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Mini Review

Microbial fuel cells, a renewable energy technology for bio-electricity generation: A mini-review

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ABSTRACT

The unsustainable nature and the environmental impact of fossil fuels have shifted attention to renewable energy and fuel cells, especially in the transportation sector. In this study, the generation of electricity based on the electrons released from biochemical reactions facilitated by microbes is evaluated. Microbial fuel cell (MFC) represents an eco-friendly approach to generating electricity while purifying wastewater concurrently, achieving up to 50% chemical oxygen demand removal and power densities in the range of 420–460 mW/m^2. The system utilizes the metabolism power of bacteria for electricity generation. This mini-review is quite comprehensive. It is different from other reviews, it is all-inclusive focusing on the; types of MFCs; substrates and microbes; areas of applications; device performances; design, and technology configuration. All these were evaluated, presented and discussed which can now be accessed in a single paper. It was discovered that higher power density and coulombic efficiency could be achieved through proper selection of microbes, mode of operation, a suitable material for construction, and improved MFC types. Also, the full-scale application of MFC is impeded by materials cost and the wastewater low buffering capacity. Though the electricity generated is still at the demonstration stage, to date, there is no industrial application. Therefore, this study reviewed articles on the technology to set new and insightful perspectives for further research and highlighted steps for scale-up while reinforcing the criteria for microbe selection and their corresponding activity.

1. Introduction

Fossil fuels which consist of coal, natural gas, and petroleum were discovered decades ago from dead plant and animal matter that had been compressed and heated over millions of years by overburden layers of sediments and rocks [1,2]. These fossil fuels can produce high-efficiency power to support engine of vehicles, electronic devices and individuals' daily life [3,4]. However, their finite nature, make them unsustainable sources of energy [5,6]. Thus, there is a need for renewable and sustainable fuels to substitute fossil fuels and develop modern industrial civilization [7,8].

MFCs is a bio-electrochemical device that converts chemical energy contained in organic substrates into electrical energy by the activities of microbes [9]. The use of organic material such as wastewater in MFC makes it an eco-friendly device that offers a dual benefit of bioelectricity generation and waste management [10,11]. Structurally a microbial fuel cell consists of two chambers known as the anode and cathode chamber (electrodes) separated by a proton exchange membrane. The anode side contains the electrochemical active microorganisms while the cathode is abiotic. The microbes (bacteria) act as biocatalyst that motivates the degradation of organic materials to produce electrons which travels to the cathode side through the electric circuit. These bacteria are called "Exoelectrogens" (Exo- for exocellular and "electrogens" based on the ability to directly transfer electrons to a chemical or material that is not immediate electron acceptor) [12]. Electrons go through the external circuit arriving at the cathode, and hydrogen ions move to the cathode and react with oxygen to form water in the internal circuit [10,13,14]. This, therefore, demonstrates that MFCs is a potential candidate of green "electricity."

Fig. 1 shows a simple conventional MFCs.

Considering a simple MFC (see Fig. 1) using acetate as a substrate in the anode and oxygen as the terminal electron in the cathode, reactions

Abbreviations: BOD, Biological oxygen demand; CE, Coulombic efficiency; ECE, Energy coulombic efficiency; LED, Light emitting diode; MFC, Microbial fuel cell; PD, Power density; PEM, Proton exchange membrane.

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(1) to (3) are presented.

$$\text{Anodic reaction}: \ CH_3COOH + H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad (1)$$

$$\text{Cathodic reaction}: \ 8H^+ + 8e^- + 2O_2 \rightarrow 4H_2O \quad (2)$$

$$\text{Overall reaction}: \ CH_3COOH + 2O_2 \rightarrow 2H_2O + 2CO_2 \quad (3)$$

In the anode chamber (anodic reaction), the microbial respiration oxidizes the acetate substrate to carbon dioxide, which results in the liberation of electrons and protons (Eq. (1)). During this reaction, electron mediator takes place; which is the diversion out of the cell membrane into the anode through direct contact with the electrochemically active carrier [16]. This, then proceed to the cathode through an external integrated circuit. Kim et al. [17] analysed that each electron that is transferred results to the corresponding proton which mitigate across proton permeable membrane to the cathodic chamber thereby sustaining charge neutrality

On the other hand, at the cathode chamber; electrons are known as the useful products from the oxidation reaction at the anode chamber which travels through a conducting wire to the cathodic chamber that contains water to the cathode electrode. Moreover, electrons react with protons and oxygen to form water molecules (reduction) as seen in Eq. (2). These protons move to the cathodic chamber through the membrane that links to both the anode and cathode chamber. However, the membrane is permeable to the proton (H^+) but at the same time does not allow electrons to pass through it. Hence, the presence of oxygen at the cathodic reaction is important for completing the reaction [18]. Interestingly, the flow of electrons from anode to the cathode through the external circuit is responsible for power generation. Usually, certain metals like platinum or palladium are used as catalyst in the cathodic reaction (Eq. (2)) which are omitted as a result of micro-organism been catalysts themselves.

The anode and cathode compartments are separated internally by the proton exchange membrane (PEM) as seen in Fig. 1. The PEM function is to act as a barrier for the restriction of oxygen diffusion from the cathode to the anode while permeable to the proton mitigation from the anode to the cathode. Also, it allows the passage of protons while ensuring that the substrate, oxygen from the cathodic chamber and electrons do not cross over [18]. Eq. (3) shows the overall reaction (anode reaction and cathode reaction), including the microorganism. The overall reaction breaks down acetate (fuel) into carbon dioxide and water. The anodic potential (E_{An}) is about – 0.300 V while that of the cathode potential (E_{Cn}) is said to be around 0.805 V. Therefore, for a MFCs using acetate and oxygen, theoretical maximum cell potential (E_{cell}) = 0.805 V – (–0.300 V) = 1.105 V [19].

Table 1 summarised the half-cell reaction of MFC using acetate as a substrate with their respective potential voltage.

Guo et al. [13] argued that the cathode potential with oxygen as a terminal electron acceptor is less than the theoretical maximum cell potential. This might be attributed to the over potential of cathodic reaction. From the electrode reaction pair in Eqs. (1) to (3), a MFCs has the potential to generate electricity from the electron flow of the anode to cathode in the external circuit.

