C-2

Journal of Environmental Management 277 (2021) 111417

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Review

Waste valorization using solid-phase microbial fuel cells (SMFCs): Recent trends and status

Mochamad Arief Budihardjo[a,*], Syafrudin[a], Agus Jatnika Effendi[b], Syarif Hidayat[b], Candra Purnawan[c], Ayudya Izzati Dyah Lantasi[d], Fadel Iqbal Muhammad[e], Bimastyaji Surya Ramadan[a]

[a] *Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, 50277, Indonesia*
[b] *Department of Environmental Engineering, Faculty of Environmental and Civil Engineering, Institut Teknologi Bandung, Bandung, 40132, Indonesia*
[c] *Department of Chemical Sciences, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, 57126, Indonesia*
[d] *Master of Environmental Sciences, School of Postgraduate Studies, Universitas Diponegoro, Semarang, 50241, Indonesia*
[e] *Master of Environmental Sciences, Wageningen University and Research, Wageningen, 6708, GA, the Netherlands*

ARTICLE INFO

Keywords:
Anaerobic digestion
Compost
Mass transfer
Microbial fuel cells
Solid-phase

ABSTRACT

This review article discusses the use of solid waste processed in solid-phase microbial fuel cells (SMFCs) as a source of electrical energy. Microbial Fuel Cells (MFCs) are typically operated in the liquid phase because the ion transfer process is efficient in liquid media. Nevertheless, some researchers have considered the potential for MFCs in solid phases (particularly for treating solid waste). This has promise if several important factors are optimized, such as the type and amount of substrate, microorganism community, system configuration, and type and number of electrodes, which increases the amount of electricity generated. The critical factor that affects the SMFC performance is the efficiency of electron and proton transfer through solid media. However, this limitation may be overcome by electrode system enhancements and regular substrate mixing. The integration of SMFCs with other conventional solid waste treatments could be used to produce sustainable green energy. Although SMFCs produce relatively small amounts of energy compared with other waste-to-energy treatments, SMFCs are still promising to achieve zero-emission treatment. Therefore, this article addresses the challenges and fills the gaps in SMFC research and development.

1. Introduction

The increase of municipal solid waste generation is an issue faced by nearly all countries, due to the expansion of industrial activities and global development. In developing countries, almost 90% of municipal waste is transported directly to landfills without any intermediate treatment that could reduce the solid waste volume (Barik and Paul, 2017). This waste management activity contributes 5% to the total global greenhouse gas emissions. Recycling, effective waste treatment, and source-segregation are the primary strategies to reduce emissions and environmental impacts due to increased waste generation (Florio et al., 2019). Waste is considered to have a relatively large energy content such that waste-to-energy is considered a viable alternative (Chiu et al., 2016). Composting and anaerobic digestion are biological treatment technologies that have been used and explored extensively in various countries (Yu et al., 2015; Xin et al., 2018). However, conventional composting under aerobic conditions requires more energy for mixing and an air supply, which could produce vast amounts of leachate (Chu et al., 2019). Anaerobic composting, which is commonly known as anaerobic digestion, can be an alternative solution to convert solid waste into reusable energy and biofuel (Khudzari et al., 2016). Recent research has shown that anaerobic digestion has many constraints, such as a long residence time, a low purification of biomethane and its conversion to electricity, and a variety of safety issues, which makes this technology an imperfect solution for zero-discharge treatment (Xin et al., 2018).

Recently, microbial fuel cells (MFCs) were found to be an alternative treatment to generate electricity from waste (waste valorization) without intermediate treatment steps because anaerobic digestion

---

* Corresponding author.
E-mail addresses: m.budihardjo@ft.undip.ac.id (M.A. Budihardjo), syafrudin@lecturer.undip.ac.id (Syafrudin), jatnika@indo.net.id (A.J. Effendi), shidayat@tl.itb.ac.id (S. Hidayat), candra_pr@staff.uns.ac.id (C. Purnawan), ayudyaizzati@students.undip.ac.id (A.I.D. Lantasi), fadel.muhammad@wur.nl (F.I. Muhammad), bimastyaji@live.undip.ac.id (B.S. Ramadan).

https://doi.org/10.1016/j.jenvman.2020.111417
Received 28 November 2019; Received in revised form 28 August 2020; Accepted 18 September 2020

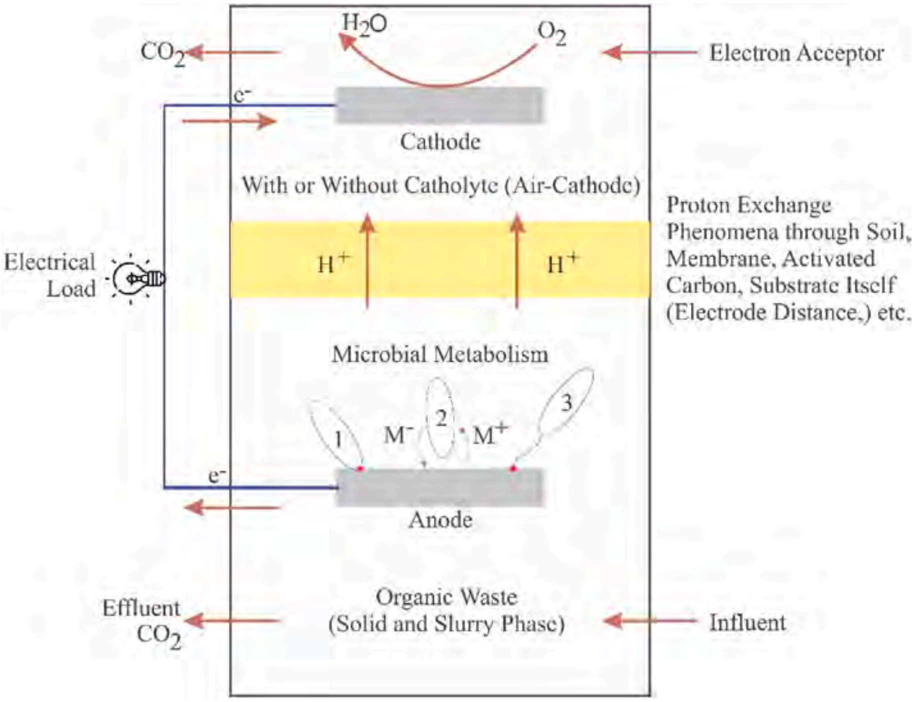

Fig. 1. Schematic illustration of the SMFC process (Modified from Nastro et al., 2017 and Logroño et al., 2015).

utilizes electrogenic (anodophilic) microorganisms (Xin et al., 2018). The bioelectric energy of MFCs depends on the electron transfer process and biodegradation efficiency of solid waste (Song et al., 2015). Many researchers use the term solid-phase MFCs (SMFCs/SPMFCs) for MFCs that convert solid waste into electricity (Logrono et al., 2015; Wang et al., 2015; Mohan and Chandrasekhar, 2011); however, some researchers use the terms compost MFCs (cMFCs) (Khudzari et al., 2016) or biogas slurry MFCs (BSMFCs) (Wang et al., 2019a). Solid-phase microbial fuel cells (SMFCs) are one of the developments in MFC technologies that can be applied to solid waste. These are claimed to accelerate the anaerobic waste degradation process, directly harvest electrical energy, and produce mature compost from organic compounds (Choudhury et al., 2017; Moqsud et al., 2013; Moqsud et al., 2015; Pandey et al., 2016; Santoro et al., 2017). SMFCs are profitable because they only require low-cost materials (Du et al., 2007; He et al., 2017). Moreover, their capability to generate electricity makes them a direct alternative source for renewable energy, which has attracted considerable attention from researchers (Do et al., 2018; Escapa et al., 2016; Xia et al., 2018). In addition, solid waste makes SMFCs an alternative method to overcome the problem of solid waste treatment because it uses the solid waste as a substrate to provide an environmentally friendly and sustainable source of electricity (Gude, 2016; Yasri et al., 2019). Therefore, SMFCs are considered capable of addressing multi-sectoral problems as they can be integrated with other processing waste treatments, such as aerobic composting or anaerobic digestion (Kadier et al., 2016; Logan, 2009; Trapero et al., 2017; Utomo et al., 2017).

