RSC Advances

Abstract

Active biocatalyst such as microorganisms or enzymes liberate electron while electron donors are consumed in biological fuel cells. Biological fuel cells are a novel technology which produces bio-electrochemical power using various materials such as complex organic waste or natural organic matter in the anaerobic anode condition. Recently, great attentions have been paid to biological fuel cells due to their mild operating conditions and using variety of biodegradable substrates as fuel. Sediment Microbial Fuel cell (SMFC) is a kind of Microbial Fuel Cell (MFC) that can produce electrical current by sediment's organic matter content and using bacterial metabolism. SMFCs have been developed in the past decade to provide a renewable power source and organic matter removal. SMFC differs from other MFCs due to the essentially complete anoxic condition on the anode and membrane less structure. To further improve SMFC technology, this paper focuses on SMFC's limitation and challenges and collects latest surveys in this field.

Keywords: Sediment Microbial Fuel cell, Mechanism, Application, Challenges and Scale up.

1. Introduction

Energy is needed to preserve our life. Different kind of energy is formed and used in different countries. These energy is dissipated into the atmosphereas and disrupt the normal atmospheric circulation pattern which cause changes in Earth’s atmosphere, temperature, greenhouse effect and etc [1]. Fossil energy is the basic engine for growth in many economies. Energy consumption is related to economic growth [2]. So in recent years, energy consumption has grown exponentially in developing economies [3]. As can be seen in Fig.1, most of the energy consumption in the world in 2012 was non-renewable energy. For example according to U.S. energy information administration, only 8% of energy consumption in 2010 in the USA came from renewable energy sources verses 9% from nuclear energy and others from non-renewable energy sources. Although energy source is shifted from fossil fuels to renewable energy sources, oil and gas still are the major primary energy sources to power the world's industries. So the demand for new renewable energy sources still remains.

Figure 1. World consumption of primary energy, 2012

Needs of energy are improving the world and traditional sources of energy such as fossil fuels have several disadvantages. Alternative sources of energy are required. Most of the energy sources that is using in the world are non-renewable energy. Thiskind of energy sourcest is finishing and utilization of them cause some problems like emission of greenhouse pollutants, including SOx, COx, NOx, CxHy, soot, ash, droplets of tars, and other organic compounds, which are released into the atmosphere as a result of their combustion. Also fossil fuels are inefficient to prepare energy requirements due to pollution and finite supplies [3-5]. So the researchers in the world are working to find new energy platform to sufficient energy without CO_2 emissions and greenhouses problems [5, 6]. So many countries all over the world have made an effort to solve energy crisis by turning the eyes into the renewable energy sources such as solar energy or energy deriving from wind or water. One of renewable alternative energy source is fuel cell which has attracted lots of attention to generate energy. Fuel cells have several advantages such as: no emissions of environmental polluting gases (such as SOx, NOx, CO_2, CO), higher efficiency, no existence of the mobile parts and, as a result, lack of sonic pollution, etc. [7, 8] In contrast, high costs as well as mass generation are the only disadvantages of these new energy sources [7, 9]. There are several kinds of fuel cells. One of most interesting fuel cells is microbial fuel cell (MFC). MFCs were discovered by Potter. In 1911, Potter observed electrical current generated by bacteria. Until early 1990s, few studied were achieved in this field [10]. Over the last 20 years and especially this last decade, we observe so rapid development in MFCs technologies [11, 12].

Figure2. Schematic diagram of a microbial fuel cell.

MFCs technologies represent a novel energy harvesting technology and energy transducer comprises an anaerobic anode and an aerobic cathode and typically a cation exchange membrane. The two electrodes are connected via a conductive wire [11, 13-15]. Figure 2 shows essential concept of MFC. Microorganisms or active biocatalysts break down organic matters in their surrounding environment [6, 16, 17]. Some of MFCs need artificial electron mediators for transfer of produced electron by biocatalyst from substrate to anode electrode [17-20]. H^+ or other cations pass through the anodic chamber to cathode chamber by proton exchange membrane. The resultant electrons from organic matter degradation transferred through cathode via external circuit and reduce oxygen according to reaction 1 [11, 13, 16, 21]:

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \qquad (1)$$

MFCs are to harvest electricity from different substrates [6, 19, 22, 23]. In addition to liquid phase substrates, solid phase substrates such as sediments, sludge and contaminated soil can be fueled by solid state microbial fuel cells [24].

Sediments in aquatic environment are potentially long-term source of water contamination. Soil and sediments are derived from plant and animal detritus, settlement of dead bacteria and plankton, fecal matter and anthropogenic organic materials [25]. Sediments' organic carbon content generally ranges from 0.4 to 2.2 wt.% [26]. Thus, sediments' organic carbon content may be seen as a sufficient energy resource in some locations. Many high cost and energy consumption physicochemical methods have been practiced for sediment remediation [27]. But these organic carbon content can be consumed by *exoelectrogens* directly transporting electrons outside of the cell. Sediment bioremediation by sediment microbial fuel cells (SMFCs) recently developed due to its cost-effectiveness and environmental benignity[27]. SMFC is a simple configuration of MFC, which generate electricity from aquatic environment.

SMFCs are bioelectricity production technique for low-power application. SMFCs enhance organic matter removal (oxidation) from submerged soil at the anode along with energy production. In fact, SMFCs are membrane free MFCs and its unique property of removing organic compounds from the sediment, attracted significant attention recently.

SMFCs consist of an anode electrode embedded in an anaerobic sediment and connected through an electrical circuit to a cathode electrode suspended in overlying water [28, 29] (Figure.4). Unlike conventional MFCs, SMFCs do not require protons to be transferred by dissolved oxygen gradient along the water depth and membranes [30-32]. SMFC differs from other MFCs in that the anode is essentially under complete anoxic condition [10]. Inspired by the experiments of Reimers and Tender, the first functional SMFCs were created about 10 years ago, [25, 33, 34].

Marine, river, fresh water, rice paddy and other aquatic sediments rich in organic matter have been used in various surveys [35, 36]. Marine microbial fuel cell (MMFC) and benthic Microbial fuel cell (BMFC) are also known as SMFC.