MFCs can be classified into two main types: mediator MFCs and mediator less MFCs [21]. This classification is based on how electrons are transported to the electrode

1.1. Mediator MFCs

Mediator MFCs focus on the transfer of electrons to the anode through electrons mediator by bacterial activities [18,22]. This type of MFCs makes use chemical mediators such as neutral red, humic acid and anthraquinone-2, 6-disulphonate and so on, which helps in the flow of electrons to the anode as shown in Fig. 1. Although, Logan [23] stated that neutral red, potassium ferricyanide and methyl viologen are the usual mediators. These chemical mediators are referred to as “electro-active metabolites”. Flimban et al. [18], suggested the need to develop alternative ways to improve the power production and decrease capital cost because of the high cost and toxicity of these mediators. The view from Flimban et al. [18] was suitable for the wastewater treatment process. In mediator MFC, anaerobic digestion is important because of the presence of oxygen which take anaerobic digestion is important because of the present of oxygen that takes the electrons, thereby interrupting the mediator work which is less electronegative than

Table 1
Half-cell reaction of MFC using acetate as a substrate with their potential voltage.

Half-cell reactions	E_{emf} (V vs NHE)
Anodic reaction:	
$CH_3COOH + H_2O\ 2CO_2 + 8H^+ + 8e^-$	– 0.300 V
Cathodic reaction:	
$8H^+ + 8e^- + 2O_2\ 4H_2O$	0.805 V
Overall reaction:	
$CH_3COOH + 2O_2\ 2H_2O + 2CO_2$	1.105 V

NHE: Normal hydrogen electrode.

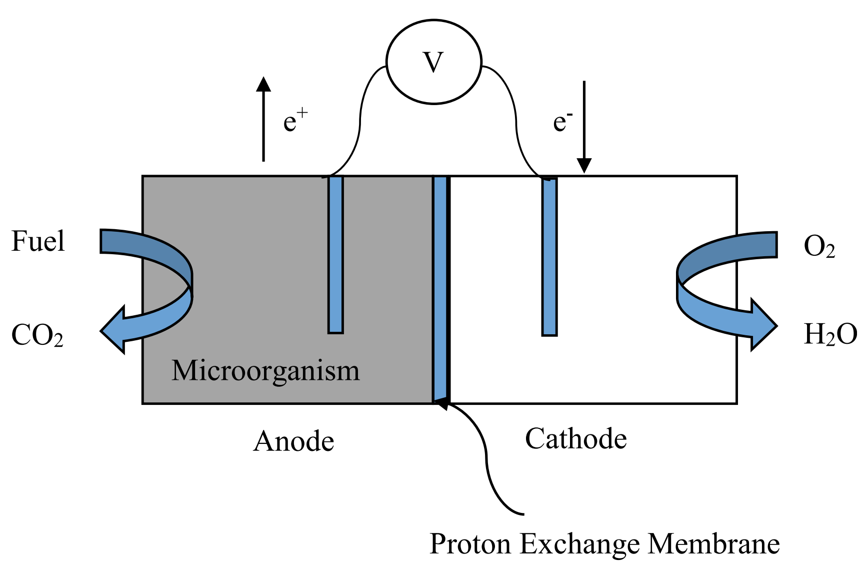

Fig. 1. Schematic diagram of simple MFC (Source from He et al. [15]).

oxygen. During the electron transfer process, the mediator enters the cell, thus accepting electrons before liberating and donating them to the anode as the final electron acceptor. At this point, the mediator is oxidized back to its initial state after depositing its electrons [18]. The study concluded that MFCs operate at a high sustained activity level due to bacteria being able to produce their mediator or directly transfer electrons to the electrode (Fig. 2).

1.2. Mediator less MFCs

Electricity can be generated without mediators using some micro-organism. In this type of MFCs, no external mediators are added into the system [22]. Most of the wastewater bacteria tend to transport electrons to electrodes, which produces electricity using long appendages called nanowires [23]. The mediator less MFCs has an advantage over the mediator MFCs type as it is non-toxic and less expensive. Oh and Logan [24]; Park et al. [25] stated that most of the mediator less MFCs are operated with the dissimilatory metal-reducing with *Clostridium butyricum*. There are some factors to be considered for the mediator less MFC; these include; the presence of electrochemically active redox enzymes for efficient electron transfer to the anode, fuel oxidation at the anode, the external resistance of the circuit, oxygen reduction at the cathode as well as the transfer of proton to the cathode through the membrane which results to variation in pH and also hinder microbial activities [18]. These factors limit the generation of electricity.

Mediator less MFCs can also derive energy directly from certain plants such as reed sweet grass, cord grass, rice, tomatoes, lupines and algae. This process or configuration is known as plant microbial fuel cell. Hence, the mediator less MFCs are designed as microbial electrolysis cell, soli based microbial fuel cell and phototrophic biofilm microbial fuel cell [26].

Previous studies including Oh and Logan [24], Das and Mangwani [27], Idris et al. [9], Barua et al. [19], Leropoulos et al. [28], Zhang et al. [29], Koroglu et al.[30] have reviewed and discussed types and application of MFC, generation of electricity by MFC, the performance of various MFC design, and the application of MFCs. However, no study has reviewed the design and configuration, materials for construction of MFC, and factors affecting MFC's performance and highlight areas for the future direction of the technology. Therefore, the study fills the knowledge gaps regarding these aforementioned areas as it involves a comprehensive detail of information from previous studies and the present contributions that can now be accessed in a single paper. The study is suitable for the audience in academics, researchers, engineers and technicians in waste to energy discipline and fuel cells. In light of this, this study's central objective is to perform a literature review on the future direction of the technology and conduct a review on the performance on MFC in the production of electricity. Additionally, the material of construction of MFC, are presented and discussed.