Over the last five years (2016–2020), 2499 review articles, 1193 book chapters, and 1513 research articles relating to the utilization of MFCs in various treatments have been published based on sciencedirect.com (beyond other scholarly databases). However, there are limited articles about the use of SMFCs for comprehensive solid waste management. Rahimnejad et al. (2015) explained the application of MFCs to anode-cathode processes; proton transfer processes through cation exchange, anion exchange, or bipolar membranes; the production of biohydrogen, bioelectricity, and biosensors; and wastewater treatment. Information concerning advanced developments in the use and manufacturing process of electrodes and MFC membranes was discussed by Palanisamy et al. (2019). Meanwhile, Zhang et al. (2016) and Khudzari et al. (2016) used bibliometric methods to measure the extent of global research trends, explicit research, and developments regarding MFCs based on the Scopus and Web of Sciences databases or in several specific journals, which are the main platforms of MFC progress reporting. However, to the authors' knowledge, there has not any article summarizing, discussing, or providing detailed descriptions of the development of SMFCs for treating solid waste. The factors that influence the performance optimization of SMFC reactors, as mentioned before, need to be further investigated through various in-depth and comprehensive studies. This review article was written to better understand and analyze the technological basis of SMFCs and their influential factors. In addition, potential obstacles are considered that may be encountered in the future with further development toward industrial commercialization. The results of recent studies on the performance optimization of SMFCs, their possible integration and comparison with other technologies, and the various improvements needed to enhance the results of electricity generation using SMFCs are collated throughout this article.

2. Fundamental process of an SMFC

An SMFC is a technology used to generate eco-friendly electricity from biomass by utilizing microorganisms (Garita-Meza et al., 2018; Mäkinen et al., 2013; Pushkar and Mungray, 2016). SMFCs employ the bioelectrogenesis capability of microorganisms to utilize organic compounds as electron acceptors to generate energy. This system directly harvests the energy generated from the microorganisms without the need for combustion (Calignano et al., 2015; Minutillo et al., 2018; Nastro et al., 2017). In general, the configuration of SMFC systems consists of two chambers: a cathode and an anode, which are separated with specified membranes. The cathode is a chamber full of oxygen where protons collect to form water molecules (Logroño et al., 2016a; Moqsud et al., 2013). The two electrode chambers are separated by a mediating membrane that allows protons to pass from the anode and transferring electrons between the two electrodes while inhibiting the entry of oxygen into the anode. However, some SMFCs do not use membranes and rely only on the distance between electrodes (Logroño

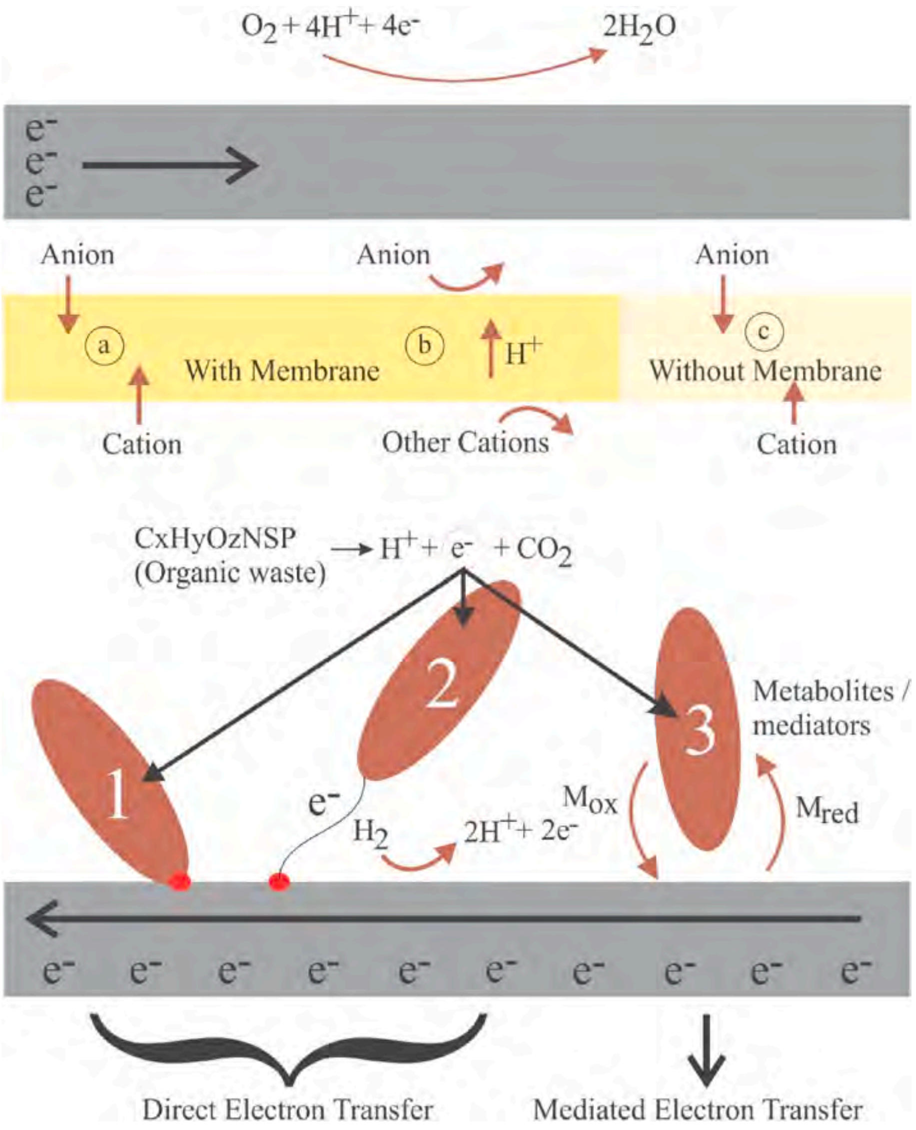

Fig. 2. Working mechanism of the electrodes and separator in SMFCs (modified from Mohan et al., 2014).

et al., 2016a, 2016b; Mohan and Chandrasekhar, 2011). Fig. 1 illustrates the general processes that occur in SMFCs.

Chemical energy present in organic waste will be oxidized by microorganisms in the anode chamber. Microorganisms extract the energy needed to build biomass through the metabolic process (Palanisamy et al., 2019). The effectiveness of the SMFC reactors is influenced by several factors, such as the oxygen supply and consumption in the cathode chamber, oxidation of the substrate in the anode chamber, electron transfer from the anode chamber to the anode surface, and the proton exchange membrane (PEM) permeability (Rahimnejad et al., 2015; Sharma and Li, 2010). In other cases, circuit connections are important as they increase the voltage output to 344.11% times more than a single reactor (Utomo et al., 2017).

2.1. Process in the anode

The anode chamber is an important component of SMFCs. Microorganisms that play a role in substrate degradation and electron production attach to the electrodes in the anode chamber, which occurs at the anode under anaerobic conditions. The presence of oxygen in the anode chamber inhibits the generation of electricity by the microorganisms. In addition, there are also substrates and mediators in the anode chamber. The general reactions that occur at the anode are as expressed in Equation (1).

$$\textit{Biodegradable organics} \xrightarrow[\text{Anaerobic environment}]{\text{Active microorganism}} CO_2 + H^+ + e^- \tag{1}$$

The microorganisms present in the anode act as catalysts that break the substrate into simpler molecules. This active biocatalyst oxidizes the substrate and produces electrons and protons. The resulting protons are transmitted to the cathode via the PEM, whereas the electrons are transmitted along the external path (Antonopoulou et al., 2010; Du et al., 2007; Ghasemi et al., 2013; Rahimnejad et al., 2011, 2015).

Modifications to the anode material influence the performance of the SMFC reactors. Previous studies have shown that the use of different electrode materials at the anode generates various amounts of electrical energy, which affects the overall performance of the SMFC reactor. Widely used materials include different forms of graphite carbon, including a fiber brush, cloth, rod, paper, and felt because they each have a high conductivity and large surface area (Quezada et al., 2010; Ghasemi et al., 2013; Sharma and Li, 2010; Xin et al., 2019).

2.2. Processes in the cathode

The cathode and anode chambers in the MFC work continuously to

Table 1
Recent studies related to improvements in MFC performances when treating wastes.