Figure3. Schematic set up of Sediment Microbial Fuel Cell

SMFCs are special kinds of MFCs which generate bioelectricity by using an active microorganism in the sediments. Although electrical current produced by bacteria was observed by Potter in 1911 [37], limited feasible results were obtained in this subject by the next 50 years [38]. At the beginning of the year 1990, the attraction of fuel cells became stronger and the field of MFCs and SMFCs initiated to improve [39]. The steep slope of MFC progress began in 1999 when it was discovered that mediator was not a required component [40, 41]. But the interests on SMFC are increased in recent year. Up to now, limited researches have been done on SMFC's scale up. In general, the most significant investigations on sediment microbial fuel cell have been conducted by Tian-Shun

Song [24, 29, 42-44], Chun-Chong Fu [45-48] and Seok Won Hong [25, 49-51]. Recently, there has been a rise in the number of published articles on this subject with the United States of America being the major source of such publications. Published articles on SMFCs. The number of articles in the field of SMFC from 2006 to 2014 is presented in figure 4 by typing the key word "sediment Microbial Fuel Cell" in the Scopus search. Within recent years and throughout the world are shown in Figure 4 and Figure 5 respectively. Published articles on SMFCs within recent years and throughout the world are shown in Figure and Figure 5 respectively.

Figure 4. Published articles on SMFCs within recent years.

Figure 4 shows the number of articles that have been published by different countries. Also figures 5 presented different countries are working on SMFCs. From figure 5, you can understand that all areas in the world have interest to work in this renewable research area.

Figure5. Published article on SMFCs throughout the world.

2. Mechanism:

Microorganisms and substrate plays important role on SMFCs performances. Figure 6, illustrates the role of microorganisms in SMFCs with a number of main reactions which are determined to occur at the anode and cathode. The anode biofilm is enriched in two types of sedimentary microorganisms: *Geobacteracea* family (most similar to *Desulfuromonas acetoxidans*) and *Desulfobulbus* or *Desulfucapsa* genera. *Geobacteracea* oxidizes acetate in the sediment directly reducing the anode, while *Desulfobulbus* or *Desulfucapsa* genera oxidize anode generated S^0 to SO_4^{2-} [52-54]. Acetate is provided by organic matter fermentation by other anaerobic microorganisms in sediment (e.g., clostridium). Another reaction occurred at the anode is the oxidation of S^{2-} to S^0. When organic matter is oxidized, O_2, MnO_2, Fe_2O_3 and SO_4^{2-} reduce orderly between sediment surface layer and anode. With increasing sediment depth, each layer accumulates more and more potent reductants [52-55]. So, as illustrated in Figure 6, produced electrons by active biocatalyst can be delivered to the anodes from 1) microbes enriched on the anode surfaces, or 2) from dissolved and solid-phase forms of reduced ions contained in the sediment (e.g., sulfides in marine sediment)[50]. Some of MFCs need electron mediators to transfer produced electrons to anode surface [17, 18, 20, 56] and also proton exchange membrane for transfer generated protons to cathode chamber [57, 58]. But SMFCs do not need proton exchange membrane and also electron mediators.

Figure 6. Microorganism's roles and main reactions in SMFCs [59, 60].

3. Advantages

SMFCs have a number of functional advantages compared to other energy sources. These include direct conversion of organic matter into current at a high efficiency, working under a wide range of environmental conditions including low operating temperatures [34, 35], low cost [61], less frequent maintenance requirements (e.g. periodic replacement) [53], simple construction, wide and cheap fuel resources [34] , easily placed in remote locations [62] and no generation of toxic components [63]. On the other hand, SMFCs have some limitations such as: nonlinear scaling up, low operating voltage, low cell potential [53, 62, 64] and failure to provide continuous power [65].

4. Application:

Two broad applications are expressed for sediment microbial fuel cells within the literatures: 1) providing renewable power sources for instruments deployed in marine, river, lake, freshwater, ocean and etc. for long-term monitoring; 2) removal of organic matters in sediments. In the following, each of these applications is explained separately.

4.1. Renewable power source

One of the main applications of SMFCs is to provide a power source for wireless equipment used for environmental monitoring, oceanographic studies, and military tactical surveillance where real-time data acquisition from remote locations is required [35, 65](Table.1). These instruments have no cable connection with the surface, so that they need to a kind of power supply such as batteries. However, batteries are associated with limited calendar lifetimes though requiring high cost of periodic replacement, especially in deep water [34]. These challenges can be overcome by application of SMFC as a power source. SMFCs can empower various wireless sensors including those identifying temperature, salinity, tidal patterns, the presence of algae and other life forms, migration patterns of fish and other marine wildlife, organic contamination from oil production, metallic compounds from other industrial processes [55], pH, humidity, aquatic life, invasive species [30], an also biological oxygen demand (BOD) biosensors, and a dissolved oxygen (DO) sensor [66].

Table1. SMFCs was used as power supplier at different practical application.

4.2.Organic matter removal

Organic- rich sediments, as an important component of aquatic environments, can be considered as an abundant potential source of renewable energy. But drainage of industrial wastewater and municipal sewage has infected the surface layer of sediments by pollutants such as organic matter, nitrogen, and phosphors[29], resulting in water-quality issues and even methane emission. Furthermore, these compounds are toxic for organisms in carcinogenic and mutagenic potential [69]. One way to remove these compounds is to reduce them as a fuel in SMFCs. There is a linear relationship between the generated current and removal efficiency of organic matter from sediments [43, 51]. A comparison of the removal efficiency of organic matter and power density by SMFC for different types of carbon sources is shown in Table 2.

