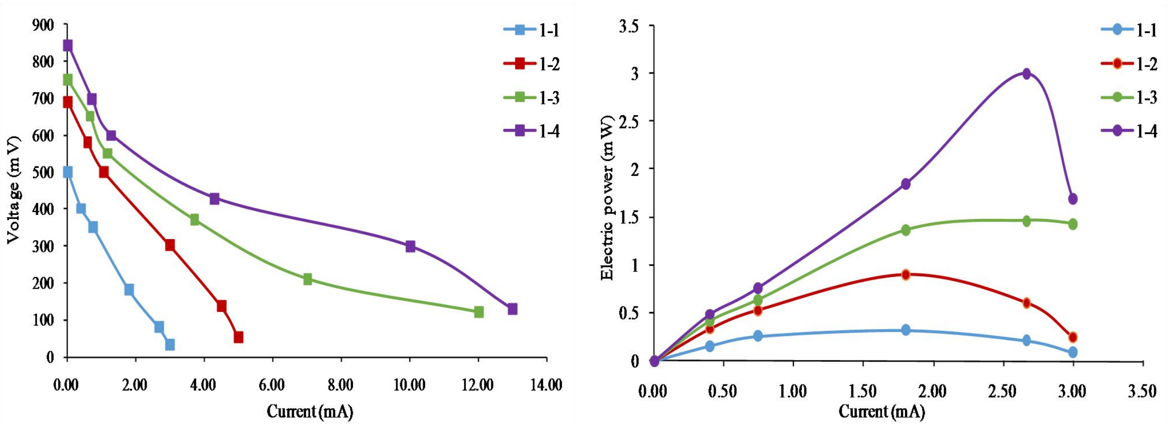

Fig.5.7 Paddy-MFC operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

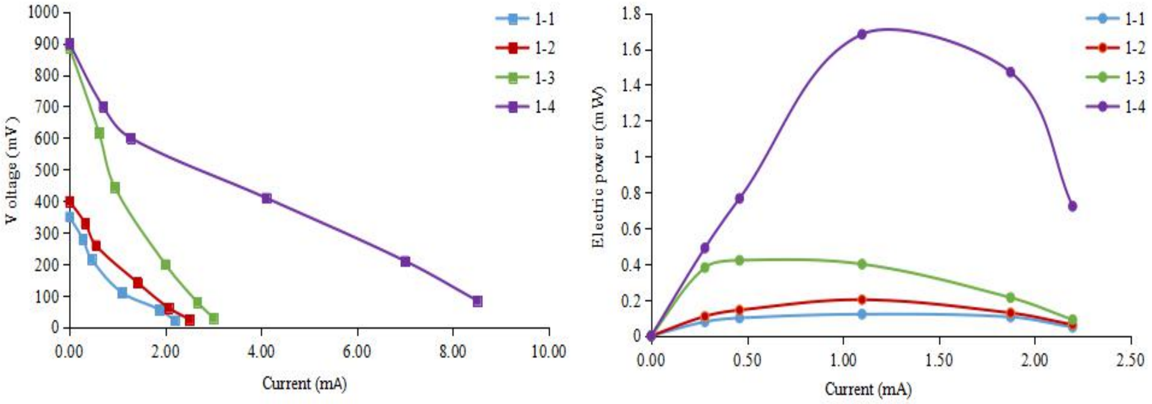

Fig.5.8 Paddy-MFC operation for the time of 30D: Curves of Current Versus Voltage and Current Versus Electric power

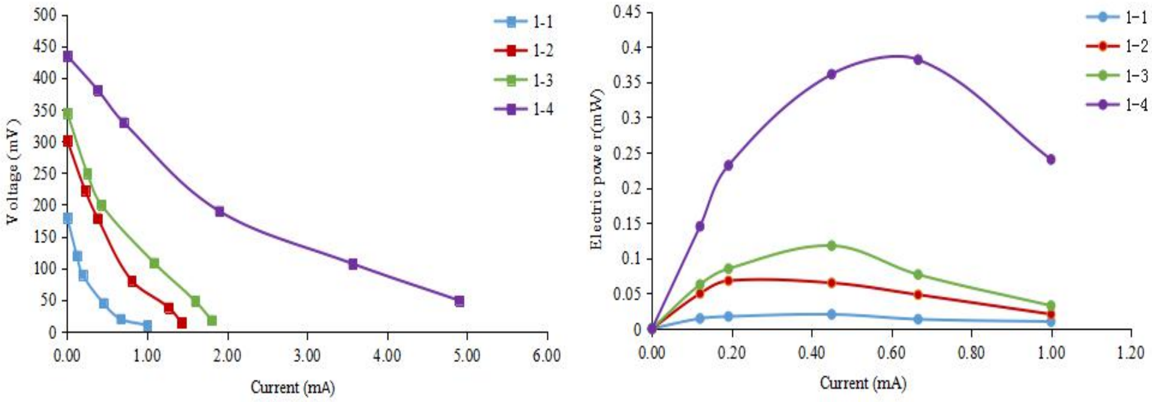

Fig.5.9 Paddy-MFC operation for the time of 60D: Curves of Current Versus Voltage and Current Versus Electric power

Table 5.3 Paddy-MFC measurements of internal resistance, maximum voltage and maximum power after time periods

Case	**MFC measurement after**								
	24 h			**30 days**			**60 days**		
	IR	V_{max}	P_{max}	**IR**	V_{max}	P_{max}	**IR**	V_{max}	P_{max}
1-1	167	0.5	39	160	0.35	15	180	0.18	2.38
1-2	138	0.69	107	160	0.4	24	211	0.3	7.74
1-3	58	0.75	175	296	0.89	48	192	0.35	14.29
1-4	56	0.85	220	106	0.9	200	89	0.44	45.48

5.3.2 Experimental results of the sweet potato-MFC system

Figure 5.10 is the relationship between voltage (electromotive force) and time under the condition of 470Ω external resistance. The voltage of 2-1 was relatively stable for the first two months, and dropped sharply two months later. When the SMFC was taken out, the iron wire melted. This may be the cause of the voltage decline, and we will consider it later. The voltage curve between 2-2 and 2-3 is almost the same. Since there is no plastic container in the SMFC in 2-2, the sweet potato roots grow inside the SMFC, which may affect the power generation capacity. The voltage value of this experiment can be measured using six different resistances and can draw a current-voltage curve. Figure 5.11 is the relationship between voltage-current and electricity-current 24 hour later. The voltage of the three sweet potato-MFCs is almost the same, and the electric power of 2-1 and 2-2 is not much different. The electric power of 2-3 is higher than 2-1 and 2-2. This may be that SMFCs are just buried in the soil for 24 h, and the weight of soil from above is small and cannot fully exert electricity. Figure 5.12 is the relationship between voltage-current and electricity-current one month later. The voltage of 2-2 and 2-3 is almost the same, and the current and power of 2-1 are significantly higher than the current and the current of 2-2 and 2-3. Figure 5.13 is the relationship between voltage-current and electricity-current three month later. The test results obtained from Figure 5.10, Figure 5.11 and Figure 5.12 are given in Table 5.4. Three months later, the current of three sweet potato-MFCs declines. 2-1's maximum electricity (per m^2) dropped by 8.9 times, 2-2's maximum power (per m^2) dropped by 87 times, C's maximum power (per m^2) dropped by 28.7 times. SMFCs in combination with sweet potato plants generated electricity (381mW/m^2) about 1.73 times higher than paddy-MFC (220mW/m^2). Figure 5.14 shows growth of sweet potatoes in different planters.It was found that the SMFCs do not influence the growth of sweet potatoes.

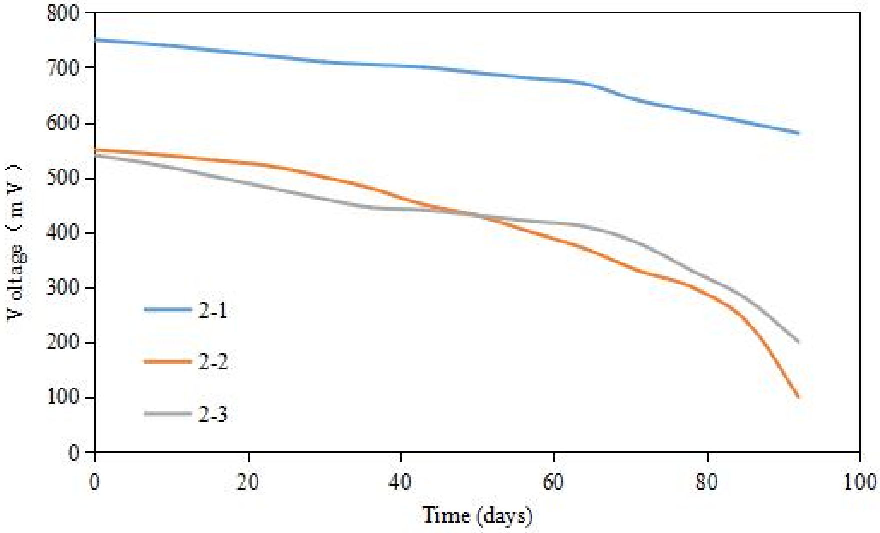

Fig.5.10 Variation of potential in Sweet potato-MFC operated using different systems [2-1 to 2-3] with respect to time