Substrate	Electrode		Separator	Bacteria	Operating Phase	System Configuration	Maximum Power Density	References
	Anode	Cathode						
Household food waste (glucose) hydrolysate	Graphite granules	MnO_2	Nd	Mixed anaerobic microbial culture	Liquid	Single chamber	11,800 mW/m^3 per anode working volume	Antonopoulou et al. (2019)
Organic fraction of municipal waste	Graphite plates	Graphite plates	Membraneless	*Lactobacillaceae*, *Bacillaceae*, *Clostridia*, and *Pseudomonadaceae*, with *Pseudomonas aeruginosa*	Solid	Single chamber	1.75 mW/m^2 per anode specific surface area	Florio et al. (2019)
Food waste hydrolysate	Carbon brush	Plain carbon cloth	Nd	*Moheibacter*, *Azospirillum*, *Geobacter*, *Petrimonas*, *Alicycliphilus*, *Rhodococcus*, *Pseudomonas*	Liquid	Single chamber	173 mW/m^2 per total working surface area	Xin et al. (2018)
Vegetable and fruit residues	Carbon fiber	Ceramic disk	Nd	Nd	Solid	Single chamber	Nd	Nastro et al. (2017)
Municipal solid waste	Carbon felt, stainless steel, carbon paper, and carbon plate		Oxygen and $K_3Fe(CN)_6$	Nd	Solid	Dual chamber	1817 mW/m^2 per anode specific surface area	Chiu et al. (2016)
Mix of apples, lettuce, green beans, and soil (potting mix)	Carbon felt	MnO_2	Nd	*Gammaproteobacteria* and *Bacilli*	Solid	Single chamber	5.29 mW/m^2 per anode specific surface area	Khudzari et al. (2016)
Dewatered sludge	Graphite fiber	Titanium wire	PEM (Nafion 117, Dupont Company)	Electricigens, the common fermentation bacterial colonies	Solid	Dual chamber	5600 mW/m^3 per anode working volume	Yu et al. (2015)
Kitchen and yard wastes	Carbon fiber	Carbon fiber	Nd		Solid	Single chamber	39.2 mW/m^2 per anode specific surface area	Moqsud et al. (2015)
Vegetable and fruit wastes	Carbon fiber		Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	Nd	Logroño et al. (2015)
Rice husks, soybean residue, coffee residue, and leaf mold	Carbon felt		Nd	Nd	Solid	Single chamber	4.6 mW/m^2 per anode specific surface area	Wang et al. (2015)
Wastes from compost facility	Tin-coated copper mesh	Coil spring	Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	47.6 mW/m^2 per anode specific surface area	Karluvalı et al. (2015)
Kitchen garbage and bamboo waste (glucose)	Carbon fiber	Carbon fiber	Soil-activated carbon	Mixed anaerobic microbial culture	Solid	Single chamber	60 mW/m^2 per anode specific surface area	Moqsud et al. (2014)
Food waste hydrolysate	Brushes	Carbon cloth	Nd	Mixed anaerobic microbial culture	Liquid	Single chamber	~556 mW/m^2 per anode specific surface area	Jia et al. (2013)
Grass cuttings, leaf mold, rice bran, oil cake, and chicken droppings	Carbon fiber	Carbon fiber	Filter paper, cellophane, and PEM	Nd	Solid	Dual chamber	394 mW/m^2 per cathode specific surface area	Moqsud et al. (2013)
Sewage sludge	Carbon felt and rod	Carbon felt and rod	Proton exchange membrane	Mixed anaerobic microbial culture	Solid	Single chamber	38.1 W/m^3 per anode working volume	Wang et al. (2013b)
Rice hull, bean residue, and ground coffee wastes	Carbon felt	Carbon felt	Nd	Nd	Solid	Single chamber	264.7 mW/m^2 per anode specific surface area	Wang et al. (2013a)

Nd: Not defined.

generate electrical energy. Protons move from the anode chamber to the cathode chamber through the PEM, which refines the electric current.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{2}$$

Radical oxygen produced in the anode chamber (Equation (2)) moves to the cathode chamber to form water that spreads on the cathode with the help of a catalyst. Equilibrium can be reached based on Equation (2) by connecting the cathode and the anode with external cable connectors. The MFC performance on the cathode is different from that on the anode. The concentration and type of electron receiver, availability of protons, performance of the catalyst, electrode structure, and capability of the catalyst all affect the cathode performance. The availability, strong oxidation potential, and nontoxic end products of oxygen make it a suitable electron acceptor for the cathode chamber. Some cathodes are configured by placing one side of the cathode in direct contact with the cathode chamber while the other side is in direct contact with free air.

2.3. Process in separator or membrane

SMFCs consist of an anode and a cathode chamber separated by a cationic membrane, a porous ceramic clayware membrane (Yousefi et al., 2017), and electrode distancing (configured placement of electrodes) (Moqsud et al., 2015) (See Fig. 2). Biopotential that occurs due to metabolic activity of the microorganisms and the condition of electron acceptors can induce bioelectricity in SMFCs. The PEM or other separators in SMFCs (which not only physically separate the cathode and anode chambers but also prevent the transfer of dissolved oxygen contained in the cathode chamber to the anode chamber) maintain the anaerobic conditions in the anode chamber (Ghasemi et al., 2013). The separators can facilitate the transfer of protons produced in the anode chamber without the transfer of the substrate or oxygen to the cathode chamber. When the membrane is not applied in SMFCs, the displacement of the oxygen and substrate can result in a decreased Coulombic efficiency (CE) and microorganism activity, which dramatically affects the system performance and stability. The cost of cationic membrane has shifted attention to alternative separators. Porous clays, such as novel porous clay earthenware (NCE), could produce higher power outputs compared to the use of PEM as a separator (Daud et al., 2020). Porous clay with a larger thickness generates less power in the SMFCs. Thickness differences can change the hydraulic pressure and transportation of fluid through the SMFC system. The flow of ions will also be slower with thicker clay membranes (Jimenez et al., 2017).

3. Factors affecting the SMFC performance

Electricity generated by SMFCs is influenced by various factors, such as the electrode material, type of membrane, salinity, alkalinity, type of waste, and composting factors such as the pH and C/N ratio. Moqsud et al. (2013) stated that SMFCs with a good performance have a low internal resistance and a high electromotive force. Table 1 shows some of the optimizations made to increase the amount of electricity generated by SMFCs.

3.1. Substrate

Substrates or materials used as organic sources for SMFCs can use various types of wastes that contain high organic matter, such as kitchen and bamboo. The voltage generated by kitchen waste increases rapidly in the initial phase and gradually stabilizes to a voltage of 620 mV. Conversely, in bamboo waste, the generated voltage gradually increases to 540 mV. This finding is expected because some fruits in kitchen waste contain significant amounts of glucose. Adequate supplies of glucose activate bacteria and produce a higher voltage (Moqsud et al., 2014). Utomo et al. (2017) used sludge from a communal waste treatment plant of different ages. They observed that the stress generated at the anode with fresh sludge material is a higher value than that with stored sludge material. Xin et al. (2019) determined the effects of complex compounds (glucose, sodium acetate, and food waste hydrolysate) used in MFCs when producing electrical energy. The electrical density produced by MFC reactors with food waste hydrolysate as a substrate was higher than with glucose and sodium acetate. Wang et al. (2013a) obtained higher power outputs using different substrates. With an adequate supply of glucose, complex substrates rich in monosaccharides, organic acids, and other micro-molecules can be used directly as the SMFC substrates so that bacteria become more active and generate higher stresses (Pant et al., 2010; Wang et al., 2019a). Similar results were obtained by Jia et al. (2013) and Li et al. (2018), where SMFCs produces a larger amount of energy with substrates of mixed carbon rather than a single carbon type.

Biogas slurries have also been used as a substrate for MFCs (BS-MFC). Biogas slurry as waste from biogas technologies has been widely applied and is considered to cause new problems. Biogas slurry is rich in monosaccharides, organic acids, and other micro-molecules that can be directly utilized as MFC substrates (Pant et al., 2010; Wang et al., 2019a). Wang et al. (2019a) found that microbial acclimation was achieved on the 10th day at 150.4 ± 14.6 mV. The second cycle, which was conducted by adding substrates, showed a voltage of 622.7 ± 30.3 mV on the 20th day. This indicates that biofilms were formed at the anode. The accumulation of electrical voltage in these three cycles reaches its maximum value and is stable for a sufficiently long period. However, the BS-MFC hydrolysis reaction and the long operational period lead to high energy demand levels and a lower average CE production of 4.1% (Wang et al., 2019a).