Table2. Removal efficiency of organic matter and power density by SMFC for different types of carbon sources

5. Evaluation of SMFCs operation

Electrical sources operation can be evaluated by their provided current, voltage, power density and current density. The current can be calculated using Ohm's law ($I = V/R_{ext}$), where I represents the current in amperes, V represents the potential difference between two electrodes in volts, and R represents the external resistance measured in ohms [10]. Voltage can be calculated by open circulate voltage (OCV) and internal resistance (R_{int}) ($V=OCV-IR_{int}$). Internal resistance is associated with ohmic losses (R_o), activation losses (R_a), and mass transfer losses (R_{mt}); giving the equation number 2 [77]:

$$R_{\text{int}} = R_0 + R_a + R_{mt} \quad (2)$$

Power generation is our other major purpose for SMFCs. The power output is calculated via:

$$P = VI \text{ or } P = \frac{I^2}{R} \quad (3)$$

It is common to normalize power production by the surface area of the anode, A, or total reactor volume, v, so that the normalized power density produced would be [10]:

$$P = \frac{I^2}{A.R} \quad (4)$$

$$P = \frac{I^2}{v.R} \quad (5)$$

6. Challenges in SMFCs

A significant portion of investigations performed on SMFCs was concerned with improving their electricity generation capacity in a longer timeframe. As shown in Table 3, the investigations were mostly focused on the anode, cathode, sediments, overlying water, equipment configuration and operational conditions, each of which will be discussed in the following.

Table3. Classification of all investigation in SMFCs.

Moreover, SMFC produce bioelectricity and remediates contaminated in sediments simultaneousl. In spite of low electricity generation from SMFC, it has been demonstrated that this system is used successfully to power low-power electronic devices in aquatic ecosystem. Nevertheless, SMFC technology is facing many challenges to be a reliable renewable energy source and research in this field of fuel cell must be continued to improve SMFC performances.

6.1. Anode

Microorganisms metabolize available organic matters in sediments and release electrons (e^-) through electron acceptor known as anode [78]. Anode reduction is done by microorganisms colonized on the anode surface [52]. Anode material, geometry and surface modifications are the key parameters in optimizing the harvested electricity from sediments. These parameters affect microbial adhesion to anode surface, electron transfer and substrate oxidation [36].

Anode material is required to be of high conductivity, environmental stability and good redox reversibility [48]. Current and power densities for different anode materials and geometry are shown in Table 4. Graphite, stainless steel and carbon are common material used in SMFCs. Maximum power and current densities for graphite tank are 100 mW/m^2 and 3500 mA/m^2, respectively [74].

Surface modification alters surface contact angle and wettability of the anode by introducing several hydrophilic groups onto the electrode surface [42] which results in higher and better adhesion of bacteria [46, 79]. Several investigated anode modifications are shown in Table 5. As can be observed, power density is significantly increased with Fe/ferric oxide in some cases such as electrolytic deposition of graphite.

Table 4. Current and power densities for different anode materials and geometry.

Table 5. Different anode modifications proposed in the literature.

6.2.Cathode

In SMFCs, electrons (e^-) harvested from sediments flow from anode to cathode through an external circuit, reducing oxygen in overlying water. Similar to the anode, cathode material and geometry are important factors in SMFCs operation. Electron transfer efficiency and oxygen reduction rate of cathode material are important factors [84]. Current and power densities for different cathode material and geometry are shown in Table 6 where maximum power and current density are obtained from Polyaniline graphene nano-sheets.

Table 6. Current and power densities for different cathode materials and geometry.

Microorganisms can catalyze reduction of oxygen in the cathode by growing a biofilm on this electrode. Biological oxygen reducing cathodes are called bio-cathodes. Advantages of this system are its low cost, self-replenishment, better sustainability and no mediator involved [11, 36, 87]. Mixed culture microorganism [87], oxygenic phototrophs [11] and iron oxidizing bacteria [88] are several biofilms used as bio-cathode.

6.3. Sediment

As mentioned before, the electrons in SMFCs are provided by the bacterial degradation of the organic matter, so that SMFCs power output can be improved by using higher organic matter contents [26]. In this regard, several researchers increased sediment organic matter (SOM) by addition of substrates such as glucose, cellulose, chitin [26, 44, 89], acetate [35, 90], biomass [24], and milk [81].

Plant microbial fuel cell (PMFC) (first reported in 2008) also can provide organic matter [91]. In PMFCs, plants grow within sediments, producing carbohydrates via the photosynthetic processes (Figure 7-B). Some percentage of the produced carbohydrates is absorbed by the roots structure [92]. Microorganisms in the rhizosphere break down these carbohydrates and produce electron. A scheme of the plant-MFC is shown in Figure 7-B. Growing plants in sediments can also solve the mass transfer limitations for electron donors to reach the anode in SMFCs [44]. Several plants used in PMFCs are presented in Table 7.

Table 7. Several plants used in PMFCs.

Microalgae and some bacteria such as *cyanobacteria* [90] contribute to increase SOM via photosynthesis [97] (Figure 7-A). This technology is called sediment-type photoMFC, where electricity generation exhibits an inverse relationship with illumination, because of the negative effect of the oxygen accumulation via photosynthesis [97, 98]. This problem can be overcome by using color filters or increasing the thickness of the sediment [98].

Figure7. A) sediment-type photo-MFC; B) Plant microbial fuel cell [97].

Sediment bed conductivity is the other important factor affects the efficiency of power generation in SMFCs. Adding conductive materials to sediment may improve the conductivity of the sediment by serve as electron conduits between bacterial cells and anodes [32, 99]. Graphite flakes [32] and colloidal iron oxyhydroxide [99] are such conductive material can be used for enhancing performance of SMFC.

The operating pH in the sediment bed [70], different pretreatment methods for sediments [29] and also affects the efficiency of power generation.

6.4.Overlying water

Nature, origin, flow conditions, characteristics, functional activities, total dissolved solid, pH and temperature of water bodies play crucial roles in power generation [51, 78]. For example stagnant water bodies showed higher power generation compared with running water bodies [78]. But dissolved oxygen (DO) is the most significant factor. Oxygen is utilized as an electron acceptor [63]. Therefore DO is another important factor of SMFCs [50, 86]. Researchers' findings indicate that different methods can be used for increasing DO in water. These methods are summarized in Table.8.

Table 8. Different methods proposed to increase DO in water.

In rotating cathode technology, rotation of the cathode disks also increases the dissolved oxygen in the overlying water (Figure.8-C). No external energy input will be required when disk drives are rotated by natural water currents [31]. In floating-SMFC (Figure.8-B), cathode is floated on the water surface, so as a part of its surface is exposed to air. This technology overlaps with air-cathode method in which the cathode is placed at the air–water interface (Figure.8-A). On the other hand, algae such as *Chlorella vulgarisis* fix CO_2 during photosynthesis, releasing oxygen as a byproduct [86] and saturating water by oxygen.