2. Substrates and micro-organisms used for MFCs

Substrate is considered as one of the main factors that affect generation of electricity using MFC [27] and also referred to as anolyte, which is the liquid solution inside the anodic chamber. This is because of its dual purpose and importance for any biological process as it serves as a nutrient and energy source [31,32]. A great variety of substrates can be used in MFCs for electricity production ranging from pure compounds to complex mixtures of organic matter present in wastewater [13]. These substrates rich in organic content are usually chosen based on their current, power densities and Faraday's efficiency. According to Chae et al. [32], the effect of substrate concerns the integral composition of the bacterial community in the anode biofilm and the performance of MFC, which include the power density and coulombic efficiency. Considering the relationship between substrate concentration and MFC current generation, this proceeds Monod's equation under normal condition. This is possible when there are no limitations for the anodic biofilm to function [33]. Some of the substrates already used in MFCs include acetate, glucose brewery wastewater, lignocellulosic biomass, synthesis wastewater, starch processing wastewater, landfill leachates, dye wastewater as well as inorganic substrates. However, recent studies have shown that acetate and glucose are the most frequently used substrate, with the highest acetate result. This motivated the need to review these two substrates for electricity production and wastewater treatment.

2.1. Acetate

Recently, in most of the research on MFC, acetate has been the widely used substrate type for electricity generation. Acetate is rich in carbon and tends to prompt electroactive microbes. They are ions contained in acetic acid and also the end product of various several metabolic pathways for higher order carbon sources [34]. According to literature, acetate as a substrate usually results in higher efficiency compared to other organic compounds in a single chambered MFC [13].

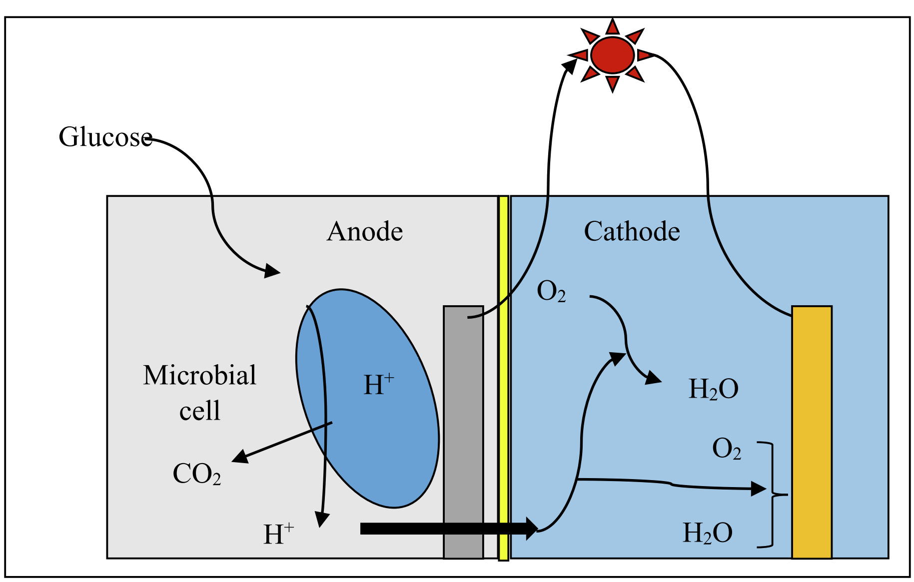

Fig. 2. Schematic diagram illustrating the flow of electron to the anode through the chemical mediator.

Acetate being a simple compound is easier to degrade in MFCs which tends to improve the power output with respect to complex substrate favoured by diverse and electrochemically active bacteria communities [13]. In Liu et al. [35] studied, acetate as a substrate for power density generation achieved 506 W/m^3, 800 mg/L of electricity in a single chamber MFC. This value tends to be 66% higher than that produced with butyrate (305 W/m^3, 1000 mg/L).

Similarly, the performance of four different substrates was investigated in term of their coulombic efficiency (CE) and power output. It was revealed that acetate fed MFC showed the highest CE of 72.3%, followed by butyrate (43.0%), propionate (36.0%) and glucose (15.0%) [32]. Furthermore, Liu et al. [36], compared acetate rich substrate with protein-rich wastewater as substrate. It was discovered that the MFC based acetate induced consortia that achieved more than two fold maximum electric power and one half optimal external load resistance when compared to the MFC based on consortia induced by a protein rich wastewater. This is attributed to acetate alternative microbial conversions (fermentation and methanogenesis) at room temperature [37]. Although, protein-rich wastewater is a complex substrate that has the possibility of enriching more diverse microbial community than acetate.

Sun et al. [38] study confirmed that acetate is a superior substrate for MFC initiation preceding bioethanol effluent utilisation. The study aimed at assessing the cell voltage development, electricity recovery and microbial community composition in response to substrate such as acetate, xylose and bioethanol effluent in a MFC operation. It was observed in the study that MFCs fed with acetate showed a shorter initiation time of one day with higher cell voltage and coulombic efficiency of 634 $\pm$ 9 mV and 31.5 $\pm$ 0.5% respectively than those fed with xylose and bioethanol effluent. Experimentally, it is shown that microbial community in acetate as a substrate for MFC is less diverse and contained more electrogenic bacteria (13.9 $\pm$ 0.4%) than the MFCs fed with bioethanol effluent. Some of these bacteria are *Geobacter sulfurreducens* and *Desulfuromonas acetexigen* [38].

Having a more diverse microbial community helps to use various substrate to convert complex organics to simpler compounds. In this case, acetate is used as the electron donor for electricity generation [13].

2.2. Glucose

Glucose is another commonly used substrate in MFCs. The presence of glucose in wastewater sludge enhances the conductivity property of the MFC. Lee et al. [39], compared the energy conversion efficiency (ECE) of acetate and glucose as a substrate for electricity in MFC technology. The study found that the ECE of acetate and glucose was 42% and 3% respectively. The 3% obtained from glucose resulted in low current and power density. Another study was conducted to evaluate the feasibility of anaerobic sludge as an alternative fuel for electricity in MFC and was compared with glucose. The findings revealed that anaerobic sludge generated a maximum power density of 0.3 W/m^3 compared with glucose in the same system with a maximum power density of 161 W/m^3 [40].