Rice husk, soybean residue, coffee residue, and leaves have also been used as substrates. The choice of substrate is based on the nature of each substrate as those rich in cellulose and biopolymers are ideal sources of organic matter. Rice husk can increase the hydraulic conductivity and porosity of SMFC reactors. Therefore, the substrate composition can affect the community of microorganisms that grow at the anode as well as the electrical energy output (Wang et al., 2015). The addition of bio-enzymes to the substrate increases the power density by a factor of up to 8.5 and can decrease the internal resistance by 31% (Wang et al., 2013b, 2015). SMFCs that use solid waste tend to have higher levels of chemical oxygen demand (COD). A study conducted by Samudro et al. (2018) determined that leaf waste, which had a COD of 16.567 mg COD/L, had a higher COD removal efficiency of up to 87.67% and a more stable power density of 4.71 mW/m^2 compared with canteen and mixed wastes. However, in this study, high levels of COD do not lead to a high COD removal efficiency or high-power density output. Thus, there is some optimum COD level that leads to high power densities.

The greatest limitation of microbial processes in solid phase ecosystems is the substrate/mass transfer rate (Rahimnejad et al., 2011). Transfer resistance is higher when the absence of a sufficient solution to homogenize the distribution of the substrate to microorganisms or electrons to the electrode. Reducing the electrode distance may increase the rate of electron transfer, but some other problems occur in this case, such as an increased oxygen penetration and active surface electrode. which leads to a decreased power output (Sharma and Li, 2010). The water content is the other critical point when working with SMFCs. Ideally, a 60% distributed moisture will allow the process to occur in good conditions (Wang et al., 2015). As many SMFC reactors operate in the gravitational direction for electrodes, the anode chamber is flooded and exceeds 60% of the moisture content soon after the process begins. The use of Xanthan 80 SF can significantly improve the performance of the SMFC reactor because it naturally maintains moisture in the compost and reduces the effects of gravity so that water does not accumulate at the bottom of the reactor. Therefore, the cathode chamber will dry and decrease the proton transfer rate, which causes a lower power production. In this case, a drainage and circulation system may be useful to maintain the power production. This is expected because the moisture in the compost is reduced, which inhibits the compost decomposition process and decreases its microbial activity. This inhibits ion transfer and energy production. These results indicate that the use of Xanthan 80 SF can increase the amount of electricity generated and extend the period of electrical energy release (Wang et al., 2017; Samudro et al., 2018). Li et al. (2019) tried solving the transfer rate problem using biochar amendment in soil, which has a limited water content. Biochar could increase the electron transfer rate and kinetics because of the presence of an electroactive surface. The addition of biochar can also support microbial colonization and increase the rate of biodegradation. Therefore, knowing the optimal biochar mass is important as biochar may decrease the electrical conductivity due to its ability to adsorb ions in soils.

3.2. Environmental factors

In addition to the type of organic solid waste used, the degree of alkalinity (Moqsud et al., 2013) and the amount of waste used as a substrate also determine the generated electrical energy (Samudro et al., 2018). Large amounts of waste can provide substrates and nutrients for microorganisms that will increase the specific energy. The addition of alkaline materials can also increase the electrical power output from SMFCs. The addition of fly ash, for example, produces a maximum electric power per cathode surface area of 54.4 mW/m^2, which is two times greater than that of SMFCs without fly ash (Moqsud et al., 2013).

The pH plays a vital role in maintaining the performance of solid-phase microbial fuel cells. The pH can activate several reactions and affect the microorganism performance in consuming substrates to produce bioelectricity (Jadhav and Ghangrekar, 2009). Higher electricity production can occur in a neutral pH range because of exoelectrogens, like the neutral environmental conditions (He et al., 2009). A low pH is likely in the anode chamber and can cause soluble metals to precipitate, which covers the cathode layer and inhibits the transfer of electrons to the cathode and protons to the membrane/separator (Makinen et al., 2013). An increase (decrease) of the pH in the cathode (anode) chamber or pH splitting can occur when a separator or PEM in the SMFC is available. This may occur as the membrane/separator cannot effectively transfer protons to the cathode chamber and electrons to the electrode (Rahimnejad et al., 2015). The greatest SMFC issue is mass transfer, including the transfer of protons and electrons in a solid-state system (Chiu et al., 2016). Mixing is essential to ensure uniformity of the mass transfer, which prevents pH splitting between the anode and cathode chambers (Nastro et al., 2017).

Another composting factor that may affect the reactor performance is the water content in the SMFC material. The power density produced by the SMFC reactor is measured as being high in the substrate, which has a high water content. The maximum measured power density is 17.74 mW/m^2 with a water content of 60%, four times the mixing frequency, and a C/N ratio of 30:1. The water content range that allows the reactor to operate at its optimum is 40–60%. Another study showed that the ideal water content for SMFCs was 60%, while a water content of 40% inhibits the fermentation process and microorganism activity (Wang et al., 2013a, 2017). Before the research was conducted, the macro- and micronutrient content, C/N ratio, and water content were determined to ensure that the electrical energy generation and compost creation are optimal (Ganjar et al., 2018; Wang et al., 2015). The C/N ratio of 31:1, water content of 60%, and pH of 6–8 ensure optimal performance, indicating that SMFCs can be integrated into the composting process.

3.3. Electrode and system configuration

A study conducted by Moqsud et al. (2013) used bamboo charcoal with iron wire as the anode material and produced the highest electrical voltage compared with carbon fiber alone or carbon fiber with iron wire. The electrical voltage generated in the reactor with bamboo charcoal electrodes with iron wire reached 420 mV, whereas that in the reactor with carbon fiber and iron wire reached 260 mV after 3 days. Their study showed that the addition of iron wire slightly increases the electrical voltage. A maximum power density of 394 mW/m^2 was achieved in reactors with carbon fiber electrode material. This is higher than that achieved in reactors with bamboo charcoal, which has only reached 8 mW/m^2 (Moqsud et al., 2013). This can be attributed to the fact that the contact biomass with electrodes is higher in carbon fiber than that in bamboo charcoal. Although bamboo charcoal is inexpensive and environmentally friendly, it is not as often recommended for use as a cathode material because its wavy shape causes low biomass contact. In addition, the performance of MFCs in generating electrical energy is improved if the surface area of the electrodes is increased with respect to the reactor volume (Nastro et al., 2017). In another study, a double anode with graphene material was used because it is considered to have a larger surface area than carbon graphite (Samudro et al., 2018). Meanwhile, carbon felt was used as an electrode because it is porous and has a large surface area, which is suitable for microorganism growth, adhesion, and a reduced impedance activation (Kim et al., 2011).

Various studies have been conducted to determine the type of separator that supports the optimization of the SMFC reactor in terms of the generated electrical energy (Li et al., 2018; Mohan and Chandrasekhar, 2011; Wang et al., 2015). Moqsud et al. (2013) stated that the voltage generated by SMFC reactors with a cellophane separator has the highest electrical output compared with SMFC reactors with filter paper and PEM. Cellophane is considered to have a lower electrical resistance than filter paper and PEM. The dry surface of PEM is considered to be the cause of its higher resistance compared with cellophane and filter paper. Filter paper is considered to be more permeable than PEM and cellophane. Meanwhile, cellophane is more easily damaged; thus, its quality is low and it cannot be reused. In another study, a single-chamber reactor was used that did not require a membrane or other separator material (Moqsud et al., 2014). However, it is known that the application of PEM can increase the internal resistance. Thus, various studies have considered different reactor configurations to suppress the MFC internal resistance, such as single-chamber MFCs, up-flow MFCs, and stacked MFCs (Rahimnejad et al., 2011, 2012, 2015).

The distance between electrodes in a single-chamber SMFC can also affect the generated electrical energy (Miran et al., 2016; Oh et al., 2010; Mohan et al., 2010). Sandwiched electrodes produce the lowest electrical power output compared to a system that has a non-zero distance between electrodes. A shorter distance between electrodes (assuming the electrode is located in the middle of the reactor) could produce more electricity because the active surface area ensures a greater electrical gradient as the protons can more easily move to the cathode (Mohan and Chandrasekhar, 2011). Therefore, the distance between electrodes can significantly reduce the generated electricity as the protons need to move further towards the cathode. This means that determining the optimal distance is essential when working with single-chamber SMFCs. Even though the distance between electrodes must be kept small, sandwiched electrodes and PEM can increase the likelihood of substrate transfer from the anode to the cathode and oxygen transfer from air to the cathode (Hassan et al., 2014; Palanisamy et al., 2019; Peighambardoust et al., 2010).