Part of produced oxygen in plant-MFC is released to rhizosphere by roots. So, rhizosphere can act as an oxygen source provided one cathode is placed in the sediment part of the SMFC [88].

DO is also a function of temperature so that it increases with decreasing temperature, leading to an increased power generation efficiency at cold seep ocean.

Figure 8. Schematic of A) an air- cathode; B) a floating cathode; C) a rotating cathode technology ;and D) biocathode

6.5. Equipment configuration

Power generation is affected by several additional factors related to SMFCs configuration. These factors include electrode spacing, water depth, depth of embedded anode, anode chamber, cathode arrangement and etc.

When the electrode spacing is increased, ohmic losses increase, decreasing the amount of current generated from SMFCs [50]. To minimize these ohmic losses, a new type of floating SMFC with a constant inter-electrode spacing can be used [51]. Increasing water and embedded anode depths also contribute to an increase in electrode spacing [105, 106], while increasing anode depth enhance the internal resistances of SMCs [107].On the other hand, at different depths of sediment, certain substrate and microorganisms are active, enhancing anode performance at greater depths [107]. Therefore, anode embedded depth should be determined locally.

A major challenge in SMFCs is anode passivation [77]. Passivation is the inhibition of the dissolution reaction caused by the formation of non-dissolving films. Anode passivation results in lost production capacity, increased power costs, and decreased cathode quality. In 2007, Nielsen *et al.* avoided this problem by a chambered SMFC design in which the anode is placed in a semi-enclosed chamber that rests securely on the seafloor (Figure. 8) [16]. By using a one-way check valve, water will solely outflow from underlying sediment into the chamber and not in opposite direction. This water is nutrient-rich and depleted of oxygen due to oxygen consumption by microbes present within the sediment [16].

According to Ohm's law, an increase in current generation should be observe by decreasing external resistance [78]. External resistance may also affect power density, so that the power density increases with external resistance. Therefore, the highest power density and produced current may not be achieved at the same external resistance; so as our ultimate goal is to determine an optimum value of external resistance.

Effect of electrode surface area ratio [50] and various electrode arrangements [30, 44, 78, 108] were also investigated in articles.

7. Scale Up

Up to now, unless by storing the energy and using it intermittently, there is no MFC (including SMFCs) capable of produce Watt-level power [109]. Power management systems (PMS) can be used to overcome low power generation issue by cyclic charging and discharging of a capacitor which converts a low potential into a high one [64]. A major component of a PMS is shown in Figure 9. In recently literatures, different PMSs have been developed for SMFCs [30, 62, 64, 65, 67, 109].

Figure 9. Major necessary components of a power management system.

It is obvious that a scalable-technology SMFC that enables Watt-level power generation will be more useful. A number of approaches to scale SMFCs up include: 1) connecting multiple MFCs in series; and 2) increasing the surface area of the electrodes equivalent to connecting multiple MFCs in parallel [110, 111],[112]. The first alternative is impossible because all the electrodes are immersed in the same solution. On the other hand, it is impossible to scale an SMFC up by increasing the surface area of the electrodes due to the resultant sharp decline in current density [109]. Indeed, the surface area needs to be increased by almost 100-fold to merely double the power output; this is clearly problematic [110]. In 2014, Ewing *et al.* made it possible to scale up SMFCs by using smaller-sized individually operated SMFCs connected to a power management system. In this system, electrodes are electrically isolated (Figure. 10).

Figure 10. Scaled-up SMFC for practical application .

8. Summary and future development

In this article, an overview was made on sediment type microbial fuel cells including issues such as new material for use in anode and cathode, sediment and overlying water properties, types of equipment configuration and etc.

It seems that fossil fuels may not supply increasing energy demand of the future, so as it is essential to find sustainable and renewable sources of energy. The results of recent studies suggest that SMFCs will be of practical use in bioenergy production and waste removal from sediments in the future. SMFCs need to provide more power output at lower costs to be considered as practically and commercially affordable. In this respect, nano-materials are examples of current research lines. However, to move this technology from laboratory trial to field application, all discussed challenges in this review need to be further considered before wide application of SMFCs can be realized. In order to further develop SMFC technology, it is suggested to evaluate energy collecting methods, develop PMS and scale-up technologies, use cost-effective materials, process monitoring and control, etc.

Until recently, most developed SMFCs were not designed for sediment remediation. For the remediation application, power output is not the major goal. In this issue, simulating sediment bioremediation, in-situ bioremediation processes, environmental, ecological and social consideration and using a moderate input of external energy (renewable energy sources) to improve bioremediation must be studied in future. Also most recent studies have been done on non-complex material in sediment/soil. So, bioremediation of complex materials in sediments should be considered hereinafter.

Further to date, most studies have been done on laboratory scale SMFCs. In near future, investigators face new challenges in transition from laboratory to aquatic environments such as: SMFCs setup installation in aquatic sediments, passivation of electrode material by electrochemical deposition, the corrosion of electrode material and connection, the SMFCs setup destruction by current flow and fish gazing and etc. On the other hand, electrode materials (such as nanomaterials which are used increasingly) and electrochemical reactions effects on surrounding environment and ecological system must be considered. Challenges in SMFCs will be overcome by the cooperation of different disciplines.

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Table1.

Instrument	Power requirement (mW)	Reference
Meteorological buoy	18	[53]
Acoustic Modem	3	[34]
Tele-communication system	300	[62]
Temperature sensor	2.2	[30]
remote sensor	2500	[67]
submersible ultrasonic receiver	15	[64]
Turbidity meter	42	[68]
Acoustic receiver	28	[68]
Wirless temperature probe	49.5	[68]

Table2.