Generally, glucose fed MFC generate low CE because of the loss of an electron by competing bacteria. However, the relatively diverse bacterial structure enabled a much wider substrate utilisation and highest power density (PD). Another reason for the low CE associated with glucose fed MFC is the fermentable substrate property presence in glucose which consumes diverse competing metabolisms like fermentation and methanogenesis that cannot produce electricity [32]. Khatar et al. [41] study aimed at improving the performance of the mediator less single-chamber MFC and to generate electrical energy from glucose. The MFC was designed and implemented using transparent Perspex as a construction material with an electrode active area of 25 cm^2. An increase in glucose concentration increases the electricity output and decreases the current as a result of the inhibition effect of the glucose in term of cyclic voltammetry. The maximum power density of 52 W/m^3 and current density of 275 A/m^3 were obtained in the study. The result demonstrates that glucose can be used for electricity generation in MFC for practical applications. The effect of glucose concentration (2.5 and 7 g/l) on the performance of two chambered microbial fuel cell was investigated by Jafary et al. [42] using *Saccharomyces cerevisiae* as biocatalyst. During the experiment, optimum results of power and current density of 39.33 W/m^3 and 85.059 A/m^2 respectively were obtained at glucose concentration of 5 g/l. An investigation of energy output from a dual-chamber anoxic biofilm MFC subjected to glucose concentration was conducted Igbomalu et al. [43]. Maximum voltage output increases as the glucose concentration increased from 66.6 mV at 2.78 mM to 96.4 mV at 5.56 mM. At further increase in the glucose concentration, there was a decrease in voltage output by 46% that is 51.9 mV at 27.78 mM, with maximum power densities of 10.42 W/m^3. According to Igbomalu et al. [43], the voltage output decrease is attributed to substrate inhibition. In a similar study, as glucose concentration increases from 1 to 5 g/l, power and current density gradually increases. When the concentration of the glucose increased from 7 to 20 g/l, it was observed that the power and current density were considerable decreased. The reason for this behavioural is attributed as a result of most glucose which remain unconsumed at high concentration. Hence, an increase in time duration to reach open circuit voltage (OCV) at a low concentration for glucose will decrease at a higher concentration because of substrate inhibition effect [44].

Table 1 presents the general properties of substrate used in MFCs

Having reviewed the major substrates used for MFCs and various works associated with them, it is necessary to look out the microorganism responsible for electricity generation through the MFC technology. Microorganism has the potential to transfer electrons derived from the metabolism of organic matter to the anode. A list of them is shown in Table 2 with their mode of operation and substrate. Organic rich sources such as the marine sediment, soil, wastewater, freshwater sediment and activated sludge are effective sources of microbes used in MFCs catalyst unit. A mixed culture is common, whereas, for anaerobic digestion of substrate, a complex mixed culture is permitted. However, some single microbes have the tendency to generate electricity because of their metabolic exploration [27]. Consequently, variety of bacteria can produce a modicum of electricity in an MFC, if a mediator is used to speed up the transfer of electrons between the bacterial cells and the anodic surface used in the system. The other types of bacteria apart from the latter is said to possess the ability to transfer electrons from fuel oxidation to a working electrode without a mediator. Table 2 summarises typical microbes used in MFCs, making reference with their mode of operation and substrate.

Having looked at the various microorganisms responsible for electricity generation with their respective substrate in Table 2, it is necessary to point out that microorganism gains energy by the process of transferring electrons from reduced substrate of low potential to an electron acceptor of high potential. However, microorganisms in an open system are influenced by various mediator substances that tend to transfer electrons from bacteria to electrode. *Geobacter* and *Shewanella* (microbes listed in Table 2) are known to be well studied in the MFC related studies. This is because of the promising capabilities of electricity producing and hydrogen generation present in MFCs and MFCs systems respectively, especially as it relate to cost, biological stability and reactive stability. However, not much has to deal with cost.

Comparing *Geobacter* and *Shewanella* species of microbes with other microbes for MFCs listed in Table 2, studies have shown that for *Shewanella*, electrons are indirectly transferred in young biofilm to produce more current. Dealing with its biological stability and reactive activity, biofilms are regarded by viable microbes that confers mechanical stability and also increases biofilm resistance to chemical and physical stresses. More also, *Shewanella* possesses outer membrane cytochromes and capable of direct electron transfer. In contrast, *Geobacter* uses prevalent direct electron transfer through the outer membrane cytochromes and iron-containing proteins that can connect the bacterial cells directly with the electrode. *Geobacter* and *Shewanella* species are

Table 2
Properties of substrates used in MFCs.

Properties	Acetic	Glucose	Butyrate	Malate	Citrate	Glycerol
Molecular formula	$C_2H_4O_2$	$C_6H_{12}O_6$	$C_4H_8O_2$	$C_6H_8O_5$	$C_6H_8O_7$	$C_3H_8O_3$
Appearance	Colourless liquid or crystal	Colourless solution	Oily and colourless liquid	–	White, crystalline powder,	Colourless hygroscopic liquid
Boiling point	118.1°c	100 °C	163.5 °C	306.4 °C	310 °C	290 °C
Solubility in water	Fully miscible	Readily dissolved in water	Insoluble in water	Soluble in water	Soluble in water and insoluble in alcohol	Miscible in water
Density	1.049 g/cm^3	1.54 g/cm^3	0.96 g/m^3	–	1.66 g/cm^3	1.26 g/cm^3
Acidity pKa	4.76	10–12	4.5–7.0	3.40–5.20	2.92–5.21	-
Concentration (mg/L)	800	500–3000	1000	-	-	-
Power density output (W/m^3)	506	3600	305	-	-	-

capable of producing nanowires, contributing to the transfer of electrons [52–54], refers *Geobacter sulfurreduces* as a strict anaerobic chemo-organotrophic microorganism which oxidizes acetate with Fe (III), Co (III), furmate or malate as the electron acceptor which contains c-type cytochromes. Also, Bond and Lovely [55] stated that *Geobacter sulfurreduces* has the property of oxidizing organic substrate completely to transfer electrons to electrode without a mediator (mediator less) noted in Table 2. Gorby and Beveridge et al. [56], went ahead to conclude that nanowires were mostly produced by *Geobacter sulfurreducens* in response behaviour of electron acceptor which brings about high efficiency of transfer of electron whereas *Shewanella* species are due to their ability to conserve energy for growth by using oxygen or ferric iron as a terminal electron acceptor.