3.4. Microorganisms

Microorganisms involved in the electricity generation process are also considered an important factor to improve the reactor performance. The substrate in SMFCs is not the only factor that influences the type of dominant microorganisms that exist in the anode. These microorganisms can also be influenced by the inoculum and the reactor conditions when operational (Parot et al., 2009). Reiche and Kirkwood (2012) stated that SMFC reactors with mixed culture biocatalysts obtained from three different types of compost produce a maximum electric power density of 12.3 mW/m^2. These compost were considered to be able to enrich the substrate and exoelectrogenic activity. The efficiency of electron transfer in SMFCs can be influenced by the selection of biocatalyst. Ion and substrate transport through solid media is an important factor that influences the performance of SMFCs. If these transports are low, then the electrochemical reactions are reduced. Therefore, transport systems in SMFC become critical as the water content is limited. In this case, maintaining the water content in optimum condition (around 60–80%) is necessary (Oliot et al., 2016; Wang et al., 2017).

Wang et al. (2019a) indicated that the type of inoculum can determine the rate of substrate decomposition and affect the generation of electrical energy. The dominant genus identified on the anode biofilm was the genus *Pseudomonas* (5%), which can produce chemical intermediaries that can transfer electrons to the electrodes. In addition, *Hydrogenophaga* (5%) was the dominant genus identified on biofilms derived from household wastewater. This genus consumes H_2 in the anode chamber and inhibits the generation of electricity from the SMFCs with biogas slurry as the substrate. In addition to the analysis of the genus, it is known that four genera of hydrolytic bacteria can break down cellulose, protein, and starch chains into organic micro-molecules. This increases the sugar degradation and volatile fatty acids in SMFCs

Table 2
Comparison of SMFCs with other conventional solid waste treatments.

Solid Waste Treatment	Energy Input	Products	Byproducts	Emissions	References
Solid Phase Microbial Fuel Cells	Half aeration in cathode and ignored when working in air-cathode Mixing (if necessary)	- Electricity - Soil conditioner - Compost - Fertilizer (in slurry phase) - Biohydrogen	Less sludge	CH_4, CO_2, NH_3, N_2O	Li et al. (2020)
Aerobic Composting	Full aeration Mixing	Compost	Leachate	Odor, CO_2, CH_4, VOC, NH_3, N_2O	Rincon et al. (2019) Smith and Aber (2018) Bernstad and la Cour Jansen (2012)
Anaerobic Digestion	Mixing (if necessary)	- Fertilizer - Biogas - Soil conditioner - Non-direct electricity (from heat) - Compost	Less sludge	CH_4, CO_2, NH_3, N_2O	Santos et al. (2020) Rincon et al. (2019)
Incineration	Full aeration	- Heat/steam - Electricity	Ash and slag	Dioxin and furan (if the waste contains plastic-based material), CO_2, N_2O	Assi et al. (2020)

with biogas slurry as the substrate. The diversity of the microorganisms genus contained in SMFCs influences the performance of the reactor because of their various roles in degrading the substrate (Lu et al., 2019; Reiche and Kirkwood, 2012; Wang et al., 2015, 2019b; Zhi et al., 2014).

4. Integration of SMFCs with other solid waste treatment

SMFCs appear to have many potential applications compared with other solid waste treatments (See Table 2). This technology requires only a relatively small energy input to support the chemical reactions in the cathode. Moreover, air-cathode MFCs do not need an oxygen supply as this is provided by the system configuration. SMFCs produce less sludge as an anaerobic power generation system and convert organic matter directly into electricity and biohydrogen. The processed organic matter could be a mature compost and fertilizer, and the used electrode could be a soil conditioner to increase its fertility. This also produces fewer emissions, such as CH_4, CO_2, NH_3, N_2O. The same characteristics can be seen in anaerobic digestion, which has the same processing stage as SMFCs. Aerobic composting requires significant energy for aeration and mixing and only produces compost with excessive amounts of leachate. This type of composting also produces a significant odor and VOCs, which interfere with the environment. While incineration has many benefits for treating solid waste, it also generates dioxin and furan, especially when working with plastic-based materials, CO_2, and N_2O. If the incineration is not properly controlled, the emissions and byproduct (fly and bottom ash/slag) may be harmful to the environment.

Typically, the maximum energy generated from MFCs at treating food and organic waste in the form of liquid fraction/hydrolysate has a COD around 0.28–0.78 MJ/kg (Xin et al., 2018; Xiao and He, 2014). The total energy can be higher until it reaching a COD of 2.48 MJ/kg when MFCs are fed by anaerobic sewage sludge and a COD of 3.52 MJ/kg from food waste hydrolysate (Wang et al., 2013b; Xin et al., 2019). These energy values may be lower, especially when compared with other waste-to-energy (WtE) technology such as incineration can result in energy values ranging from 3.60 to 6.00 MJ/kg of food waste (Carmona-Cabello et al., 2018; Chen and Christensen, 2010). Although the MFC energy generation is promising as only 8 to 12 SMFC systems may achieve the same energy output as combustion, the energy generation sustainability is doubted compared to thermal processing technologies, such as incineration. The situation is more challenging when SMFCs are implemented to process a solid fraction of municipal waste. The maximum electricity generation from solid-phase MFCs is relatively small and amounted to 0.072 MJ/kg of food waste, as reported by Moqsud et al. (2014). This is related to its mass transfer limitations, which result in the low electricity generation of SMFCs. Therefore, these values are still at laboratory scales (no SMFCs at larger scales). Thus, the process efficiency is suspected to be much lower than a pilot or even industrial scales. At the pilot/industrial scale, MFC reactors must be constructed with minimal dimensions to ensure the power per unit area of the electrode or reactor volume is lower to increase the energy generation. An ideal substrate supply rate can also be provided in smaller reactors (Greenman and Ieropoulos, 2017). This limitation may be solved by integrating other waste processing technologies.

Dark fermentation (DF) is a commonly used approach to recover biohydrogen from high cellulose content materials. Fermentation reactions hydrolyze cellulose to hexoses and produce acetate and hydrogen gas (Wang et al., 2011). However, the DF system can only recover one-third of the total theoretical energy that could be recovered. The combination of MFCs and microbial electrolysis cells (MFC-MEC) to treat the DF effluent could increase the bioenergy production. The MFC could support the MEC energy demands to convert the substrate into H_2, as well as direct electricity for the system overall (Chookaew et al., 2014). Increased power density in MFCs also results from the use of DF effluents where the maximum power density becomes 4 times more significant based on research conducted by Varanasi et al. (2017). The combination of the DF-SLS (solid-liquid separation)-MFC can also be used to treat cellulose waste, such as swine manure and rice bran. As a post-treatment of DF and SLS, MFCs can improve the energy recovery process in the form of bio-electricity. The MFC efficiency will also increase due to the higher degradable COD as available from DF and SLS processes (Schievano et al., 2016). The potential to utilize integrative technology could be explored more intensely to obtain a better system durability and sustainability.

Xin et al. (2018) showed that the amount of electric power generated by MFCs is greater than from anaerobic digesters (ADs). This is attributed to the fact that the AD process requires a longer residence time than MFC technologies, which affects the size of the reactor. Thus, the MFC reactor can be 5.5 times smaller than the AD reactor. The MFC application is considered to be more practical, more environmentally friendly, and more economically feasible in terms of electricity conversion and production costs than the AD. The MFC is expected to be a solution for processing food waste that ensures the rapid recovery of resources and electricity while not producing any additional waste. Antonopoulou et al. (2019) added to this scheme by proposing a food waste management system using an integrated biochemical process. Food waste is ground and heated as a waste pre-processing system, and the carbonaceous COD is extracted to produce liquid and solid product fractions. The liquid fraction is continuously processed using MFCs and the solid fraction is processed using the AD. This is considered to be applied at the pilot-scale because it produces more energy recovery at