Type of fuel	Removal efficiency (%)		Power density (mW/m^2)	References
Aquaculture water	Max COD (g/m^2d)	3.99	4.52	[70]
	Max TN (g/m^2d)	0.21		
Fresh water sediments	Phenanthrene	99.47 ± 0.15	-	[69]
	Pyrene	94.79 ± 0.63		
Waterlogged Soil	Phenol	90.01	29.45	[71]
Tidal river sludge	Carbon removal	9.6 ± 1.1	7.5 ± 0.3	[72]
Fresh water sediment	Carbon removal	29 ± 1	-	[25]
Hydrocarbon contaminated sediments	Carbon removal	24 ± 4	6.3 ±0.2	[73]
Aquaculture pond water	COD	84.4	0.241	[74]
Lake sediment	Nitrate	62	42	[75]
	Nitrite	77		
Fresh water lake	COD	95.5	86.7	[76]
Lake sediment	COD	76.2	72	[76]
River sediment	Organic matter remove	29	1000	[36]
Fresh water sediment	COD	28.3 ± 1.9	3.15 ±0.07	[43]

Table3.

Overall Classification	Partial Classification
Anode	Material Geometry Surface Modification
Cathode	Material Geometry Bio-cathode
Sediment	Sediment Organic Matter (SOM) availability Pre-treatment Conductivity pH Mass Transfer Conductivity TDS
Overlying water	Dissolved Oxygen (DO) pH Flow Pattern Temperature Nature Substrate
Equipment Configuration	Electrode Spacing Electrode Surface area ratio Water depth Anode Chamber Depth of Embedded Anode Electrode Configuration External Resistance Parallel SMFCs
Operational condition	Temperature

Table 4.

Anode Material	Anode geometry	Current density (mA/m^2)	Power density (mW/m^2)	References
Graphite	plate	3	-	51
	felt	10	-	51
	felt		33 .5 ± 1.5	42
	felt	-	45	80
	tank	3500	100	81
	rode	23.72	19.57 ± 0.35	35
	disk	5.39	8.72 ± 1.39	35
Stainless steel	grid	8200	-	50
	-	100	10	81
	plate	140	23	82
activated carbon	fiber felt		10.6	42
carbon	sponge	100	55	55
	Cloth	50	19-27.5	55
	fiber	5.0	4.5	55
	Reticulated vitreous (RVC)	0.8	0.2	55

Table 5.

Material	Modification	Power density (mW/m^2)	References
Graphite	anthraquinone-1,6-disulfonic acid (AQDS)	98	52
	1,4-naphthoquinone (NQ)	-	52
	hydroxyl and carboxyl groups	358.1	83
	Electrolytic deposition with Fe/ferric oxide	740	46
	sulfide oxidizing Sb(V)	-	59
	Oxidize	-	59
Ceramic–graphite composite	Mn^{2+} and Ni^{2+}	105	52
Graphite paste	Fe_3O_4 and Ni^{2+}	-	52
	Fe_3O_4	-	52
	sulfonated polyaniline powder with a PTFE solution	129.1	48
	Sulfonated polyaniline/vanadate composite powder with a PTFE solution	187.1	48
Glassy carbon	anthraquinone-1,6-disulfonic acid (AQDS)	-	59
	sulfide oxidizing Sb(V)	-	59
	oxidize	-	59

Table 6.

Cathode Material	Cathode geometry	Current density (mA/m^2)	Power density (mW/m^2)	References
graphite	felt	-	23.6	42
	disk		7	85
	Thick felt (porous)	45.4	2.00 ± 0.11	49
	Thin felt (porous)	37.6	2.00 ± 0.11	49
	Plate (non-porous)	13.9	1.25± 0.15	49
stainless steel	plate	140	23	82
Activated carbon	round	-	1.0	44
	granule	-	3.5	44
Carbon	Cloth	80	55	85
	Paper		0.2	85
	reticulated vitreous (RVC)		12	85
	sponge		38	85
	Nanotube[#]		38	86
Co- TMPP *	-		32	85
Fe–Co TMPP	-	160	62	85
platinised carbon (Pt/C)	-		8	85
PANI-GNS**	Nano sheet	479.8	99	84

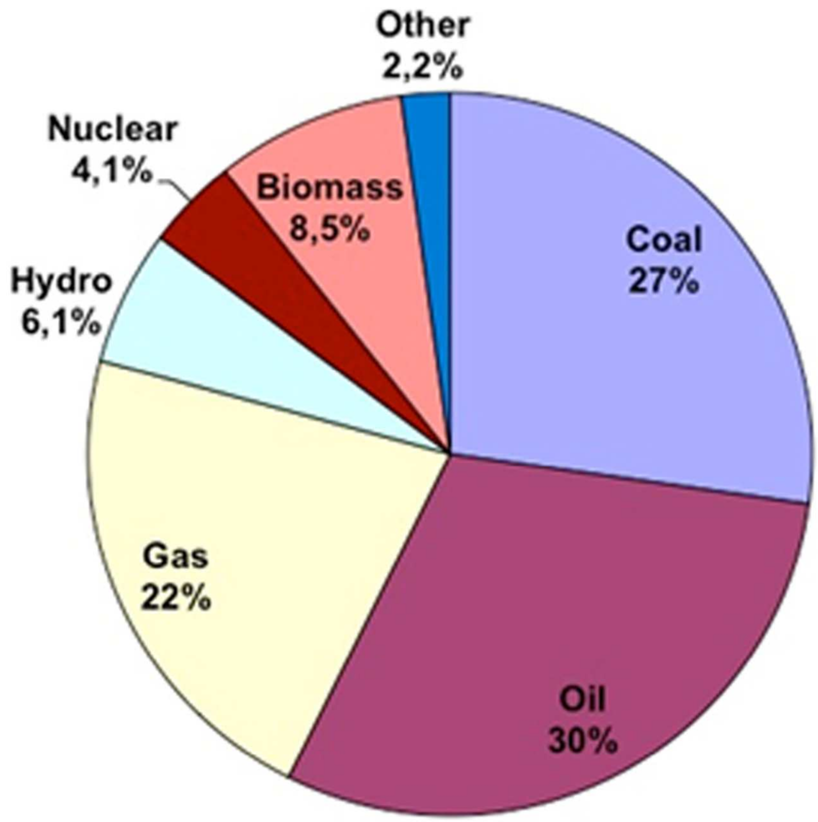
[#] algae-assisted cathode
*** tetramethoxyphenyl porphyrin**
**** Polyaniline graphene nanosheets**

Table 7.