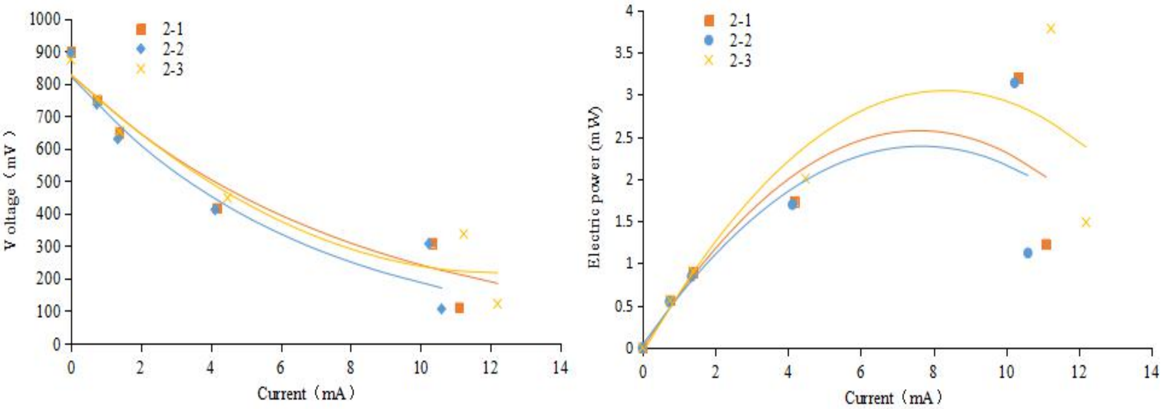

Fig.5.11 Sweet potato-MFC operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

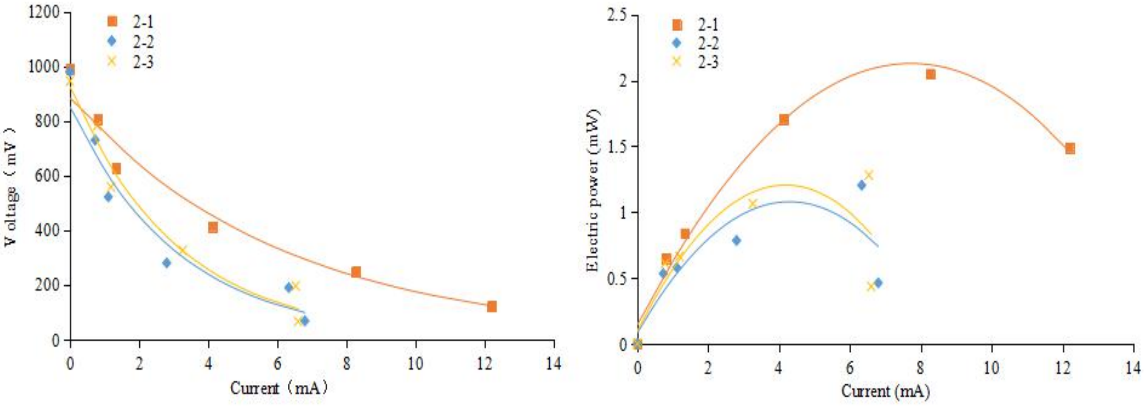

Fig.5.12 Sweet potato-MFC operation for the time of 30D: Curves of Current Versus Voltage and Current Versus Electric power

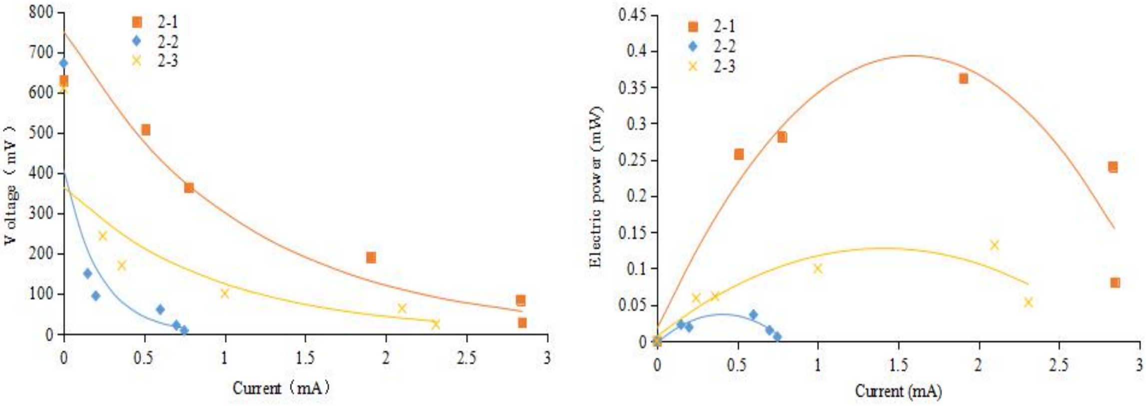

Fig.5.13 Sweet potato-MFC operation for the time of 90D: Curves of Current Versus Voltage and Current Versus Electric power

Table 5.4 Sweet potato-MFC measurements of internal resistance, maximum voltage and maximum power after time periods

Case	MFC measurement after								
	24 h			30 days			90 days		
	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}
2-1	81	0.9	381	81	0.99	244	222	0.61	43
2-2	84	0.9	375	144	0.98	143	90	0.67	4.29
2-3	72	0.87	451	143	0.95	152	264	0.61	15.74

Fig.5.14 Growth of sweet potatoes in different planters

5.3.3 Experimental results of the potato-MFC system

Figure 5.15 is the relationship between voltage (electromotive force) and time under the condition of 470Ω external resistance. The voltage of the potato-MFCs dropped sharply 20 days later.The voltage value of this experiment can be measured using six different resistances and can draw a current-voltage curve. Figure 5.16 is the relationship between voltage-current and electricity-current 24 hour later. The electromotive force of the potato-MFCs was more than 800 mV. SMFCs in combination with potato plants generated electricity power more than 3 times higher than paddy-MFC and sweet potato-MFC. Figure 5.17 is the relationship between voltage-current and electricity-current one month later. SMFCs in combination with potato plants generated electricity power more than 2 times higher than paddy-MFC and sweet potato-MFC. Figure 5.18 is the relationship between voltage-current and electricity-current two months later. The test results obtained from Figs.5.15~5.17 are given in Table 5.5. Whether it is the maximum voltage or the maximum power, 3-1 is lower than the 3-2, indicating that the power generation of SMFCs with plastic boxes is greater. The maximum power per anode area is 519 mW/m^2 for the potato-MFC with plastic boxes. SMFCs in combination with potato plants generated electricity (519mW/m^2) about 1.36 times higher than sweet potato-MFC (381mW/m^2). Figure 5.19 shows growth of potatoes in different planters. It was found that the SMFCs do not influence the growth of potatoes.

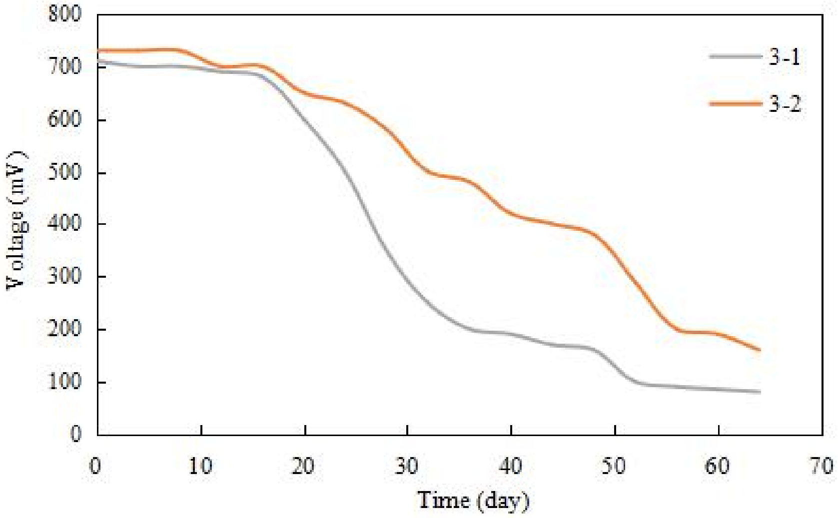

Fig.5.15 Variation of potential in Sweet potato-MFC operated using different systems [① to③] with respect to time

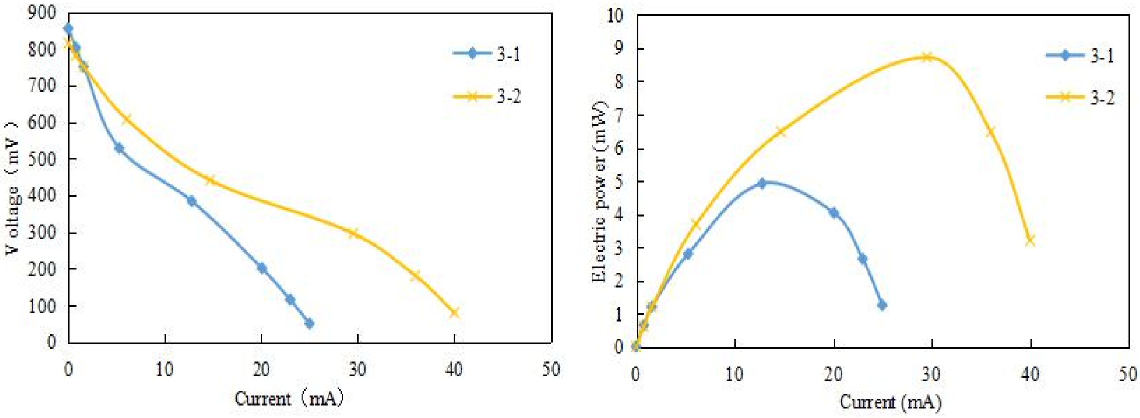

Fig.5.16 Potato-MFC operation for the time of 24 h: Curves of Current Versus Voltage and Current Versus Electric power