However, considering the biological stability and reactive stability in terms of the effects of micro-organism to temperature, mechanical stress, pH, and environmental change on MFC, Sahu [57], study reported a case whereby there is an increase in temperature as time increases (days) as well as sudden decrease in temperature as time increases also. On the other hand, the pH parameter decreases as the time (days) increases. The behaviour performance as it relates to temperature and pH was attributed to the anaerobic microbial reaction of the microorganism that occurs in acidic medium and also the present of heat that was released. Another study conducted by Tang et al. [58] affirmed that MFC is a very robust device when subjected to change in temperature and pH. The objective of the study was to determine the response of MFC performance to temperature and pH in an inoculated MFC with a mixed consortium. It was revealed that the voltage output decreases sharply as temperature decreases. Considering previous studies, similar results were reported in connection to the response of temperature and pH in MFC. According to Gonzalez del Campo et al. [59], the influence of microbial metabolism, membrane permeability and ohmic resistance of the electrolyte are factors responsible for temperature on MFC voltage output.

Regarding the pH on the power generation of MFC, the acidification of the anode affects the electricity generation by inhibiting the microbial activity. The microorganism *Shewanella Putrefacien* (see Table 2) is known to enhance bio anode performance because of its alkaline medium, which increases biosynthesis of riboflavin [60].

Table 3 presents the electron donors and acceptor used in MFC for the anode and cathode chamber. Notably, a higher potential difference at the anode will enhance the activities of the bacteria by gaining much energy needed to deliver the electron to the anode. This confirms why the anode acts as an electron acceptor.

3. Previous studies on the performances of MFCs

This section provides a summary on the performance of MFCs in terms of electricity generation. In Idris *et al* [9], sludge was used as chemical waste in MFC for electricity generation. The MFCs consist of two chambers, iron electrodes, copper wire, air pump, water, sludge and salt bridge as shown in Fig. 3. The study results showed that the MFC

Table 3
Microbes used for MFCs with respective mode of operation and substrate present.

Microbe for MFCs	Mode of operation	Substrates	References
Erwinia dissolven	Mediator MFC	Glucose	[45]
Proteus mirabilis	Mediator MFCs	Glucose	[45,46]
Aeromonas hydrophila	Mediator less MFCs	Acetate	[45,47]
Geobacter metallireducens	Mediator less MFCs	Acetate	[45,48]
G. sulfurreducens	Mediator less MFCs	Acetate	[45]
Rhodoferax ferrireducens	Mediator less MFCs	Glucose	[45,49]
Shewanella putrefacien	Mediator less MFCs	Lactase, pyruvate, acetate, glucose	[45]
Klebsiella pneumoniae	Mediator MFCs	Glucose	[50]
Lactobacillus plantarum	Mediator MFCs	Glucose	[45]
Aeromanas hydrophila	Mediator less MFCs	Acetate	[32]
S. oneidensis MR-1	Mediator less MFCs	Lactase	[45,51]

achieved up to 202 mV (0.202 V) and 153 mV in the presence and absence of air pump, respectively. The air pump in the MFCs increased the efficiency of the electric charges produced from bacteria, as it supplied more oxygen to the biotic ecosystem. The salt bridge also helped in the transportation of proton from cathode to anode to give a higher electricity generation. A longer salt bridge will give a higher voltage compared to a shorter bridge because of the huge effect of the longer salt bridge on the microbial fuel cell performance. Irrespective of the 202 mV reported in the study, which shows a good sign in the study, the authors reported that the voltage produced did not last long because of the slowdown of the activities of the bacteria.

A single and double chamber MFC was used to isolate an enriched microbial consortium for electricity generation from organic waste in a similar study. The findings of the study showed that Bacillus *sp* and Bacillus *licheiformis* produced voltage ratings of 0.93 V and 0.95 V, respectively [19]. The successful application of MFCs is a function of the concentration and biodegradability of the organic matter in the substrate, waste temperature and the absence of toxic chemicals. Santoro et al. [4], pointed out that the limitations of MFCs in electricity generation are associated with low power output and scaling up. Barua et al. [19], recommended that more research is needed to make MFC technology more efficient, and widely accepted.

Another study focused on developing an effective small scale MFC for energy generation using human urine as a substrate. In this study, the impacts of two different biomass-derived catalysts, and the effect of electrode length was investigated. The study results showed that doubling the electrode length increases the power density from 0.053 to 0.580 W/m^3 and the use of biomass derived oxygen reduction reaction

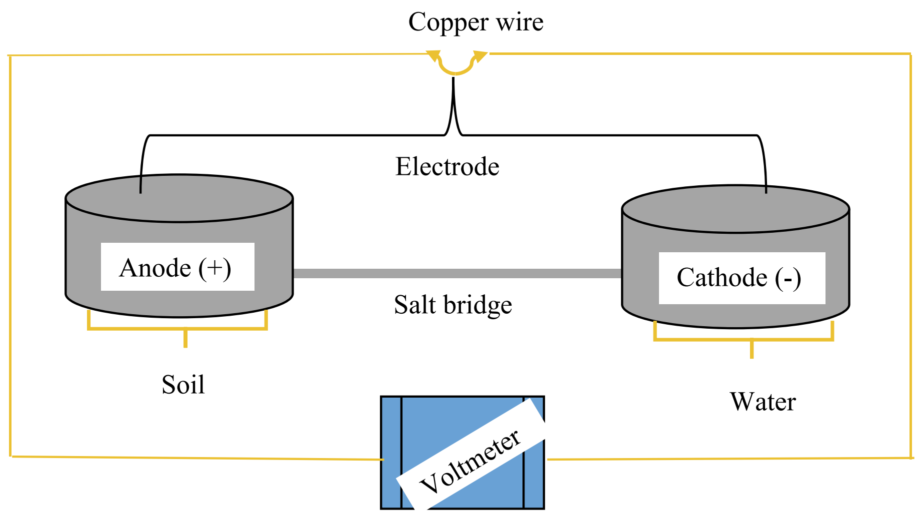

Fig. 3. Schematic MFC set up used in the study.

catalyst increases the power density generated by the MFC by 1.95 W/m^3 [62].