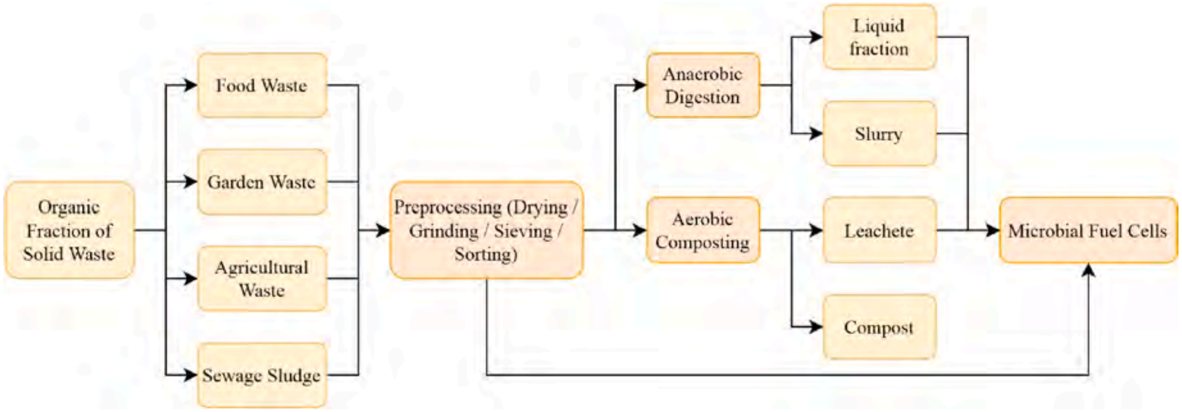

Fig. 3. SMFCs and other solid waste treatments to achieve sustainable energy production (modified from Antonopoulou et al. (2019) and Xin et al. (2018)).

12.32 MJ/kg of total solids (TS), which is nearly that of the maximum net calorific value using various types of combustion (amounting to 18.09–18.38 MJ/kg TS). The total energy produced from MFCs and the AD is still positive, especially when covering the pre-processing energy needs of 8 MJ/kg TS (Antonopoulou et al., 2019; Wang et al., 2013b; Xin et al., 2018). This energy balance can still be reduced if it uses cheap and energy-friendly drying technologies, such as bio-drying or low-cost decanters, to reduce the excessive water content in food waste (Velis et al., 2009). When integrating with aerobic composting, the leachate can be processed using MFCs for further substrate conversion. The generated energy could be used as a self-supporting system to aerate the compost pile. On the other hand, MFCs themselves can be used to directly treat the organic fraction of solid waste without the help of anaerobic or aerobic composting. However, this option is not feasible as the energy generated is lower. This needs further investigation to enhance the productivity of electricity. Fig. 3 shows the proposed mechanism to integrate other solid waste treatments with SMFCs.

5. Conclusions

SMFCs are an alternative technology to generate electricity that is environmentally friendly and sustainable. Various studies have determined the optimum configuration of the MFC reactor and its development potential to generate electrical energy. The various factors that affect the performance of SMFC reactors include the substrates, electrodes, microorganisms involved, and reactor configuration, which require further investigations. The presence of a separator and the electrode distance in the SMFC reactor are important as they are related to the electron and proton transfer. Mass transfer is important in the solid phase as it ensures the microorganism can properly breakdown the substrate. Therefore, this limitation may be further studied, and the best configuration may enhance the electricity generated by SMFCs. Integrating this technology with other solid waste processing systems could be possible and reliable, as SMFCs themselves have many limitations. The proposed system sequentially combines the preprocessing system, AD, composting, and SMFCs. After solid waste is processed using the pretreatment technology, it is sent to the composter, both anaerobic or aerobic composting. Then, the leachate, slurry, or hydrolysate from the process may be treated using SMFCs. Direct electricity can be used as an alternative energy source for other treatment needs. The SMFCs could also be used as a single solid waste treatment, but the efficiency may be lower than the proposed system and not feasible for field applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research was financially supported by SAPBN Universitas Diponegoro, Number 205-09/UN7.P4/3/PP/2019.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111417.

References

Antonopoulou, G., Ntaikou, I., Pastore, C., di Bitonto, L., Bebelis, S., Lyberatos, G., 2019. An overall perspective for the energetic valorization of household food waste using microbial fuel cell technology of its extract, coupled with anaerobic digestion of the solid residue. Appl. Energy 242, 1064–1073.
Antonopoulou, G., Stamatelatou, K., Bebelis, S., Lyberatos, G., 2010. Electricity generation from synthetic substrates and cheese whey using a two-chamber microbial fuel cell. Biochem. Eng. J. 50, 10–15.
Assi, A., Bilo, F., Zanoletti, A., Ponti, J., Valsesia, A., Spina, R.L., Zacco, A., Bontempi, E., 2020. J. Clean. Prod. 245, 118779.
Barik, S., Paul, K.K., 2017. Potential reuse of kitchen food waste. J. Environ. Chem. Eng. 5, 196–204.
Bernstad, A., la Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems – current status and potential improvements. Waste Manag. 32, 2439–2455.
Calignano, F., Tommasi, T., Manfredi, D., Chiolerio, A.J.S.r., 2015. Additive manufacturing of a microbial fuel cell—a detailed study. Sci. Rep. 5, 17373.
Carmona-Cabello, M., Garcia, I.L., Leiva-Candia, D., Dorado, M.P., 2018. Valorization of food waste based on its composition through the concept of biorefinery. Curr. Opin. Green Sustain. Chem. 14, 67–79.
Chen, D., Christensen, T.H., 2010. Life-cycle assessment (EASEWASTE) of two municipal solid waste incineration technologies in China. Waste Manag. Res. 28 (6), 508–519.
Chiu, H., Pai, T.Y., Liu, M.H., Chang, C.A., Lo, F.C., Chang, T.C., Lo, H.M., Chiang, C.F., Chao, K.P., Lo, W.Y., Lo, S.W., Chu, Y.L., 2016. Electricity production from municipal solid waste using microbial fuel cells. Waste Manag. Res. 34, 619–629.
Choudhury, P., Uday, U.S.P., Mahata, N., Nath Tiwari, O., Narayan Ray, R., Kanti Bandyopadhyay, T., Bhunia, B., 2017. Performance improvement of microbial fuel cells for waste water treatment along with value addition: a review on past achievements and recent perspectives. Renew. Sustain. Energy Rev. 79, 372–389.
Chookaew, T., Prasertsan, P., Ren, Z.J., 2014. Two stage energy conversion of crude glycerol to energy using dark fermentation linked with microbial fuel cell or microbial electrolysis cell. N. Biotech. 31 (2), 179–184.
Chu, Z., Fan, X., Wang, W., Huang, W., 2019. Quantitative evaluation of heavy metals' pollution hazards and estimation of heavy metals' environmental costs in leachate during food waste composting. Waste Manag. 84, 119–128.
Daud, S.M., Daud, W.R.W., Bakar, M.H.A., Kim, B.H., Somalu, M.R., Muchtar, A., Jahim, J.M., Ali, S.A.M., 2020. Low-cost novel clay earthenware as separator in microbial electrochemical technology for power output improvement. Bioproc. Biosyst. Eng. 43, 1369–1379.
Do, M.H., Ngo, H.H., Guo, W.S., Liu, Y., Chang, S.W., Nguyen, D.D., Nghiem, L.D., Ni, B. J., 2018. Challenges in the application of microbial fuel cells to wastewater treatment and energy production: a mini review. Sci. Total Environ. 639, 910–920.
Du, Z., Li, H., Gu, T., 2007. A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. Biotechnol. Adv. 25, 464–482.
Escapa, A., Mateos, R., Martínez, E.J., Blanes, J., 2016. Microbial electrolysis cells: an emerging technology for wastewater treatment and energy recovery. From laboratory to pilot plant and beyond. Renew. Sustain. Energy Rev. 55, 942–956.

Florio, C., Nastro, R.A., Flagiello, F., Minutillo, M., Pirozzi, D., Pasquale, V., Ausiello, A., Toscano, G., Jannelli, E., Dumontet, S., 2019. Biohydrogen production from solid phase-microbial fuel cell spent substrate: a preliminary study. J. Clean. Prod. 227, 506–511.

Ganjar, S., Syafrudin, S., Irawan, W.W., Cagayana, C., Meishinta, A., Erika, L., 2018. Effect of Moisture Content on Power Generation in Dual Graphene Anode Compost Solid Phase Microbial Fuel Cells (DGACSMFCs), E3S Web of Conferences. EDP Sciences, 05004.

Garita-Meza, M.A., Ramírez-Balderas, L.A., Contreras-Bustos, R., Chávez-Ramírez, A.U., Cercado, B., 2018. Blocking oscillator-based electronic circuit to harvest and boost the voltage produced by a compost-based microbial fuel cell stack. Sustain. Energy Technol. Assess. 29, 164–170.