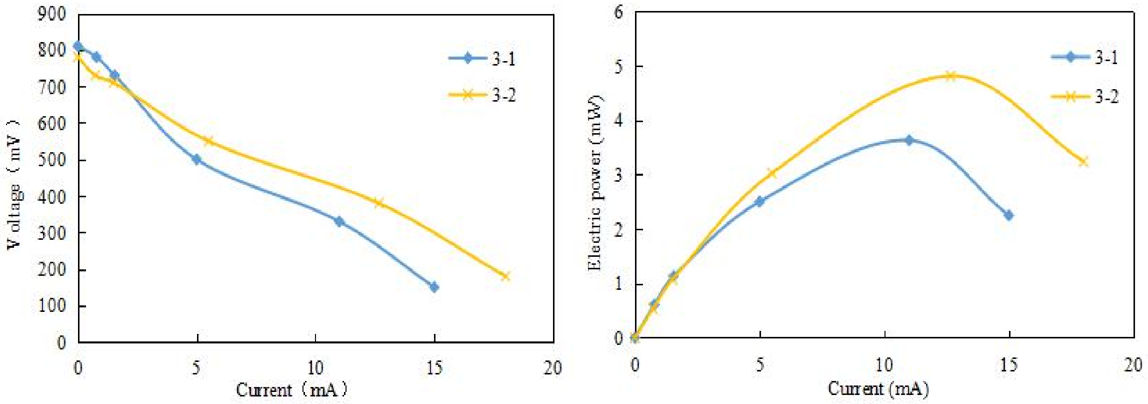

Fig.5.17 Potato-MFC operation for the time of 30D: Curves of Current Versus Voltage and Current Versus Electric power

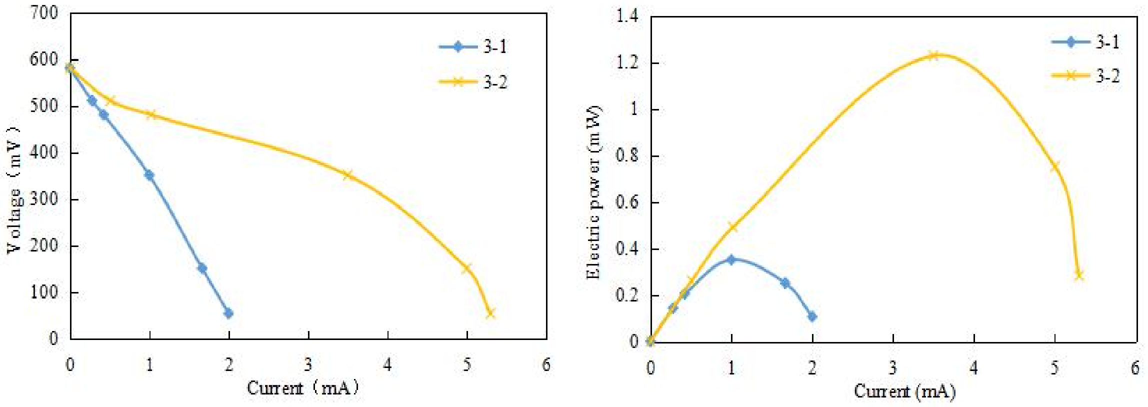

Fig.5.18 Potato-MFC operation for the time of 60D: Curves of Current Versus Voltage and Current Versus Electric power

Table 5.5 Potato-MFC measurements of internal resistance, maximum voltage and maximum power after time periods

Case	MFC measurement after								
	24 h			30 days			60 days		
	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}	IR	V_{max}	P_{max}
3-1	68	0.85	292	54	0.81	216	210	0.42	5.95
3-2	41	0.81	519	43	0.78	287	109	0.58	72.92

Fig.5.19 Growth of potatoes in different planters

5.3.4 The combination of Peat MFCs and paddy plants

Figures 5.20 ~ 5.24 show the relationship between voltage-current and voltage-electric power in the paddy-peat MFCs after 1 day, 10 days, 20 days, 20 days, 30 and 40 days , respectively. The test results obtained from Figures 5.20 ~ 5.24 are given in Table 5.6. The maximum voltage and maximum electricity power of 4-1to 4-4 decreased day by day. The paddy-peat MFCs when connected to an external resistor of 470 Ω was measured with a power output of 543mW/m^2 initially after a day but decreased to 357mW/m^2 after 20 days (decrease of ~ 35%). Due to the external resistance, the power generation was lessened to 172mW/m^2 at the end of 40 days with a loss of about 68% power after 40 days.

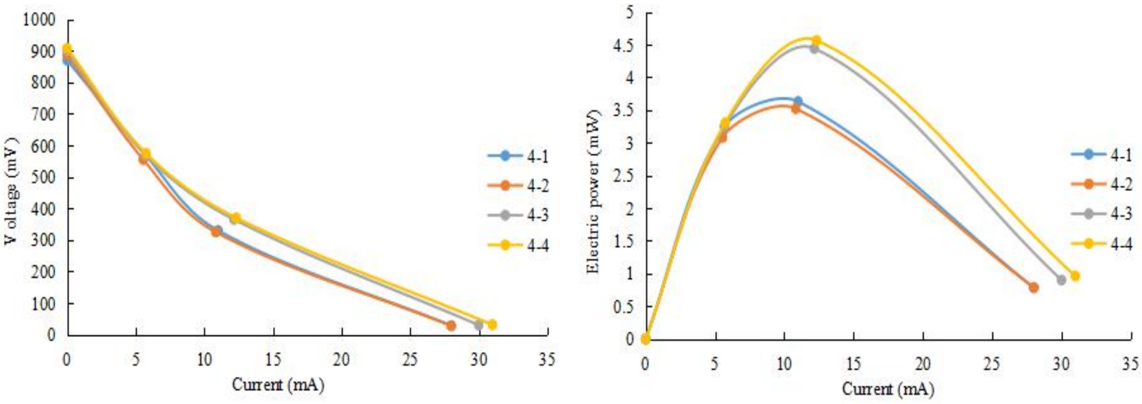

Fig.5.20 Functioning of paddy plant with peat MFCs: Curves of Current Versus Voltage and Current Versus Electric power on the first day

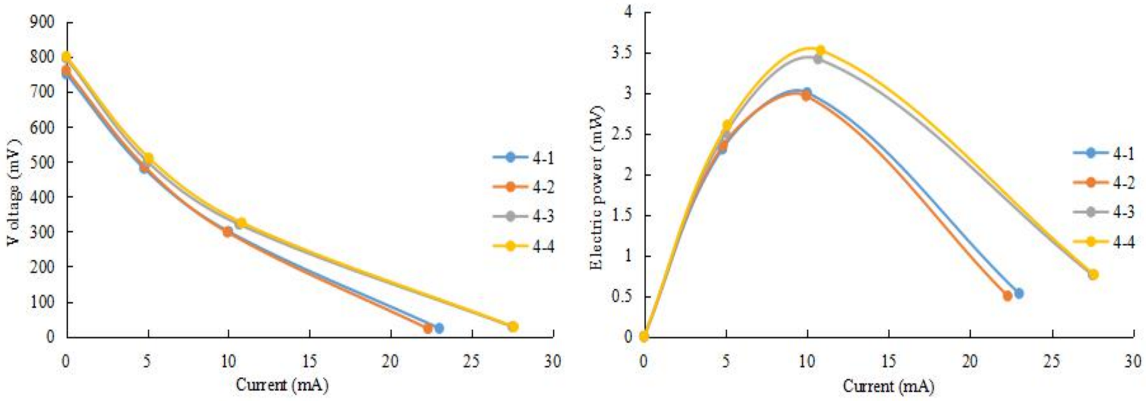

Fig. 5.21 Functioning of paddy plant with peat MFCs: Curves of Current Versus Voltage and Current Versus Electric power on the 10th day

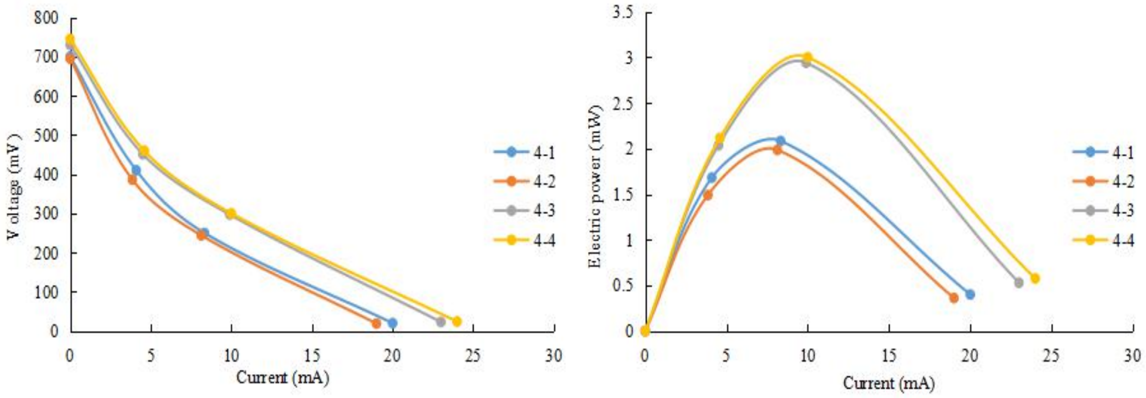

Fig. 5.22 Functioning of paddy plant with peat MFCs: Curves of Current Versus Voltage and Current Versus Electric power on the 20th day

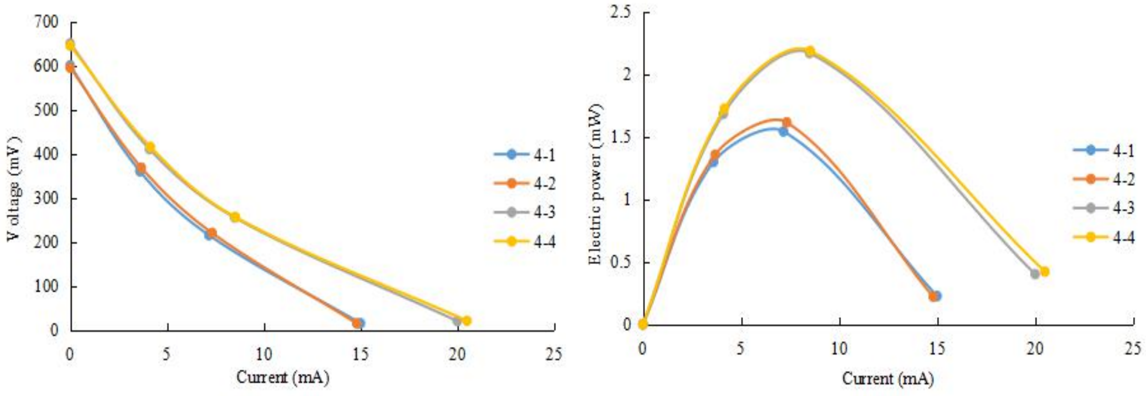

Fig. 5.23 Functioning of paddy plant with peat MFCs: Curves of Current Versus Voltage and Current Versus Electric power on the 30th day