Similarly, Leropoulos et al. [28], demonstrated the possibility of using human urine as a substrate in MFC. The study showed that undiluted urine could be used as the main feedstock for different types of MFCs as well as stacks of small scale MFC, for electricity production. The findings revealed an increase in power density of 1.5 W/m^3 when 48 small scales were connected as a stack and fed with urine.

Generation of electricity by microbial communities in wheat straw biomass powered MFC was investigated by Zhang et al. [29]. The study aimed to test wheat straw as a potential fuel in an MFC for electricity production. From the findings, it was demonstrated that stable power could be generated from wheat straw. A power density of 123 W/m^3 and columbic efficiency range of 37.1% − 15.5% was obtained in the study. The result shows wheat straw biomass as a potential substrate in which suspended bacteria and biofilm ferment the complex fuel into simple fermentation products, which can be utilized by anode electrochemical bacteria to generate electricity. The study also revealed that different bacteria play different roles as regards to electricity generation from the hydrolysate.

A study aimed to use organic materials to increase power production performance of a double chamber MFC reactor made of Plexiglas as shown in the Fig. 4, with the temperature set at 25° C for 45 days. The study obtained a power density and current density of 16 W/m^3 and 1385 A/m^2 using Ti-TiO_2/Nafion combination with 78% COD removal efficiency Ti-TiO_2/CM1700 generated current and power density of 750 A/m^2 and 5 W/m^3 respectively [30].

A maximum power density of 1.86 W/m^3 and columbic efficiency range of 1.8% −11.1% using air diffusion cathode MFC was reported. The study showed that food waste leachate can be used as a fuel for power generation in a MFC [63].

From previous studies, the authors are of the view that research progress has been made to improve the performance of MFC technology, which has to deal with the employment and utilisation of pure culture or mixed culture (Synergistic) microbial consortium using microbes.

4. Factors affecting the performances of MFCs

4.1. Electrode material

The electrode material tends to poise as one of the greatest challenges in making MFC a cost-effective and scalable technology [64]. Although it is one of the factors responsible for the efficiency of MFC. Electrode material has certain resistance however, the most effective ones are known as the least resistive [12]. Electrode material for the anode and cathode chamber of a MFC should be non-corrosive, non-fouling, conductive in nature and cost-effective. Some of the materials used for MFC and their power density generation performance by various authors are shown in Table 5. It has been shown that the use of highly efficient electrode material such as platinum is not feasible economic as it regards to large scale applications. As a result of this, investment on more cost effectiveness has become of priority in research dealing with MFC. In the area of material characteristic which poises critical importance for effective electron transfer, Wei et al. [65] commented that this should be of high conductivity and mechanical strength. Fig. 7 shows examples of electrode materials used for MFCs. Studies have shown that electrode with nanoparticle modification generates more electricity than the plain electrode. This was investigated in

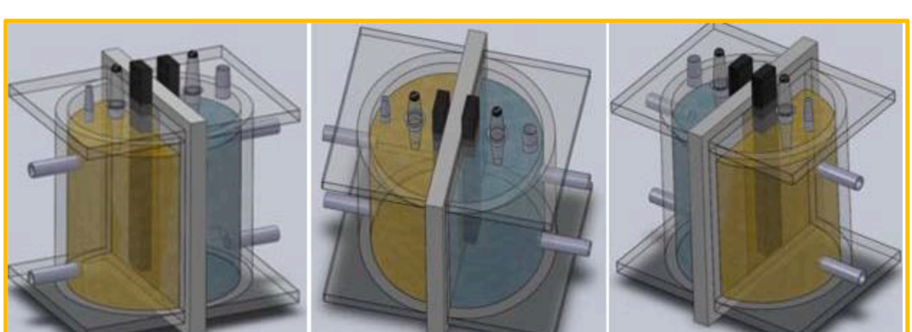

Fig. 4. Set up of two-chamber MFC.

the study reported by Alatraktchi et al. [66], in which electrode with magnetic nanoparticles increased the current production in the MFC using *G. Sulfurreducens* as an inoculum. The study revealed that nanoparticle increased the electrical conductivity of biofilm electrode by 1.22 – 1.88 times higher than that obtained with plain carbon paper electrode and boosted the transfer of electron mechanism [67]. On the other hand, platinum or platinum-coated cathode at the cathode chamber produces higher electric current compared to a plain cathode containing no catalyst [55]. De Juan [12] demonstrated that the electrode surface area should be increased and divided into several configurations such as plane, packed and brush structure for optimising bacteria adhesion.

4.2. Various materials for MFCs construction

One of the objectives of the anode chamber in the MFC reactor is to serve as a receptor of electrons for electric current. To achieve this objective, the anode material should be highly conductive, non-corrosive, non-fouling, and inexpensive and have a high specific surface area. However, corrosion tends to increase the current through galvanic current production and the increased surface area or decrease the current through the generation of toxic product. Logan and Zhu [69], conducted a study that compared the use of corrodible metal anodes in a MFCs. The findings revealed MFC with Cu anodes showed a high current generation and produced low power density of about 2 W/m^3.

Furthermore, the simplest materials for anode electrode are graphite plates or rods; they are inexpensive, easy to handle and have a defined surface area [70,71]. Higher surface area can be achieved by the use of compact material such as reticulated vitreous carbon. This is said to be available with different pore sizes or layers of packed carbon granules or beads. However, any of the cases required maintaining high porosity to avoid clogging. To increase the performance of the anode, Park and Zeikus [70], proposed the use of chemical and physical strategies, such as the incorporation of Mn (IV) and Fe (III) which were used to covalently link neutral red to mediate the electron transfer to the anode. In another study, Lowy et al. [72]; Niessen 2004 [73] and Schroder et al. [51], the use of electro-catalytic materials such as polyaniline and Pt composites to improve current generation by the process of direct oxidation of microbial metabolites were considered. This directs the water flow through the anode material, and this can be another option to increase the power generation in a MFC. This was also confirmed in a study conducted by Cheng et al. [74], in which the flow directed through carbon cloth toward the anode and reducing the electrode spacing (from 2 cm to 1 cm) increased the power density from 811 W/m^3 to 1540 W/m^3 in an air cathode MFC.