Used Plant	Power density (mW/m^2)	Current density (mA/m^2)	References
Rice paddy field	6	-	[93]
Spartina anglica at roof top	88	-	[91]
Duckweed (*Lemna minuta*)	380 ± 19	1620 ± 100	[94]
Duckweed (*Lemna valdiviana*)	-	226 ±11	[92]
rice paddy rhizosphere	1.3	-	[88]
Glyceria maxima	12	-	[95]
grass species *Spartina anglica*	679	2080	[87]
Spartina anglica	21	31	[96]
Arundinella anomala	10	39	[96]
Arundo donax	not stable electricity production	-	[96]

Table 8.

DO increasing method	References
Rotating Cathode	[31, 100]
Floating Cathode	[36, 61]
Air Cathode	[66, 73, 101, 102]
Cold Seep Sediments	[54, 103]
Algae assisted cathode	[86]
Plant rhizosphere	[88]
Bio cathode	[8, 104]



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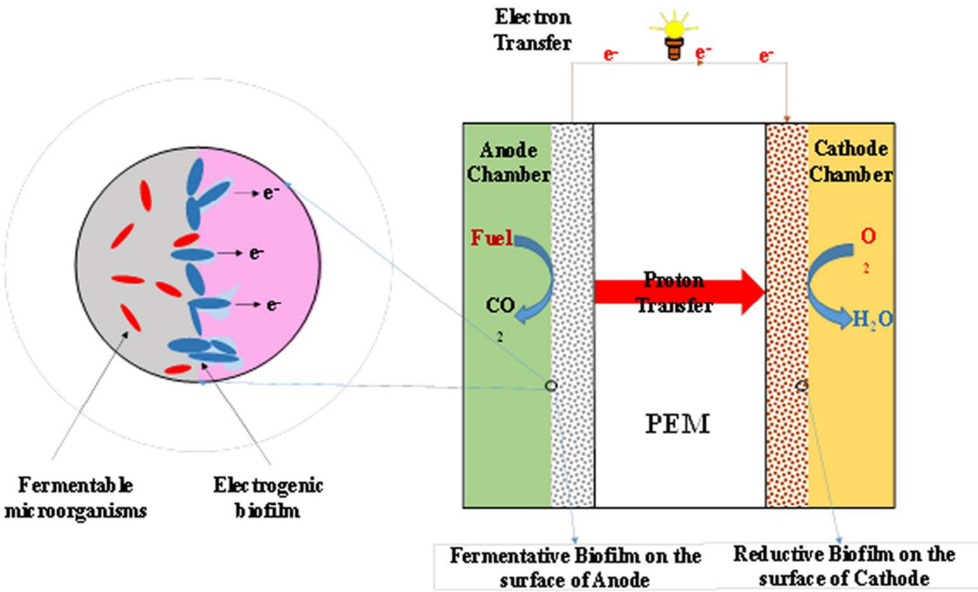

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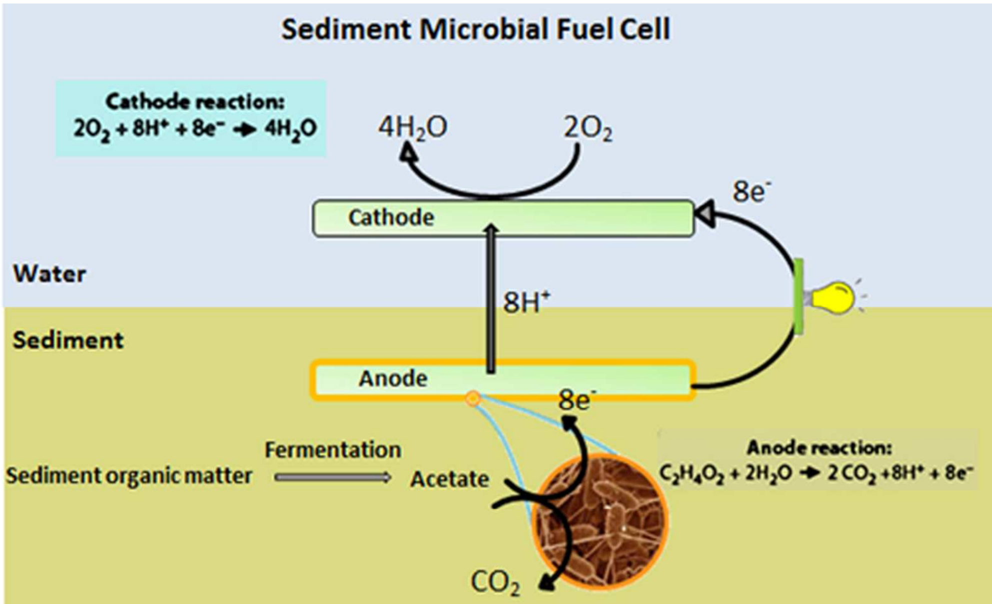

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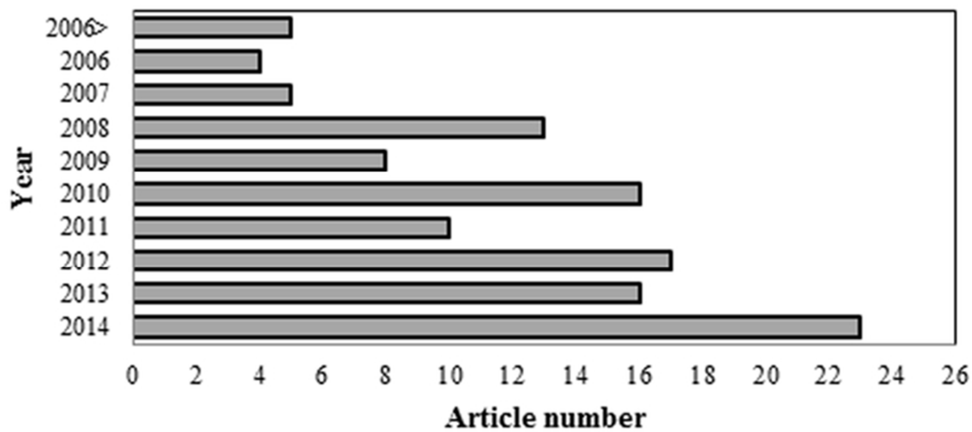