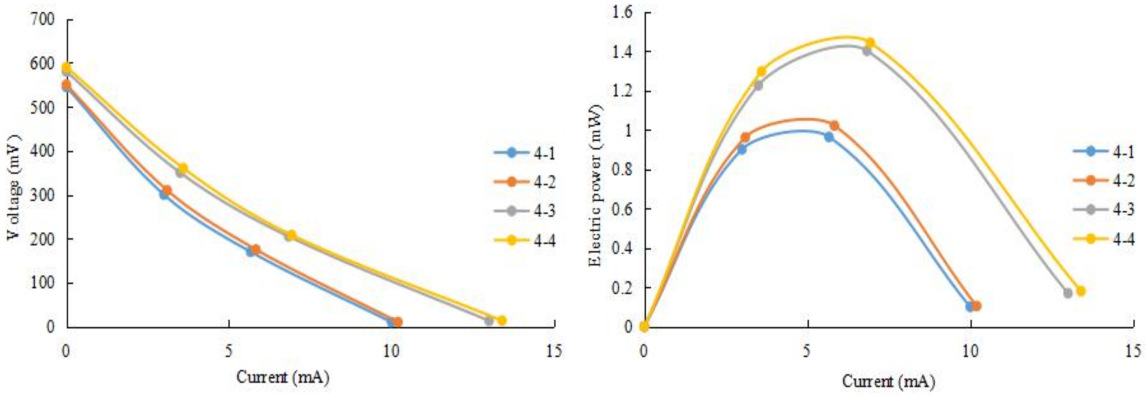

Fig. 5.24 Functioning of paddy plant with peat MFCs: Curves of Current Versus Voltage and Current Versus Electric power on the 40th day

Table 5.6 Microbial Fuel Cell measurements of internal resistance, maximum voltage and maximum power after time periods

Case	**MFC measurement after**														
	24 h			**10 days**			**20 days**			**30 days**			**40 days**		
	IR	V_{max}	P_{max}	**IR**	V_{max}	P_{max}	**IR**	V_{max}	P_{max}	**IR**	V_{max}	P_{max}	**IR**	V_{max}	P_{max}
4-1	58	0.87	432	56	0.75	357	70	0.7	248	60	0.6	192	79	0.55	115
4-2	59	0.89	419	56	0.76	352	84	0.67	236	60	0.6	192	79	0.55	122
4-3	60	0.9	529	55	0.8	406	61	0.73	350	57	0.65	258	61	0.58	167
4-4	61	0.91	543	55	0.8	419	62	0.75	357	57	0.65	260	62	0.59	172

5.4 Conclusions

In this study, we investigated the development of soil microbial fuel cells and plant microbial fuel cells. By combining the two, continuous power generation can be achieved.

(1) For paddy-MFC, compared with bamboo charcoal, granular activated carbon generates more electricity as cathode. Whether the granular carbon has a plastic box affects the production of voltage and power, especially the measurement of paddy-MFC with plastic boxes. For paddy-MFC (1-4), the measured electricity is 220mW/m^2 (24 h) is the highest. The less water, the higher the voltage.

(2) The maximum power obtained on the three PMFC systems is 519mW/m^2. It was the highest so far in PMFCs research.

(3) The results after one month of PMFC operation are as follows: the voltage of ordinary PMFC is 500mV, and the maximum power generation per unit area is 40.3mW/m^2. The voltage of the paddy-MFC system is 900mV, and the maximum power generation per unit area is 200mW/m^2. The voltage of the sweet potato-MFC system is 1000mV, and the maximum power generation per unit area is 244mW/m^2. The voltage of the potato-MFC system is 800mV, and the maximum

power generation per unit area is 287mW/m^2. Therefore, plant selection has an impact on PMFC. In addition, PMFC does not affect the growth of the plant itself while generating electricity.

(4) The maximum power generation per unit area measured by the combination of peat MFC and paddy plant is 543mW/m^2 (24 h), which is about 2.5 times the paddy-MFC system. Compared with the separate peat MFC, the power of peat MFC in paddy plant in the early stage is lower, and the electricity of the peat MFC in paddy plant is higher than that of peat MFC after 30 days.

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6. Microbial fuel cells based on organic waste and peat: Performance and Applications

6.1 Introduction

Presently, renewable and sustainable energy resources are necessary for human life across the world. Day to day, increasing world population and industrial activities are generating a huge amount of waste which needs to be converted into energy by some advanced techniques to full fill the requirement of energy demand (AL Shaqsi et al., 2020, Ahmad and Zhang, 2020). Alternative renewable energy sources are growing rapidly with extensive research areas in solar (Mao et al., 2020), piezoelectric generator (Sezer and Koç, 2021), thermoelectric generator (Jaziri et al., 2020), tidal current energy (Uihlein and Magagna, 2016), geothermal energy (Barasa Kabeyi and Olanrewaju, 2022), triboelectric nanogenerator (Sriphan and Vittayakorn, 2022) and biomass energy generation (Wang et al., 2022). At present, solar technology is used for power generation due to several reasons such as non-toxic behavior, good reliability and abundance of earth mature manufacturing technology processes and silicon materials (Raza and Ahmad, 2022).The electricity generated by renewable energy sources is very low as compared to conventional energy sources like fossil fuel (Karatayev et al., 2021). Also, renewable energy sources like wind energy, solar energy, piezoelectric and thermoelectric generators have some limitations and are not always available (Jaziri et al., 2020). Therefore it is essential to introduce some new type of energy source which can provide electricity any time and everywhere.

Microbial fuel cell (MFC) technology has high conversion efficiency and is environment friendly, which converts biochemical energy into electricity without causing any pollution (Logan et al., 2006, Nihal et al., 2021). During the last decade, the advancement of the MFC in biotechnology studies provides an entirely new innovation that converts organic materials such as biomass and wastewater into electricity by microbes (Aelterman et al., 2006, Gil et al., 2003).

MFC generates very low voltage (Prasad and Tripathi, 2018b, Zabihallahpoor et al., 2015). The voltage and power generated by MFC are insufficient to run an electrical device. To increase the output voltage, making large SMFC is not effective because the voltage does not increase proportionally to the surface area of the anode. Most researchers have used high-cost electrode materials, proton exchange membranes and pre-treatment electrodes, as well as some chemical substances added to the electrolytes; as a result, the overall cost of MFC rises (Kim et al., 2007). Therefore, multiple MFCs can be connected to the series-parallel connection to increase the voltage to power a high power-rating device. In the past few years, MFC serves as a promising technology for wastewater ranging from single sugars to complex wastewater as well as industrial effluents. It provides a pre-treatment and post-treatment option in addition to conventional sewage treatment plants.

Apart from wastewater treatment and contaminant removal from industrial effluent, MFC can also serve as an external power source for operating different electronic appliances and sensors. MFC offers online and in-situ measurement of environmental water quality monitoring parameters such as biological/chemical oxygen demand, dissolved oxygen concentration, heavy metal dose, volatile fatty acids, toxicity detection, gas detection, microbial activities estimation (B. Liu, Y. Lei, B. Li, 2014). MFC also acts as an external power source for operating the small electronic sensors used for various applications such as photo-sensors, LED bulbs, pH sensors, mobile charging, etc (T. Kim, J.I. Han, 2013, A. Kaur, J. Rae, et al.,2013).

The climate in different countries is changing remarkably, depending upon humidity and temperature. Therefore, soil structures and soil moisture are different from zone to zone. Soil moisture is a critical factor in climate systems and plays a vital role in plant growth, especially in the agriculture field. Soil moisture is diverse, so it determines the vegetational cover and plant growth of each area. As a result, the water stress of plants is the consequence of water deficiency in the soil that brings about considerable production decline. Consequently, the assessment of soil moisture plays an important role in the management of irrigation schedules to reach high yield productivity in agriculture. Sensing soil moisture is challenging work because of time-consuming, critical testing places and difficulties in equip-installation.

Soil moisture sensors are widely used in the ground environment and agricultural fields. Currently, there are many types of soil moisture sensors currently available, such as ARP, EC-5, and TDR. These soil moisture sensors measure the dielectric rate. These can be used for a wide range of moisture distribution soil water measurement, but usually requires data logoga and costs more. Many soil moisture sensors used by laboratory and professional farmers are more than 20,000 yen, and the threshold is high for life. Also, if you want to place multiple sensors over a wide area, it costs too much. The commercially available inexpensive soil moisture sensor is a metal electrode that is easy to corrode.

In this study, a inexpensive sensor that can visualize the water condition of the soil is developed by combining a metal-oxide-semiconductor field-effect transistor (MOSFET) and a carbon rod. The performance is clarified by inserting an electrode into a sample that has changed the volume moisture content and measuring the voltage of the circuit. On the other hand, the applicability of peat MFCs as a power supply of soil moisture sensor is considered, connected a small LED to the sensor, and when the soil is dry or low water, the LED is lighted or contains soil moisture. If the amount is high, build a mechanism to turn off the LED. The purpose of this study is to combine a MOSFET with an LED light and develop a peat MFC as power supply of a small sensor. In order to verify the applicability, the electrode is inserted into a sample that has changed the volume of the soil, and the voltage and measurement of the circuit are performed and the LED light is observed.