Most times, the same anode materials (see Table 4) can be used as cathode materials. In the cathode chamber, ferricyanide (K_3 [Fe (CN) $_6$]) is very popular as an experimental electron acceptor in MFC because of its good performance [72]. Despite the advances of ferricyanide, the insufficient re-oxidation by oxygen, which has resulted in the usual replacement of catholyte tends to be a limitation [52]. Logan et al. [75], mentioned oxygen as the most suitable electron, because of its high oxidation potential, availability and low cost as well as sustainability. To increase, the rate of oxygen reduction, platinum catalyst or open-air gas diffusion cathode is usually used for dissolved oxygen [54]. However, to decrease the costs for the MFC, the Platinum load can be kept as low as 0.1 mg cm^{-2} as recommended by Cheng et al. [74]. The need for the long stability of platinum needs to be studied, as there are new types of catalysts that are not expensive in the market. A proposal has been made for such catalysts such as pyrolyzed iron (III) and phthalocyanine by Cheng et al. [74]; Zhao et al. [76].

Table 4
Selected electron donor and acceptor used in MFC for electricity generation [10,61].

Electron donor/acceptor for Anode chamber	Electron donor/acceptor for Cathode chamber
Acetate	Oxygen
Glucose	Bicarbonate
Butyrate	Iron
Glycerol	Ferricynaide
Malate	Nitrite
Citrate	Nitrate
Sulphur	Manganese oxide

Fig. 8 shows some of the materials used for MFCs.

The proton exchange membrane (PEM)'s primary purpose is to keep anode and cathode solution while allowing ion transfer. Material for PEM should be permeable to chemicals such as oxygen, ferricyanide, other ions or organic matter used as substrate. The most commonly used material for PEM is Nafion however, Ultrex CMI is also used as an alternative. Rozendal et al. [77] opined the view of more systematic studies to evaluate the effect of the membrane on performance and long term stability. Table 5 presents a summary of the materials used for MFCs with advantages and disadvantages.

4.3. Proton exchange system (PES)

The PES is regarded as the proton exchange membrane (PEM) between the anode and cathode chamber in a MFC. It affects the internal resistance and concentration of the polarisation loss of the MFC system and influences the power output of the MFC. This is because of the pores with a charged sidewall that helps the movement of proton from anode to cathode [71,74]. One interesting thing about the PEM, is that it enables hydrogen ions or protons (responsible for electricity generation) to pass through them as illustrated in Fig. 5. The diffusion of the anolyte through the membrane to the cathode causes fouling of the membrane and inhibition to the passage of proton to cathode, which decreases the power output of the MFC. In addition, the passage of catholyte to the anode chamber affects the performance of the bacteria for electricity generation in MFC. Furthermore, the membrane increases the MFC's internal resistance and the diffusion of ions or electrolytes, which affects the current generation of the fuel cell. The Nafion material (Du point, Wilington and Delaware) is the most commonly used PEM in the MFC technology because of its permeable selectivity property to the proton [71]. Although there have been various studies and research in finding a less and more durable alternative, however, Nafion has remain the best choice of material for this purpose. For instance, lost cost separator such as non-woven fabric polypropylene (PP80) exhibited maximum voltage of 0.477 V, similar to that of Nafion (0.481 V). This resulted in the highest power density of 121 W/m^3 for the non-woven fabric polypropylene against the Nafion of 118 W/m^2. Concerning the oxygen diffusion, all types of size selective separators exhibited high oxygen mass transfer which is why low coulombic efficiencies (CE) compared to Nafion and cation exchange membrane. The study reported CE of 44% for PP80 as regards to 50% for Nafion. The above results were the research on low-cost separators for enhanced power production and field application of microbial fuel cells (MFCs) carried out by Kondaveeti et al. [80]. The authors conclude that low-cost separator could be useful for field application of MFCs and higher cell voltage while minimising oxygen diffusion. A novel porous clay earthenware (NCE) was fabricated as a low-cost separator to replace the high-cost PEM (Nafion 117). During the experiment conducted by Daud et al. [81], it was revealed that the highest power and current density recorded was 2250 ± 21 mW/m^2 and 6.0 A/m^2 respectively having a CE of 44 ± 21% using the NCE low separator while the MFC using Nafion 117 as PEM produced a lower power and current density of 1350 ± 17 mW/m^2 and 3.0 A/m^2 respectively having a CE of 23 ± 15%. From the study, it can be seen that the low-cost separator NCE performed much better than the high-cost Nafion 117, generating higher power and current density as well as CE.

In MFC, there is always the ratio of the PEM surface area to the volume of the MFC system, which impacts the power output. Studies conducted by Oh and Logan [24] and [Gill et al. [71] revealed that power output of below a critical threshold is as a result of the impact of

Table 5
Selected electrode material used with their power density generation performance in MFC.