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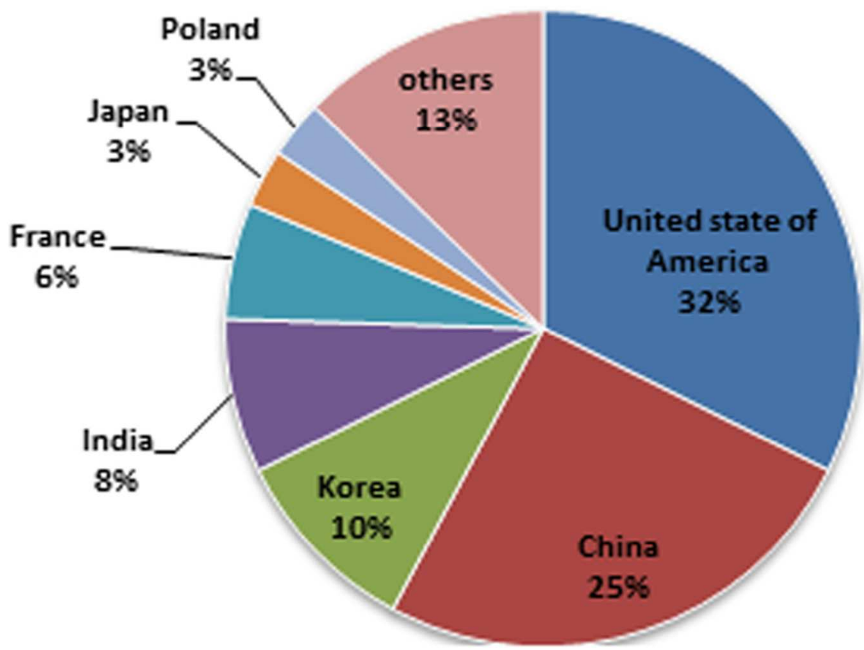

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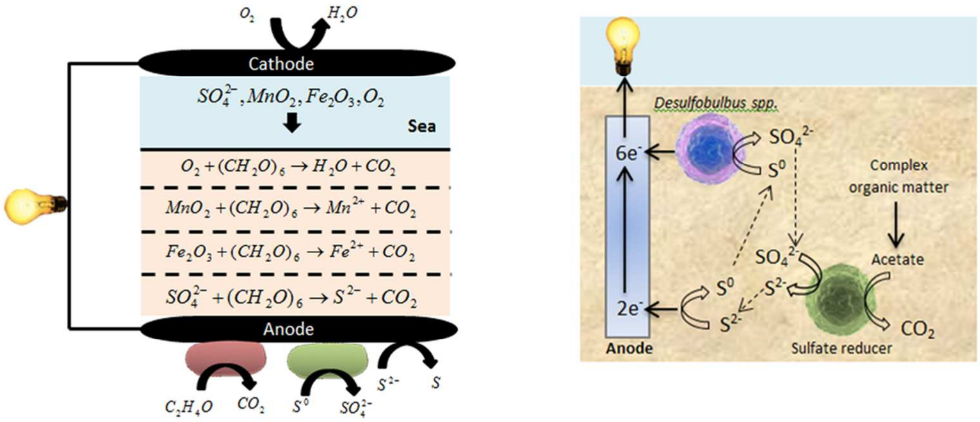

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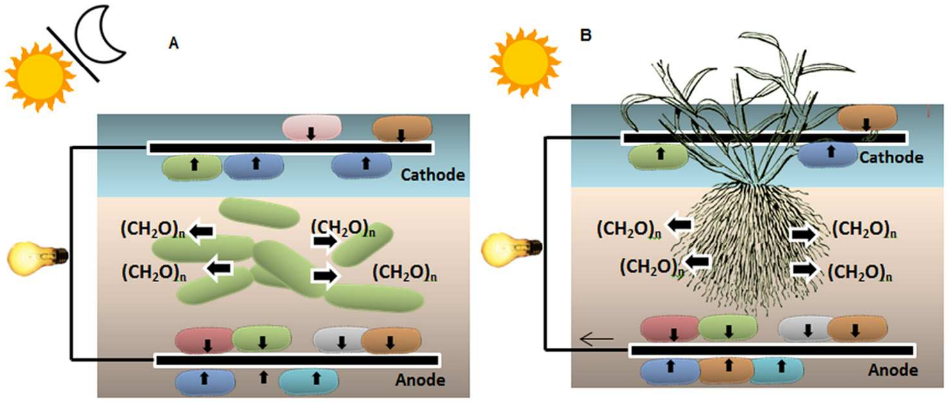

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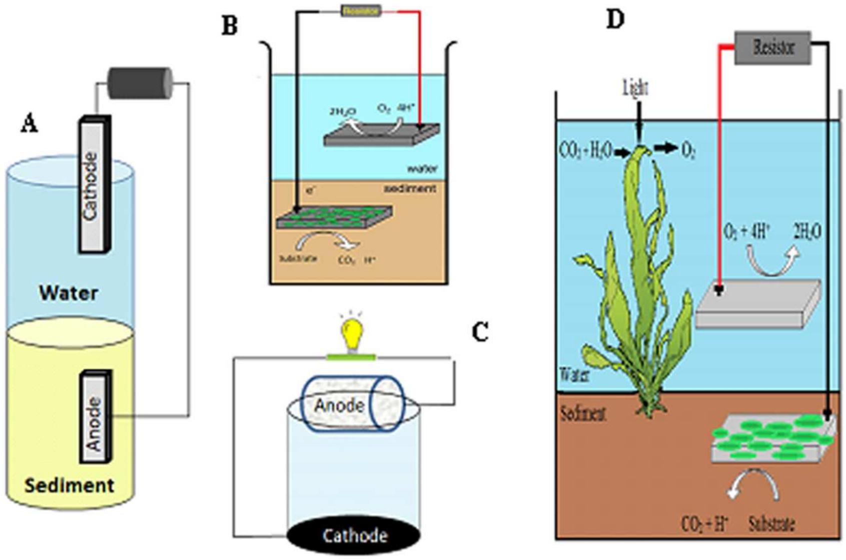