Ghasemi, M., Wan Daud, W.R., Ismail, M., Rahimnejad, M., Ismail, A.F., Leong, J.X., Miskan, M., Ben Liew, K., 2013. Effect of pre-treatment and biofouling of proton exchange membrane on microbial fuel cell performance. Int. J. Hydrogen Energy 38, 5480–5484.

Greenman, J., Ieropoulos, I.A., 2017. Allometric scaling of microbial fuel cells and stacks: the lifeform case for scale up. J. Power Sources 356, 365–370.

Gude, V.G., 2016. Wastewater treatment in microbial fuel cells–an overview. J. Clean. Prod. 122, 287–307.

Hassan, S.H.A., Gad El-Rab, S.M.F., Rahimnejad, M., Ghasemi, M., Joo, J.-H., Sik-Ok, Y., Kim, I.S., Oh, S.-E., 2014. Electricity generation from rice straw using a microbial fuel cell. Int. J. Hydrogen Energy 39, 9490–9496.

He, L., Du, P., Chen, Y., Lu, H., Cheng, X., Chang, B., Wang, Z., 2017. Advances in microbial fuel cells for wastewater treatment. Renew. Sustain. Energy Rev. 71, 388–403.

He, Z., Huang, Y., Manohar, A.K., Mansfeld, F., 2009. Effect of electrolyte pH on the rate of the anodic and cathodic reactions in an air-cathode microbial fuel cell. Bioelectrochemistry 74, 78–82.

Jadhav, G.S., Ghangrekar, M.M., 2009. Performance of microbial fuel cell subjected to variation in pH, temperature, external load and substrate concentration. Bioresour. Technol. 100, 717–723.

Jia, J., Tang, Y., Liu, B., Wu, D., Ren, N., Xing, D., 2013. Electricity generation from food wastes and microbial community structure in microbial fuel cells. Bioresour. Technol. 144, 94–99.

Jimenez, I.M., Greenman, J., Ieropoulos, I., 2017. Electricity and catholyte production from ceramic MFCs treating urine. Int. J. Hydrogen Energy 429, 30–37.

Kadier, A., Simayi, Y., Abdeshahian, P., Azman, N.F., Chandrasekhar, K., Kalil, M.S., 2016. A comprehensive review of microbial electrolysis cells (MEC) reactor designs and configurations for sustainable hydrogen gas production. Alexandria Eng. J. 55, 427–443.

Karluvalı, A., Köroğlu, E.O., Manav, N., Çetinkaya, A.Y., Özkaya, B., 2015. Electricity generation from organic fraction of municipal solid wastes in tubular microbial fuel cell. Separ. Purif. Technol. 156, 502–511.

Khudzari, J.M., Tartakovsky, B., Raghavan, G.S.V., 2016. Effect of C/N ratio and salinity on power generation in compost microbial fuel cells. Waste Manag. 48, 135–142.

Kim, Y., Hatzell, M.C., Hutchinson, A.J., Logan, B.E., 2011. Capturing power at higher voltages from arrays of microbial fuel cells without voltage reversal. Energy Environ. Sci. 4, 4662–4667.

Li, X., Liu, G., Sun, S., Ma, F., Zhou, S., Lee, J.K., Yao, H., 2018. Power generation in dual chamber microbial fuel cells using dynamic membranes as separators. Energy Convers. Manag. 165, 488–494.

Li, D., Shi, Y., Gao, F., Yang, L., Kehoe, D.K., Romeral, L., Gun'ko, Y.K., Lyons, M.G., Wang, J.J., Mullarkey, D., Shvets, I.V., Xiao, L., 2020. Characterising and control of ammonia emission in microbial fuel cells. Chem. Eng. J. 389, 124462.

Logan, B.E., 2009. Exoelectrogenic bacteria that power microbial fuel cells. Nat. Rev. Microbiol. 7, 375–381.

Logroño, W., Guambo, A., Pérez, M., Kadier, A., Recalde, C., 2016a. A terrestrial single chamber microbial fuel cell-based biosensor for biochemical oxygen demand of synthetic rice washed wastewater. Sensors 16, 101.

Logroño, W., Perez, M., Urquizo, G., Echeverria, M., Rákhely, G., Recalde, C., 2016b. Microalgae biofilm assisted-cathode in a single chamber microbial fuel cell (SMFC) powered with dye textile wastewater. In: 10th International Society for Environmental Biotechnology Conference. Barcelona,, pp. 153–154.

Logroño, W., Ramírez, G., Recalde, C., Echeverría, M., Cunachi, A., 2015. Bioelectricity generation from vegetables and fruits wastes by using single chamber microbial fuel cells with high Andean soils. Energy Procedia 75, 2009–2014.

Lu, L., Lobo, F.L., Xing, D., Ren, Z.J., 2019. Active harvesting enhances energy recovery and function of electroactive microbiomes in microbial fuel cells. Appl. Energy 247, 492–502.

Mäkinen, A.E., Lay, C.-H., Nissilä, M.E., Puhakka, J.A., 2013. Bioelectricity production on xylose with a compost enrichment culture. Int. J. Hydrogen Energy 38, 15606–15612.

Minutillo, M., Flagiello, F., Nastro, R.A., Trolio, P.D., Jannelli, E., Perna, A., 2018. Performance of two different types of cathodes in microbial fuel cells for power generation from renewable sources. Energy Procedia 148, 1129–1134.

Miran, W., Nawaz, M., Jang, J., Lee, D.S., 2016. Conversion of orange peel waste biomass to bioelectricity using a mediator-less microbial fuel cell. Sci. Total Environ. 547, 197–205.

Mohan, S.V., Chandrasekhar, K., 2011. Solid phase microbial fuel cell (SMFC) for harnessing bioelectricity from composite food waste fermentation: influence of electrode assembly and buffering capacity. Bioresour. Technol. 102, 7077–7085.

Mohan, S.V., Mohanakrishna, G., Sarma, P.N., 2010. Composite vegetable waste as renewable resource for bioelectricity generation through non-catalyzed open-air cathode microbial fuel cell. Bioresour. Technol. 101, 970–976.

Mohan, S.V., Velvizhi, G., Annie Modestra, J., Srikanth, S., 2014. Microbial fuel cell: critical factors regulating bio-catalyzed electrochemical process and recent advancements. Renew. Sustain. Energy Rev. 40, 779–797.

Moqsud, M.A., Omine, K., Yasufuku, N., Bushra, Q.S., Hyodo, M., Nakata, Y., 2014. Bioelectricity from kitchen and bamboo waste in a microbial fuel cell. Waste Manag. Res. 32, 124–130.

Moqsud, M.A., Omine, K., Yasufuku, N., Hyodo, M., Nakata, Y., 2013. Microbial fuel cell (MFC) for bioelectricity generation from organic wastes. Waste Manag. 33, 2465–2469.

Moqsud, M.A., Yoshitake, J., Bushra, Q.S., Hyodo, M., Omine, K., Strik, D., 2015. Compost in plant microbial fuel cell for bioelectricity generation. Waste Manag. 36, 63–69.

Nastro, R.A., Jannelli, N., Minutillo, M., Guida, M., Trifuoggi, M., Andreassi, L., Facci, A. L., Krastev, V.K., Falcucci, G., 2017. Performance evaluation of microbial fuel cells fed by solid organic waste: parametric comparison between three generations. Energy Procedia 105, 1102–1108.

Oh, S.T., Kim, J.R., Premier, G.C., Lee, T.H., Kim, C., Sloan, W.T., 2010. Sustainable wastewater treatment: how might microbial fuel cells contribute. Biotechnol. Adv. 28, 871–881.

Oliot, M., Galier, S., Roux de Balmann, H., Bergel, A., 2016. Ion transport in microbial fuel cells: key roles, theory and critical review. Appl. Energy 183, 1682–1704.

Palanisamy, G., Jung, H.-Y., Sadhasivam, T., Kurkuri, M.D., Kim, S.C., Roh, S.-H., 2019. A comprehensive review on microbial fuel cell technologies: processes, utilization, and advanced developments in electrodes and membranes. J. Clean. Prod. 221, 598–621.

Pandey, P., Shinde, V.N., Deopurkar, R.L., Kale, S.P., Patil, S.A., Pant, D., 2016. Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. Appl. Energy 168, 706–723.