6.2 Materials and methods

6.2.1 Structure and features of MOSFET

A metal–oxide–semiconductor field-effect transistor (MOSFET) is a field-effect transistor (FET with an insulated gate) where the voltage determines the conductivity of the device. It is used for switching or amplifying signals. The ability to change conductivity with the amount of applied voltage can be used for amplifying or switching electronic signals. MOSFETs are now even more common than BJTs (bipolar junction transistors) in digital and analog circuits. The silicon dioxide forms the Gate of the MOSFET. It is used to provide isolation by preventing the direct flow of charges on the gate to the conducting channel. They can be made with either p-type or n-type semiconductors. MOSFETs are particularly useful in amplifiers due to their input impedance being nearly infinite which allows the amplifier to capture almost all the incoming signal. The main advantage is that it requires almost no input current to control the load current and that's why we choose MOSFET. It is a there-terminal device with Source (S), Drain (D), Gate (G) terminals. The body is frequently connected to the source terminal, reducing the terminals to three. It works by varying the width of a channel along which charge carriers flow (electrons or holes).

Figure 6.1 shows what used this time (Nch: 2SJ681, Pch: 2N7000).In both cases, the current between the source and the drain can be controlled by imposing the voltage to the gate, and has the opposite switching effect. In the case of the N channel, if the voltage on the gate is higher than the reference value and the P channel is below the reference value, the current flows between the source and the drain, and in the case of the opposite, the current does not flow.

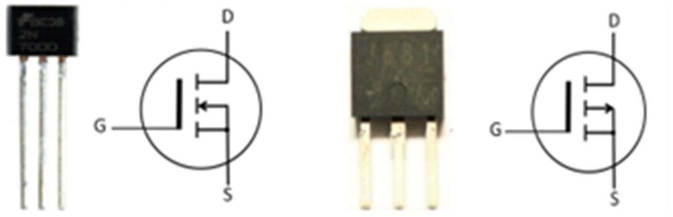

Fig.6.1 MOSFET (Left: Nch [2SJ681], right: Pch [2N7000])

6.2.2 MOSFET circuit and selection of electrode materials

Figure 6.2 is a visual sensor circuit diagram that combines MOSFET and LED light. 470Ω is connected because the LED light may be damaged by over current, and 10000Ω connects the gate to the negative electrode to stabilize the circuit. If the soil moisture is high, the resistance of the soil will be reduced, so the gate voltage will increase, the power of the P channel circuit is OFF, and the N channel circuit is turned on. If it is dry, the soil resistance value is very large, so the gate voltage is reduced, and ON/OFF is opposed. When the electrode A and the electrode B are soaked in the water, the red LED light is on. When the electrode A and electrode B do not touch the water, the blue LED light is always lit. When the water is touched, the blue LED light will be turned off.

When the MOSFET is applied to the circuit, the current flows between electrode A and electrode B. Compare four electrodes of stainless steel, steel, graphite sheets, and carbon rods (Figure 6.3). When experimenting with stainless steel and needle, the tip of the electrode A and B is confirmed to melt it when the stainless steel line and a needle are melted. Graphite board is fragile and easy to break, whether it is applied to the water for a long time. Carbon rods have low resistivity, high heat resistance, high voltage resistance and excellent conductivity. By mixing with conductive carbon powder and clay compressing carbon rods, it has high chemical stability at room temperature. It is not corroded due to strong acidity, alkaline or organic solvent, and it is difficult to rupture and cheap. Therefore, we will use carbon rods (5 mm diameter) to develop sensors. However, if the stainless steel wire is used to connect the carbon rod, even if the waterproof tape is used, the part may be dissolved. Therefore, the experiment uses the connection between the network cable and the carbon rod, and then inserts into the plastic hose to prevent entering the water. Even in the on-site experiments, as long as the length of the ethylene-based pipe increases, rainwater will not enter.

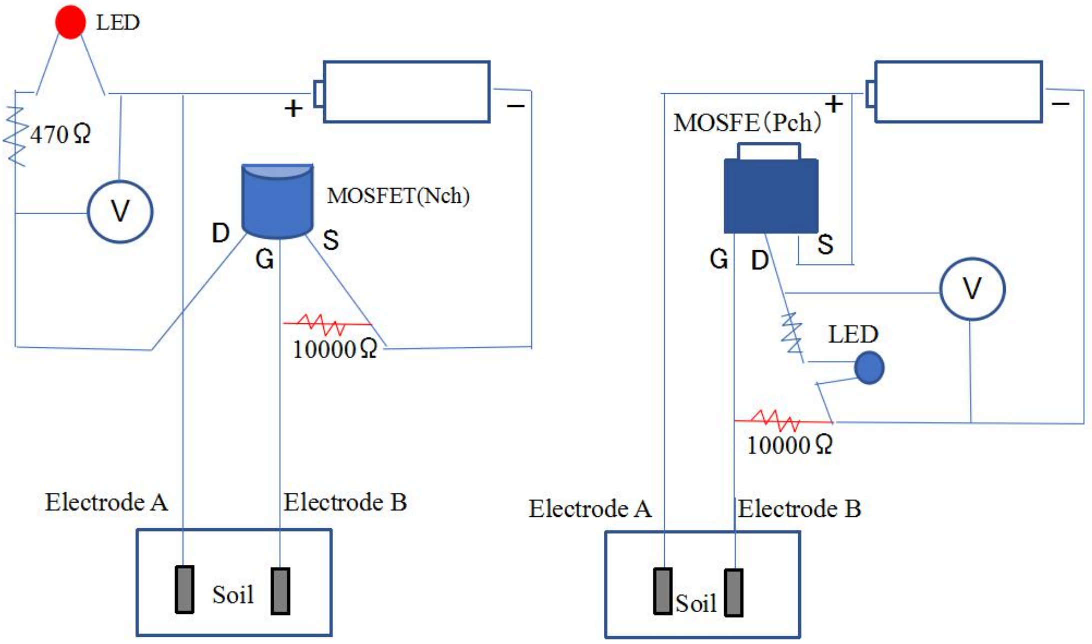

Fig.6.2 MOSFET circuit with electrodes and LED light.

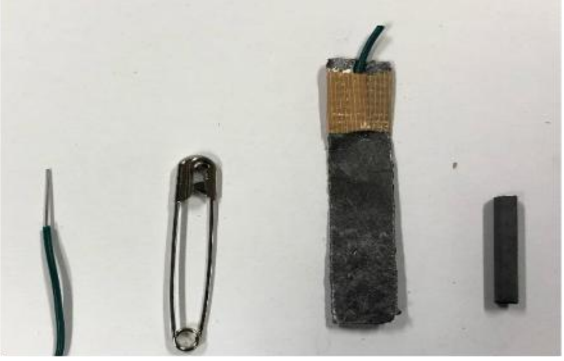

Fig.6.3 Electrode materials (From left to right: stainless steel, pin, graphite sheet, carbon bar)

6.3 Results and discussion

6.3.1 SMFC as the application of a small soil moisture sensor power supply

In this study, 200g of bamboo powder, 200g of leaf mould, and 300ml fulvic acid (100 times dilution) were mixed to make the SMFC. Due to the running state, the voltage of a SMFC is maintained about 0.7 to 0.9 V, but the voltage of a manganese battery is 1.5V, so the voltage of two SMFCs are equal to the voltage of a manganese battery. Figure 6.4 is a comparative test diagram of the performance of SMFCs and manganese battery. When connecting the 470Ω resistor, the battery capacity of the two SMFCs connected in series is about 430 mWh, and the battery capacity of the manganese battery is about 770 mWh. It can be seen from Figure 6.4 that the battery capacity of the 1 manganese battery is 1.8 times that of the battery capacity of 2 SMFCs, so the battery capacity of the 4 SMFCs are almost the same as the battery capacity of a manganese battery. In order to drive a small sensor, it is necessary to increase the output voltage of soil microorganisms to be above 3V, so at least 4 SMFCs are required. The easiest way to obtain high voltage is to connect multiple soil microbial fuel cells in series. The method of obtaining high power is to connect multiple soil microbial fuel cells in parallel. The voltage of the two manganese batteries is 3V. In order to achieve the battery capacity of the 2 manganese batteries, about 8 SMFCs are required, each four SMFCs connecting series, and then connected in parallel. Each SMFC was connected to an external load, so the electrical connection was individual. Once the steady state was reached, parallel, series and combination of both electrical connections were tested. The parallel connection was carried out by connecting all the anodes leading to a unique anodic output while in series, the cathode of the first SMFC is connected to the anode of the second SMFC and so on until the last SMFC of the stack. In this case, the anode of the first anode and the cathode of the last MFC remain unconnected so the electrical circuit is closed by connecting them. The connection method is shown in Figure 6.5. The two devices in Figure 6.2 are placed in the soil, add 20 g water every time, measure the voltage of two LEDs, and compare the brightness of the two LEDs. The volume moisture content can be calculated based on the amount of dry soil and water, and the relationship between water content and voltage can be obtained (Figure 6.6). Figure 6.6 is the relationship between the voltage of the red and blue LEDs and the volume moisture content of decomposed granite soil. By inserting electrodes after gradually increasing the water and mixing uniformly, we can observe the changes of the red and blue LEDs by measuring the voltages of the red and blue LEDs respectively. It can be seen from the figure that the brightness of the LED changes according to the value of the flowing voltage. When the value of the flowing voltage is large, it will light up, and when the value of the flowing voltage is small, its light will become weaker.