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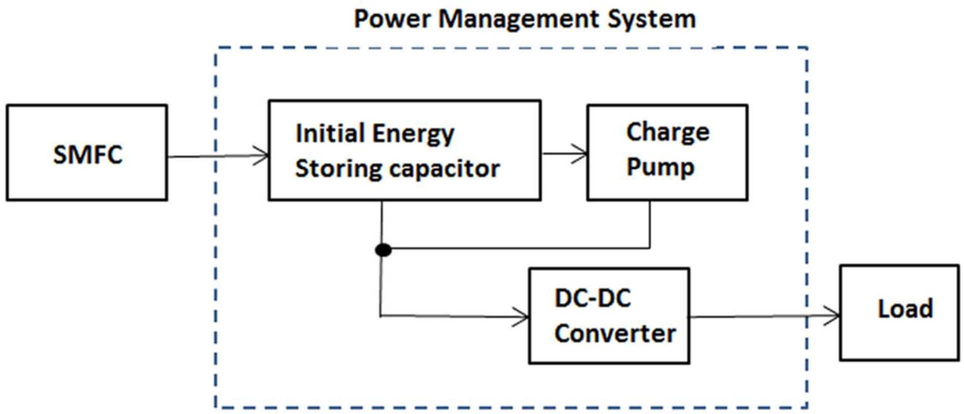

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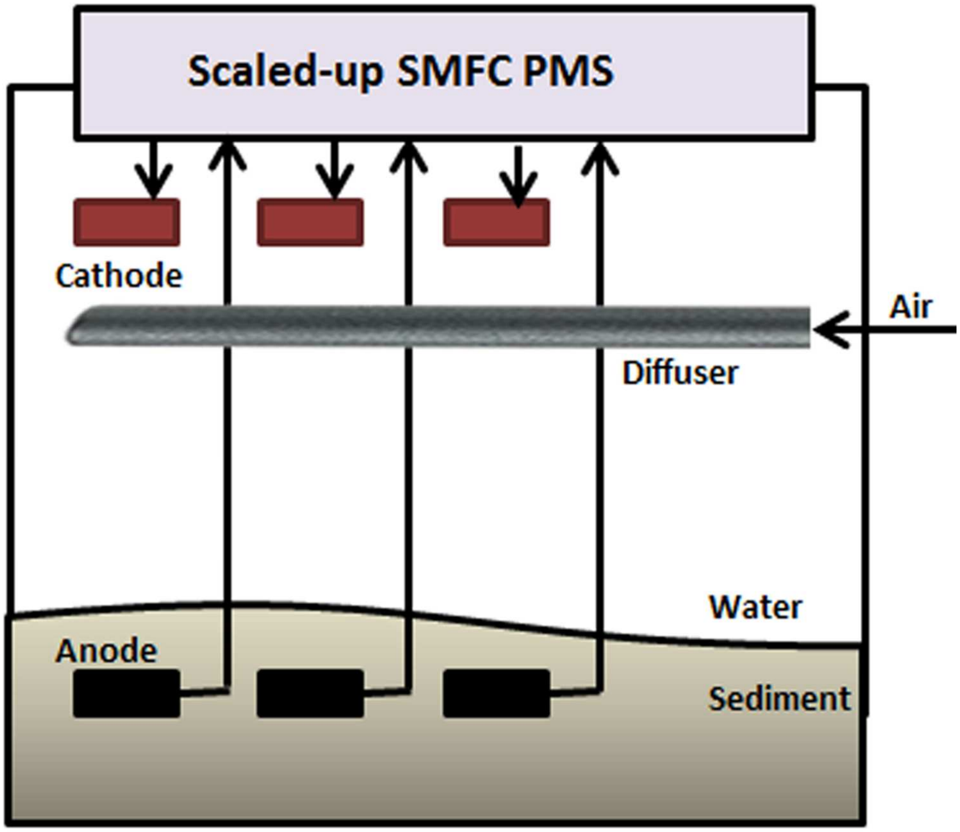

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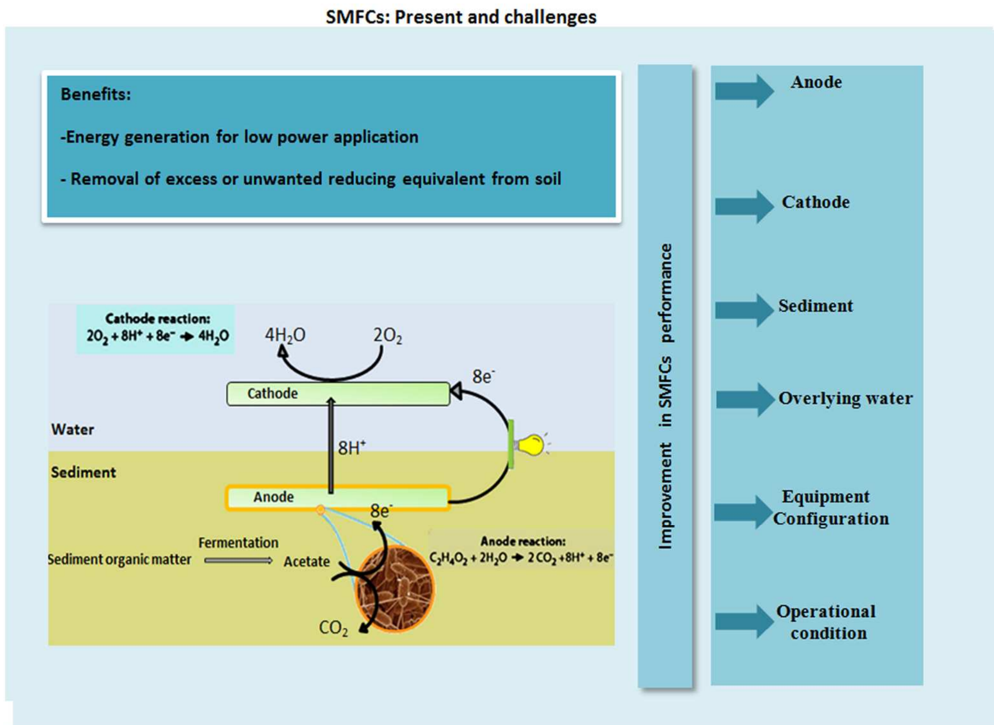

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