Pant, D., Van Bogaert, G., Diels, L., Vanbroekhoven, K., 2010. A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. Bioresour. Technol. 101, 1533–1543.

Parot, S., Nercessian, O., Delia, M.L., Achouak, W., Bergel, A., 2009. Electrochemical checking of aerobic isolates from electrochemically active biofilms formed in compost. J. Appl. Microbiol. 106, 1350–1359.

Peighambardoust, S.J., Rowshanzamir, S., Amjadi, M., 2010. Review of the proton exchange membranes for fuel cell applications. Int. J. Hydrogen Energy 35, 9349–9384.

Pushkar, P., Mungray, A.K., 2016. Real textile and domestic wastewater treatment by novel cross-linked microbial fuel cell (CMFC) reactor. Desalin. Water Treat. 57, 6747–6760.

Quezada, B.C., Delia, M.L., Bergel, A., 2010. Testing various food-industry wastes for electricity production in microbial fuel cell. Bioresour. Technol. 101, 2748–2754.

Rahimnejad, M., Adhami, A., Darvari, S., Zirepour, A., Oh, S.-E., 2015. Microbial fuel cell as new technology for bioelectricity generation: a review. Alexandria Eng. J. 54, 745–756.

Rahimnejad, M., Ghoreyshi, A.A., Najafpour, G.D., Younesi, H., Shakeri, M., 2012. A novel microbial fuel cell stack for continuous production of clean energy. Int. J. Hydrogen Energy 37, 5992–6000.

Rahimnejad, M., Najafpour, G., Ghoreyshi, A.A.J.I., 2011. Effect of mass transfer on performance of microbial fuel cell. IntechOpen 5, 233–250. Mass Transfer in Chemical Engineering Processes.

Reiche, A., Kirkwood, K.M., 2012. Comparison of Escherichia coli and anaerobic consortia derived from compost as anodic biocatalysts in a glycerol-oxidizing microbial fuel cell. Bioresour. Technol. 123, 318–323.

Rincon, C.A., Guardia, A.D., Couvert, A., Roux, S.L., Soutrel, I., Daumoin, M., Benoist, J. C., 2019. Chemical and Odor Characterization of Gas Emissions Released during Composting of Solid Wastes and Digestates.

Samudro, G., Nugraha, W.D., Sutrisno, E., Priyambada, I.B., Muthi'ah, H., Sinaga, G.N., Hakiem, R.T., 2018. The Effect of COD Concentration Containing Leaves Litter, Canteen and Composite Waste to the Performance of Solid Phase Microbial Fuel Cell (SMFC), E3S Web of Conferences. EDP Sciences.

Santoro, C., Arbizzani, C., Erable, B., Ieropoulos, I., 2017. Microbial fuel cells: from fundamentals to applications. A review. J. Power Sources 356, 225–244.

Santos, L.A.d., Valenca, R.B., Silva, L.C.S.d., Holanda, S.H.d.B., Silva, A.F.V.d., Juca, J.F. T., Santos, A.F.M.S., 2020. Methane generation potential through anaerobic digestion of fruit waste. J. Clean. Prod. 256, 120389.

Schievano, A., Sciarria, T.P., Gao, Y.C., Scaglia, B., Salati, S., Zanardo, M., Quiao, W., Dong, R., Adani, F., 2016. Dark fermentation, anaerobic digestion and microbial fuel cells: an integrated system to valorize swine manure and rice bran. Waste Manag. 56, 519–529.

Sharma, Y., Li, B., 2010. The variation of power generation with organic substrates in single-chamber microbial fuel cells (SCMFCs). Bioresour. Technol. 101, 1844–1850.

Smith, M.M., Aber, J.D., 2018. Energy recovery from commercial-scale composting as a novel waste management strategy. Appl. Energy 211, 194–199.

Song, Y., Xiao, L., Jayamani, I., He, Z., Cupples, A.M., 2015. A novel method to characterize bacterial communities affected by carbon source and electricity generation in microbial fuel cells using stable isotope probing and Illumina sequencing. J. Microbiol. Methods 108, 4–11.

Trapero, J.R., Horcajada, L., Linares, J.J., Lobato, J., 2017. Is microbial fuel cell technology ready? An economic answer towards industrial commercialization. Appl. Energy 185, 698–707.

Utomo, H.D., Yu, L.S., Zhi Yi, D.C., Jun, O.J., 2017. Recycling solid waste and bioenergy generation in MFC dual-chamber model. Energy Procedia 143, 424–429.

Varanasi, J.L., Sinha, P., Das, D., 2017. Maximizing power generation from dark fermentation effluents in microbial fuel cell by selective enrichment of exoelectrogens and optimization of anodic operational parameters. Biotechnol. Lett. 39, 721–730.

Velis, C.A., Longhurst, P.J., Drew, G.H., Smith, R., Pollard, S.J.T., 2009. Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering. Bioresour. Technol. 2747–2761, 2009.

Wang, A., Sun, D., Cao, G., Wang, H., Ren, N., Wu, W.-M., Logan, B.E., 2011. Integrated hydrogen production process from cellulose by combining dark fermentation, microbial fuel cells, and a microbial electrolysis cell. Bioresour. Technol. 4137–4143, 2011.

Wang, C.-T., Lee, Y.-C., Liao, F.-Y.J.S., 2015. Effect of composting parameters on the power performance of solid microbial fuel cells. Sustainability 7, 12634–12643.

Wang, C.-T., Liao, F.-Y., Liu, K.-S., 2013a. Electrical analysis of compost solid phase microbial fuel cell. Int. J. Hydrogen Energy 38, 11124–11130.

Wang, C.-T., Lin, T.-H., Chen, Y.-J., Chong, W.-T., 2017. Using xanthan 80 (SF) on enhancing the performance of solid Microbial Fuel Cell. Energy Procedia 105, 1160–1165.

Wang, F., Zhang, D., Shen, X., Liu, W., Yi, W., Li, Z., Liu, S., 2019a. Synchronously electricity generation and degradation of biogas slurry using microbial fuel cell. Renew. Energy 142, 158–166.

Wang, Y., Chen, Y., Wen, Q., Zheng, H., Xu, H., Qi, L., 2019b. Electricity generation, energy storage, and microbial-community analysis in microbial fuel cells with multilayer capacitive anodes. Energy 116342.

Wang, Z., Ma, J., Xu, Y., Yu, H., Wu, Z., 2013b. Power production from different types of sewage sludge using microbial fuel cells: a comparative study with energetic and microbiological perspectives. J. Power Sources 235, 280–288.

Xia, C., Zhang, D., Pedrycz, W., Zhu, Y., Guo, Y., 2018. Models for microbial fuel cells: a critical review. J. Power Sources 373, 119–131.

Xiao, L., He, Z., 2014. Applications and perspectives of phototrophic microorganisms for electricity generation from organic compounds in microbial fuel cells. Renew. Sustain. Energy Rev. 32, 550–559.

Xin, X., Hong, J., Liu, Y., 2019. Insights into microbial community profiles associated with electric energy production in microbial fuel cells fed with food waste hydrolysate. Sci. Total Environ. 670, 50–58.

Xin, X., Ma, Y., Liu, Y., 2018. Electric energy production from food waste: microbial fuel cells versus anaerobic digestion. Bioresour. Technol. 255, 281–287.

Yasri, N., Roberts, E.P.L., Gunasekaran, S., 2019. The electrochemical perspective of bioelectrocatalytic activities in microbial electrolysis and microbial fuel cells. Energy Rep. 5, 1116–1136.

Yousefi, V., Mohebbi-Kalhori, D., Samimi, A., 2017. Ceramic-based microbial fuel cells (MFCs): A review. Int. J. Hydrogen Energy 42 (3), 1672–1690.

Yu, H., Jiang, J., Zhao, Q., Wang, K., Zhang, Y., Zheng, Z., Hao, X., 2015. Bioelectrochemically-assisted anaerobic composting process enhancing compost maturity of dewatered sludge with synchronous electricity generation. Bioresour. Technol. 193, 1–7.

Zhang, Q., Hu, J., Lee, D.-J., 2016. Microbial fuel cells as pollutant treatment units: research updates. Bioresour. Technol. 217, 121–128.

Zhi, W., Ge, Z., He, Z., Zhang, H., 2014. Methods for understanding microbial community structures and functions in microbial fuel cells: a review. Bioresour. Technol. 171, 461–468.