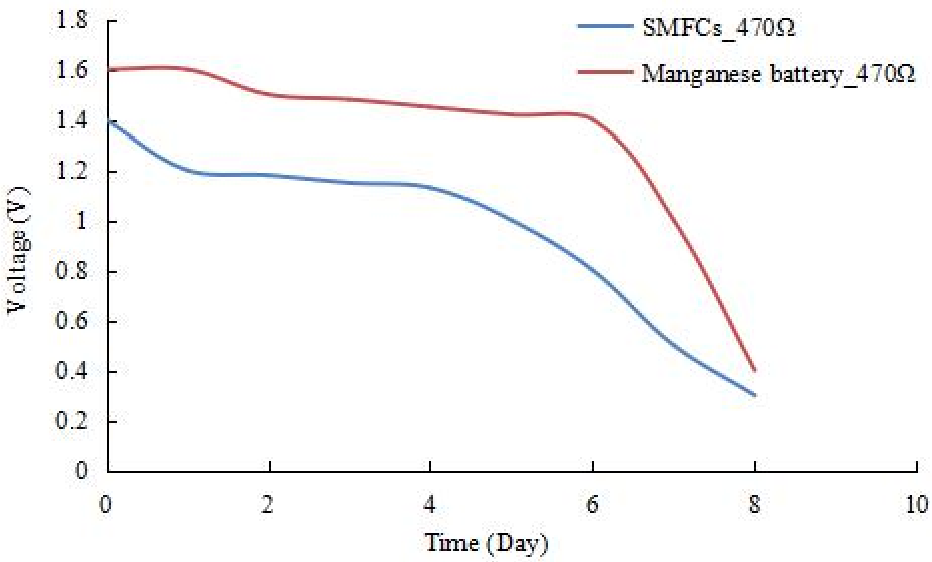

Fig.6.4 Comparative test diagram of the performance of SMFCs and manganese battery

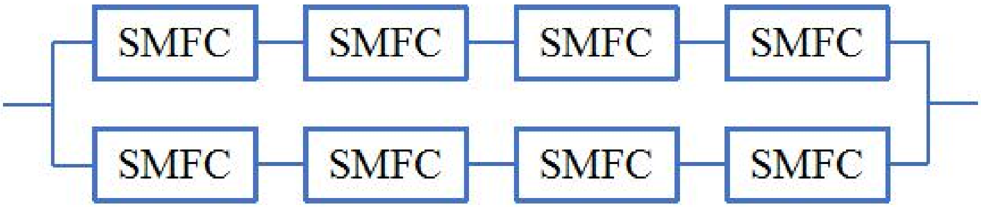

Fig.6.5 The connection method of SMFCs

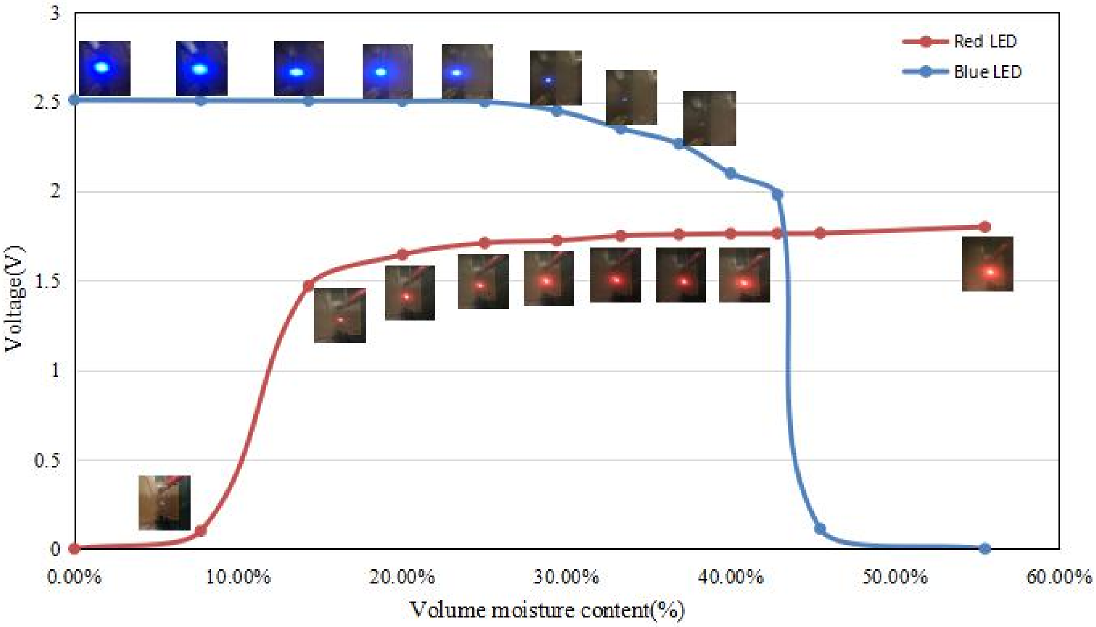

Fig.6.6 Relationship between the volume moisture content of decomposed granite soil and the LED voltage

6.3.2 Use peat MFCs as a power supply for a small soil moisture sensor

6.3.2.1 Development of soil moisture sensor using MOSFET circuits

Figure 6.2 is two circuits made through MOSFET, which is inconvenient in practical applications. Therefore, combine Nch and Pch to make circuits. In this study, a combination of Nch and Pch was created to create a soil moisture sensor circuit (Figure 6.7). This is a mechanism in which the voltage output increases when soil water is lowered below a certain value. As the water in the soil decreases, the electrical resistance of the soil increases, the Pch switch is turned off, and the voltage of the Pch increa rises. This voltage may be unstable, but by connecting it to Nch G, it becomes more stable and the voltage rises when the Nch switch is turned on. Since the resistance value of the soil is greatly affected by the amount of water, the voltage on the Pch gate is reduced when it is dry, and as a result, current flows between the Nch source and the drain. It is thought that the volume of the volume can be grasped by using the change in the electrical resistance of the soil according to the amount of water. The carbon rod was inserted into a sand with a different amount of water, applied a voltage, and the resistance value was changed from 22kΩ to 10 mΩ to examine the relationship between volume water containing and voltage.

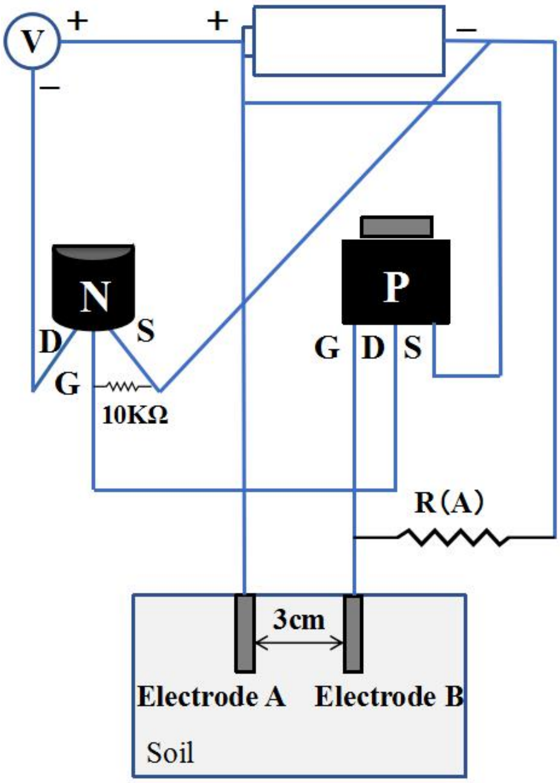

Fig.6.7 Soil moisture sensor circuit

6.3.2.2 Development of soil moisture sensor using dry batteries as power supply

Insert electrodes A and B into different moisture content sand, and the resistance value (R) is changed from 22kΩ to 4700kΩ to check the relationship between water content and voltage. Sands with different water content have been prepared for 16 samples, of which the volume moisture content is 0.5 % to 20 %. Figure 6.8 is a variable resistor used, which can change the resistance value in the 1Ω unit. First of all, an experiment was performed with a 5V power voltage, but the control of the MOSFET circuit became unstable, so it is difficult to distinguish the water volume of 5 % or more volume moisture content. After that, when 3 to 3.3V did not fluctuate, the voltage value would not fluctuate. Here, the measurement is performed with a 3.3V power supply. Because the voltage caused by the resistance value also changes, the characteristics of MOSFET can be used to change the amount of soil water to open/level. The resistance (R) is 12kΩ, 33kΩ, 47kΩ, 56kΩ, 56kΩ, 68kΩ, 100kΩ, 220kΩ, 470kΩ, 680kΩ, 680kΩ, 1000kΩ, 4700kΩ). Insert 30 mm into sand with different volume of water content and record the voltage change. Figure 6.9 shows the relationship between the volume content and voltage when connecting to different resistors is displayed.The larger the resistance, the more sensitive changes in the volume moisture content. When the small resistance (22kΩ) is connected, the volume moisture content is close to 18 %, the voltage decreases. The more accurate the accuracy of the soil volume can be measured by changing the resistance. The PF value suitable for the soil cultivated by plants is about 1.7 to 2.3. Converted to volume moisture content is about 4 % to 16 %. For example, if the sensor is used in irrigation equipment, it is necessary to irrigate when the volume moisture content is 5 %, then a 100kΩ resistor needs to be connected.

In order to stabilize the equipment, the length of the carbon rod electrode was also checked. In previous experiments, 30mm carbon rods were used, but similar experiments of 10mm and 50mm were performed, and the results were compared. As shown in Figure 6.10, when the electrode inserted the soil with the different volume moisture content, the resistance value was dropped to 0V. The vertical shaft is used for numbers. Compared with the result of 30mm carbon rods, the resistance value of the carbon rod 10mm is higher than 30mm, while the resistance value of the carbon rod 50mm is lower than 30mm. From the experimental results, the use of long carbon rods tend to switch through low resistance values, while using short carbon rods, switch with high resistance. In any case, the stability of the voltage is the same. Therefore, the circuit can be adjusted by adjusting the length of the carbon rod electrode and the contact area between the soils.

Fig.6.8 State of experiments using variable resistors

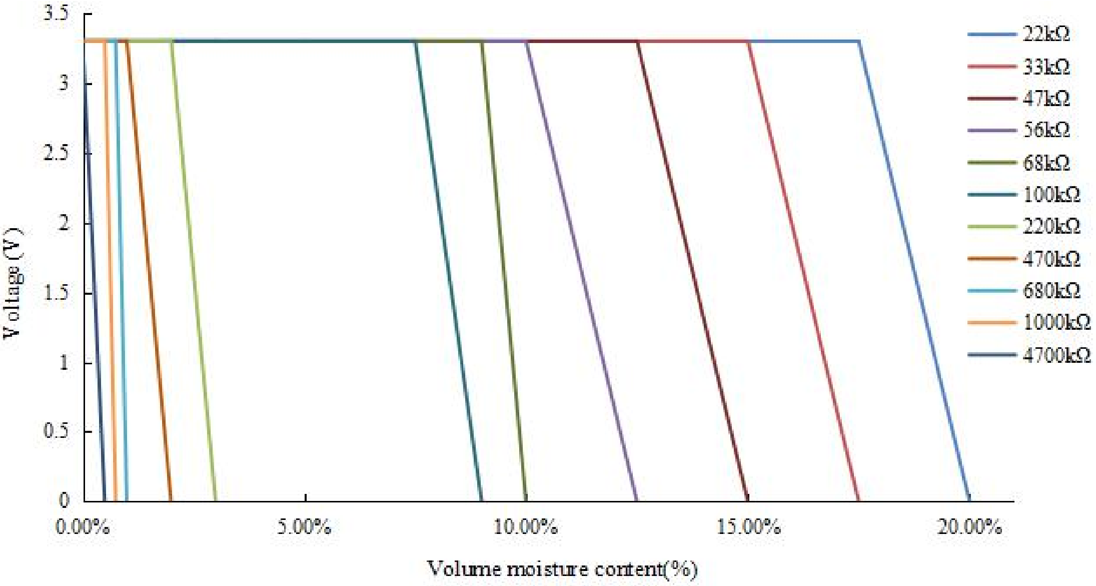

Fig.6.9 Relationship between volume moisture content and voltage

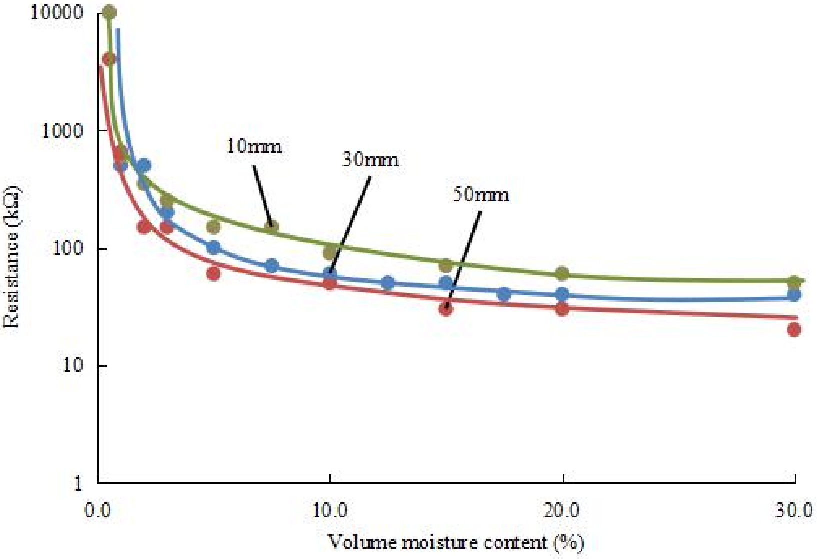

Fig.6.10 The relationship between the volume moisture content and resistance in different lengths of the carbon rod

6.3.2.3 Application of peat MFCs

One of the options to scale-up the electrochemical reactor is to connect the number of MFCs into electrically stacked arrangements (either series or parallel) depending upon desired power output to operate the electronic appliances (X.A. Walter, J. Greenman, I.A. Ieropoulos, 2020). Modular design of multi-electrode assembly along with electrical circuit for charge storage is one of the proposed models for stacking of MFCs in real field application (I. Ieropoulos, J. Greenman, 2008). In this study, use 400g peat and 120ml distilled water to make peat MFC. The resultant output power can be sufficient to operate the different electronic appliances and monitoring sensors of low power requirement. In stacked arrangement, internal resistance of MFC is limited by parameters such as transport, kinetic, and Ohmic resistance, which had to be diminished to improve the output of current (H. Mehravanfar, M.A. Mahdavi, R. Gheshlaghi, 2019). Due to the running state, the voltage of a peat MFC is maintained about 1V, but the voltage of a manganese battery is 1.5V, so use two peat MFCs. Figure 6.11 is a comparative test diagram of the performance of peat MFCs and manganese battery. When connecting the 470Ω resistor, the battery capacity of the two SMFCs connected in series is about 806 mWh. It can be seen from Figure 6.11 that the battery capacity of the two peat MFCs are higher than the battery capacity of a manganese battery. In order to drive a small sensor, it is necessary to increase the output voltage of soil microorganisms to be above 3V, so at least 3 peat MFCs are required. The connection method is shown in Figure 6.12. Figure 6.13 is the relationship between time and voltage. The voltage of soil microorganisms is very stable. Figure 6.14 is the curves of current versus voltage and current versus electric power. The electric power of the six peat MFCs is about 3.3V and the maximum power is 11.3 mW.

The voltage of peat MFCs (Figure 6.12) is about 3.3V. The 3.3V voltage is enough to open a LED. Therefore, the LED can be used instead of the position of the voltage meter in Figure 6.7, and the brightness of the LED can be observed to determine the humid state of the soil. Figure 6.15 is an experimental device added a LED to the circuit diagram in Figure 6.7. As shown in Figure 6.15, connect a 3.3V constant voltage regulator in the circuit to stabilize the voltage of the peat MFCs to 3.3V, when the electrodes are inserted into a dry soil, the red LED lights are lighting. At this time, it becomes a visual soil moisture sensor. When the soil is dry or water is small, the LED light will be on; the water content of the soil is large, the LED light will be off. As shown in Figure 6.16, when the electrode inserted the soil with the different volume moisture content, the resistance value was dropped to 0V. It can be seen that there are many points that overlap in Figure 6.16. By setting these points as an approximation curve, an approximate formula in the figure can be obtained. It can be seen that soil microorganism batteries can be replaced by the dry battery as a power supply for soil moisture sensor.

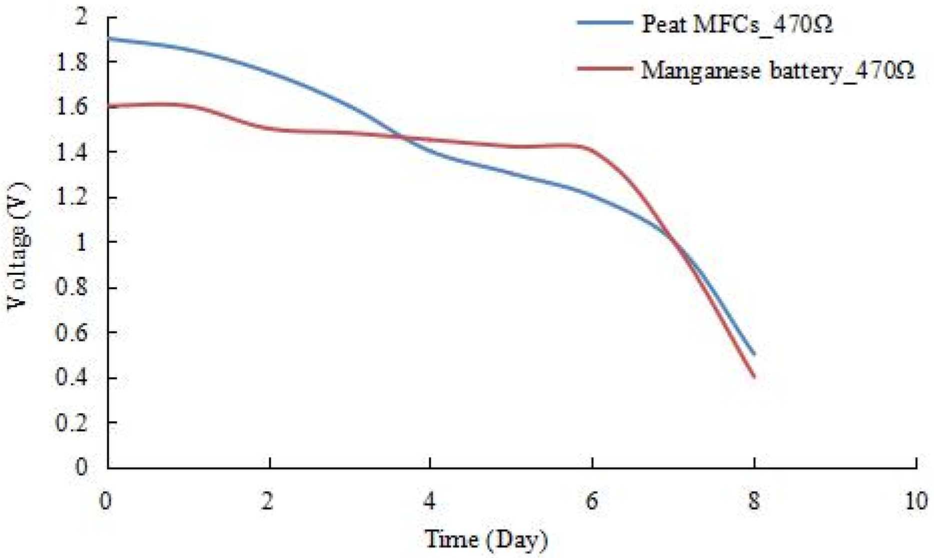

Fig.6.11 Comparative test diagram of the performance of peat MFCs and manganese battery

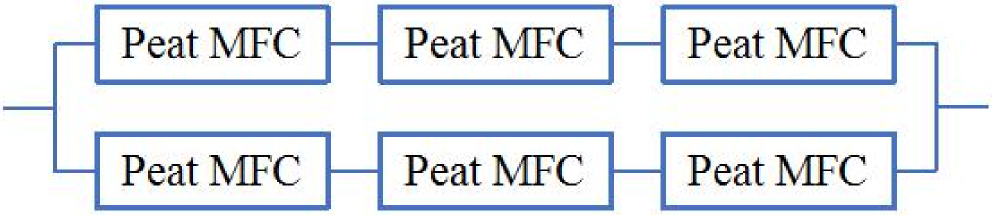

Fig.6.12 The connection method of peat MFCs

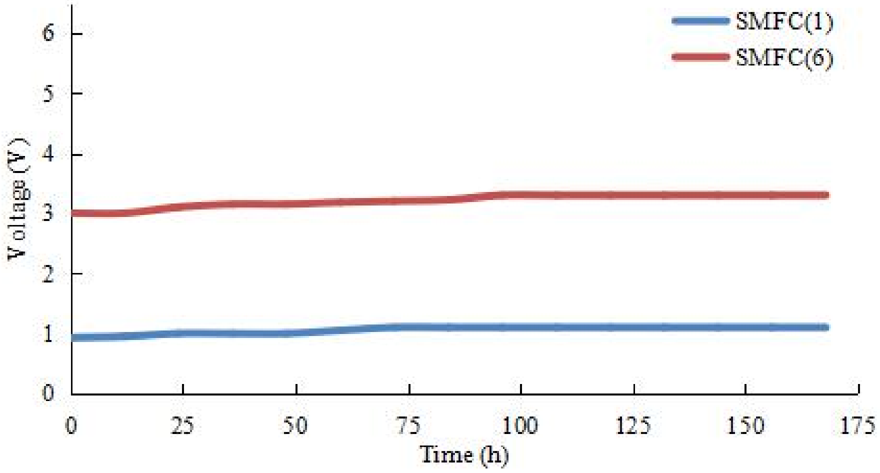

Fig.6.13 the relationship between time and voltage

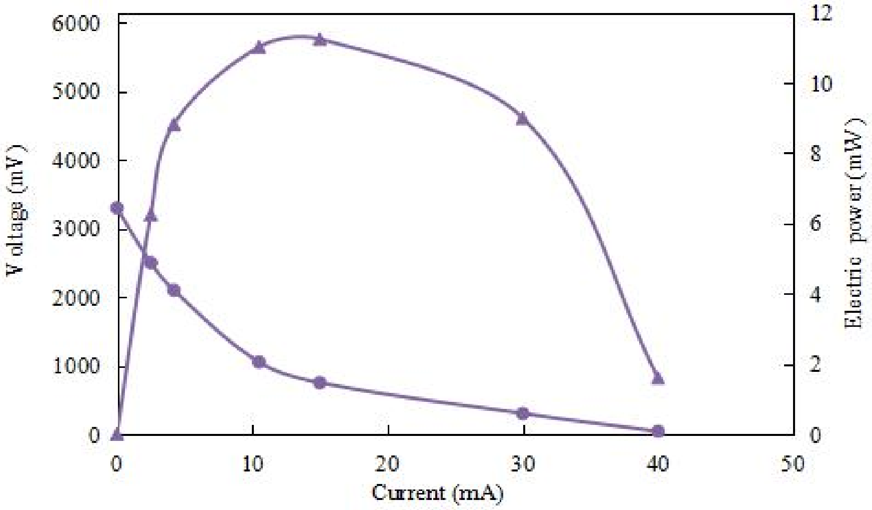

Fig.6.14 Curves of Current Versus Voltage and Current Versus Electric power

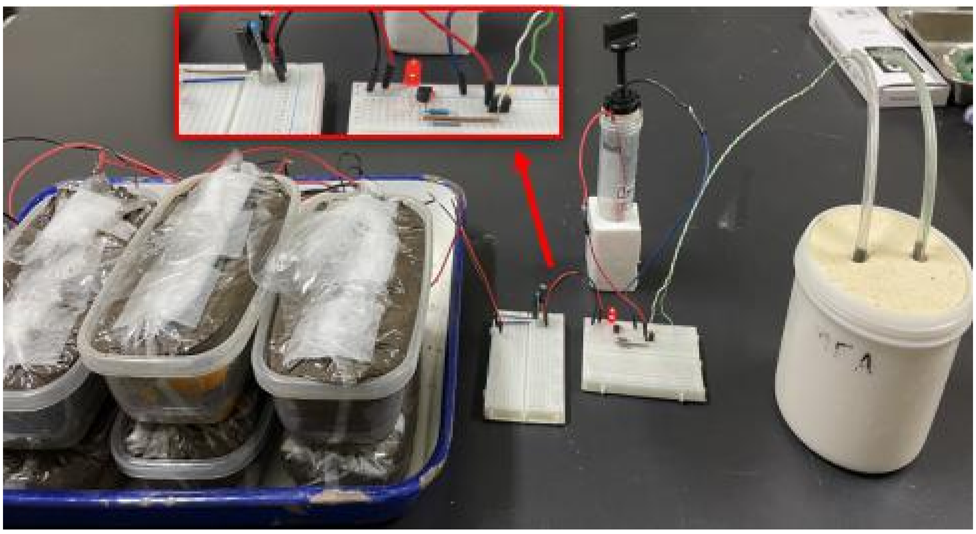

Fig.6.15 Experiment using peat MFCs as a power supply

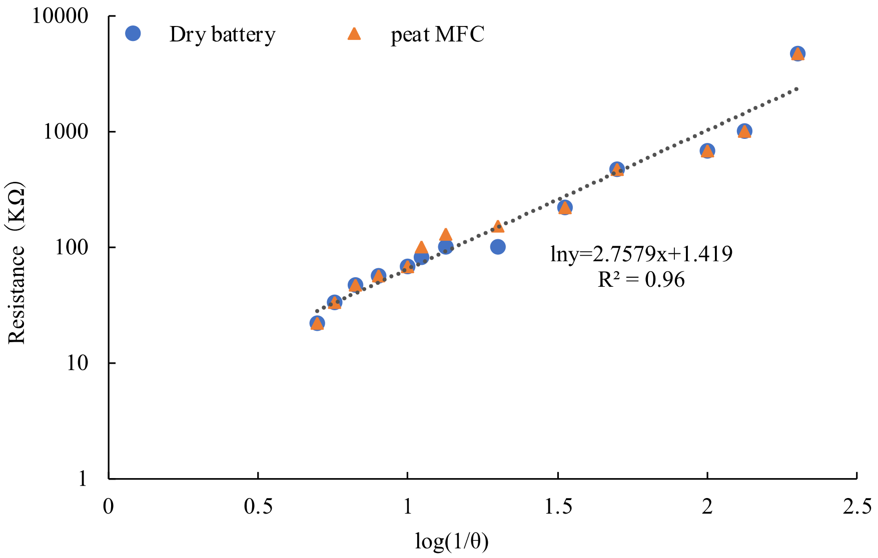

Fig.6.16 Relationship between volume moisture content and resistance

6.4 Conclusions

From this work, the following conclusions can be drawn:

(1) This time, we were able to create low cost soil moisture sensors using MOSFET and carbon rods without using equipment such as microcomputers. The use of this soil moisture sensor is to roughly determine whether the soil is dry or not. It responds sensitively with a small amount of water. The value of the resistance connected to the MOSFET gate has an effect on the soil moisture sensor. The timing of ON/OFF switching can be changed depending on the resistance value compared to the circuit. However, the point that the switching function of MOSFET with a high water containing rate remains unstable, and it is necessary to improve carbon rods and resistance values. From the test results, it is indicated that the simple sensors using MOSFET are useful for measurement of soil moisture.

(2) Since the LED can visualize changes in the water condition in the soil using a soil water detection sensor, it is possible to match the irrigation device. If the volume containing the soil that is necessary to irritate is determined in advance, the connected resistor can be selected. When the soil is dry or when the water is low, the LED light up and requires watering. When the amount of water in the soil is high, the LED turns off, and there is no need to water. For this reason, it is considered that it can be used as a sensor for automatic irrigation.

(3) Compared with the results so far, peat MFC is more suitable for power supply as a small sensor than SMFC. Its voltage is more stable and the power is higher. The gap between practicability and reality of MFC technology transformation lies in scalability of MFC either by stacking arrangements and are subjected to certain design and operational limitations. The understanding

regarding the microbial reactions happening within a live reactor is still in the initial stages and much research has to be done for having a clear picture of microbial activity in the scale-up reactors. However, MFC is far away as to be utilized as an independent external power source. Application of MFC for sensor use along with valuable resource recovery is the key successive indicators for future hope towards the commercialization of such complex bioelectrochemical systems.

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7. Summaries

The main conclusion is summarized in this chapter, as follows:

In Chapter 2, a performance of paddy plant microbial fuel cell (PMFC) is evaluated by experiments using container of bucket. Two types of electrodes, namely carbon fiber and activated bamboo charcoal, are used on paddy PMFC. Influences of electrode material and existence of iron wire attached to anode on voltage generation are investigated. The result suggests that the voltage of the case with organic fertilizer increased gradually and maximum voltage reached was 0.68V. The voltage of the case with organic fertilizer and using anode with iron wire increased gradually and maximum voltage reached was 0.85V. Compared with carbon fiber, the voltage and electricity of the PMFC of the activated bamboo charcoal is greater.It was also observed that the growth of paddy plant is promoted when iron wire is used. The maximum power per anode area of 69mW/m^2 was obtained on the PMFCs with activated bamboo charcoals electrodes and activated bamboo charcoals electrodes (with iron wire).

In Chapter 3, the possibilities of generating power due to the microbial degradation of chosen organic wastes and their admixtures were explored. Soil MFC using less expensive and easily available organic admixtures was developed. An inexpensive SMFC was designed using organic wastes/admixtures using bamboo carbon anode with iron windings and granular charcoal as cathode for the generation of electric power. The maximum electrical output of 1071 mW/m^2 was achieved for an organic admixture containing Bamboo powder, Leaf mould and Rice Bran in the presence of Fulvic acid. The EIS study inferred the influence of admixture composition and its moisture content in altering the resistance values. The SEM, FTIR, Raman and BET studies corroborated the participation of surface carbon atoms leading to the modification of anodic carbon as a consequence of the bio-electrochemical activity. The cost analysis confirmed that the fabrication of SMFC unit is inexpensive thanks to the consumables from sustainable sources.

In Chapter 4, several MFCs made of peat are mainly studied. Peat is rich in organic acids, rich in minerals, high water retention capacity, and can promote the growth of microorganisms. On adding Bamboo waste and fulvic acid to peat, the generated power was raised to 1371 mW/m^2 and 1488 mW/m^2 for an output voltage of 0.80±0.01V after a day period. It is commendable that the addition of peat soil to bamboo waste and water reduced the internal resistance by 91.4% by escalating the power generation up to 11.5 times after 24 h. The voltage of MFC made of peat can reach 1V, and the maximum power generation of the unit area is 2719 mW/m^2. The role of wounded iron wire over anodic bamboo carbon enhanced the power generation along with the decomposition of organic matter in peat soil.

In Chapter 5, PMFC systems were constructed with different plants. By combining the SMFC and plants, continuous power generation can be achieved. In the experiment of combining SMFC and plants, the potato-MFC system is the largest, and the maximum power generation per unit area is 287mW/m2.The maximum power generation per unit area measured by the combination of peat MFC and paddy plant is 543mW/m^2 (24 h).

In Chapter 6, a low-cost sensor has been developed, which can visualize soil moisture status by combining voltage-controlled elements (MOSFET) and LEDs. The performance was elucidated by inserting electrodes into samples with different volumetric water contents and measuring the circuit voltage. On the other hand, the applicability of SMFCs and peat MFCs as a power source for soil moisture sensors has been investigated.