Electrode material	Configuration	Size of Electrode material (cm)	Source of inoculation	Type of reactor configuration	Power density (W/m^3)	References
Carbon paper	Plane	22.5	Primary clarifier overflow	Double chamber	600	[68]
Carbon (cloth)	Plane	7	Bacteria from an active MFC	Single chamber	46	[29]
Carbon (granular)	Packed	–	Domestic wastewater	Single chamber	5	–
Carbon brush	Brush	4	Bacteria from an active MFC	Single chamber	2400	–
Metal Plate	Plane	0.12	Marine sediment	Artificial marine	23	–

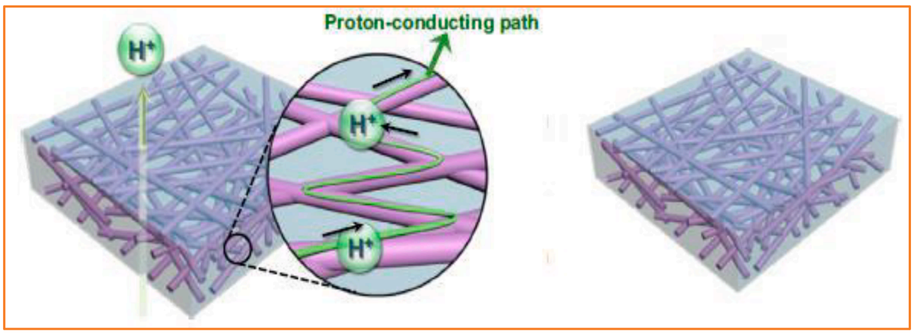

Fig. 5. Structure of PEM responsible for the flow of hydrogen ion.

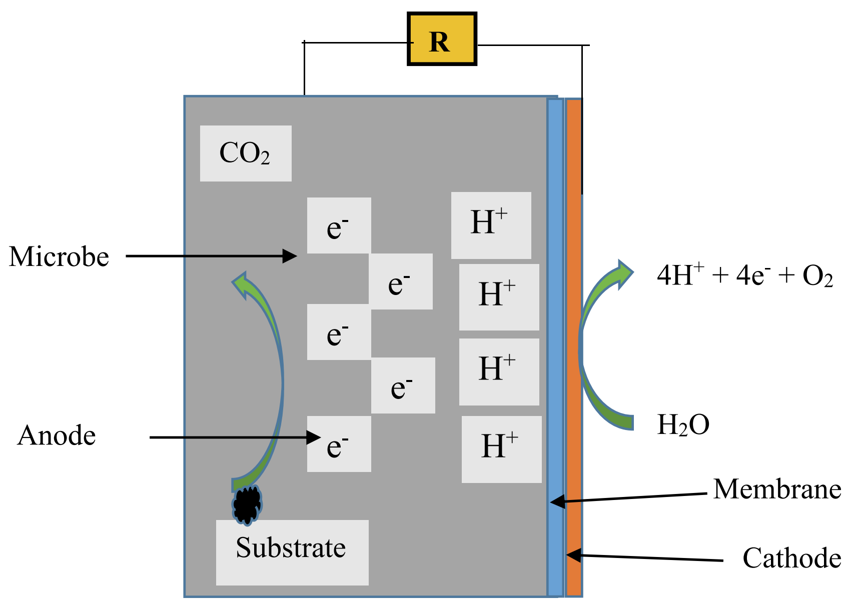

Fig. 6. Single chamber MFCs.

large surface area of the PEM. This is attributed to the decrease in MFC internal resistance which increases the PEM surface area. A comparison study was conducted by Min et al. [48] on the performance of PEM and salt bridge using G, *metallireducens*. Using a salt bridge MFC, power output of 2.2 W/m^3 was reported, which was lower than the achieved using Nafion. Similar experiment revealed that a relatively low performance was recorded when different membrane (preparation of inter-polymer cation exchange membrane with polyethylene by sulfonation using chlorosulfonic acid solution) instead of the common Nafion material. The highest voltage achieved using *E.coli* was 67 mV with a total resistance of 830 O using a 17 cm^2 surface area of graphite electrode [99]. In Park and Zeikus [70] study, Kaolin was used as a PES instead of the Nafion using sewage sludge as biocatalyst. It was reported that current and power density of 1750 A/m^2 and 788 W/m^3 respectively was generated. Although no obvious reason and explanation was given regarding the performance observed using kaolin to Nafion in the study. Membrane and Kaolin tend to be prone to fouling if the fuel is something like municipal wastewater. However, membrane-less MFCs are needed if fouling or cost of the membrane seems to be a problem in such an application. Hence, Gil et al. [72], recommend the need for membrane-less MFCs as future research regarding large scale application.

4.4. pH

Bacteria responsible for electricity generation in a MFC are more active at pH value between 6 and 8 in the anode chamber and neutral or little higher pH in the cathode chamber. In Gil et al. [72] study, maximum coulombic efficiency and current density were obtained at anode operating pH between 7and 8. However, the reduction in current density and coulombic efficiency usually occurs at pH of 6 and 9. Hence, current increases significantly with an increase in pH from 7.5 to 8.0 and decreases sharply above pH 9.0 [82]. The anodic microbial process is

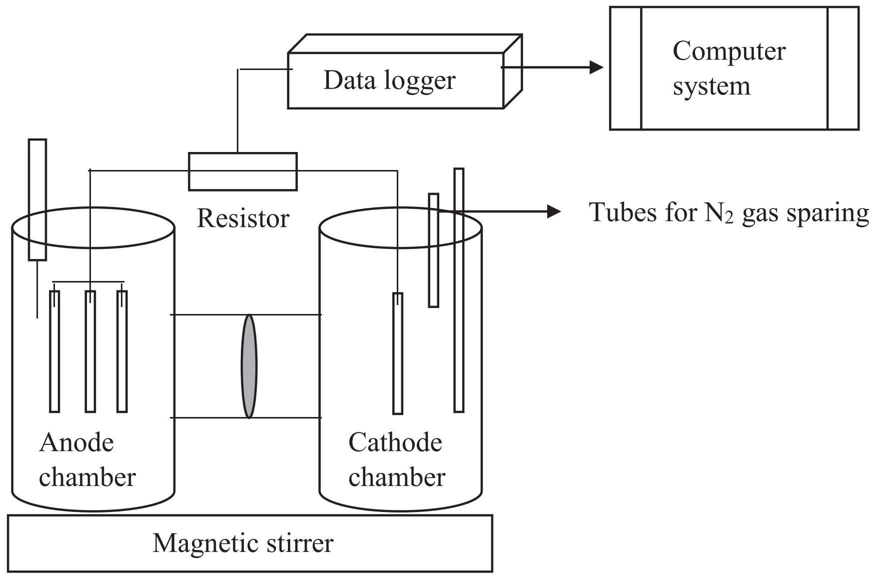

Fig. 7. Double chamber MFCs.

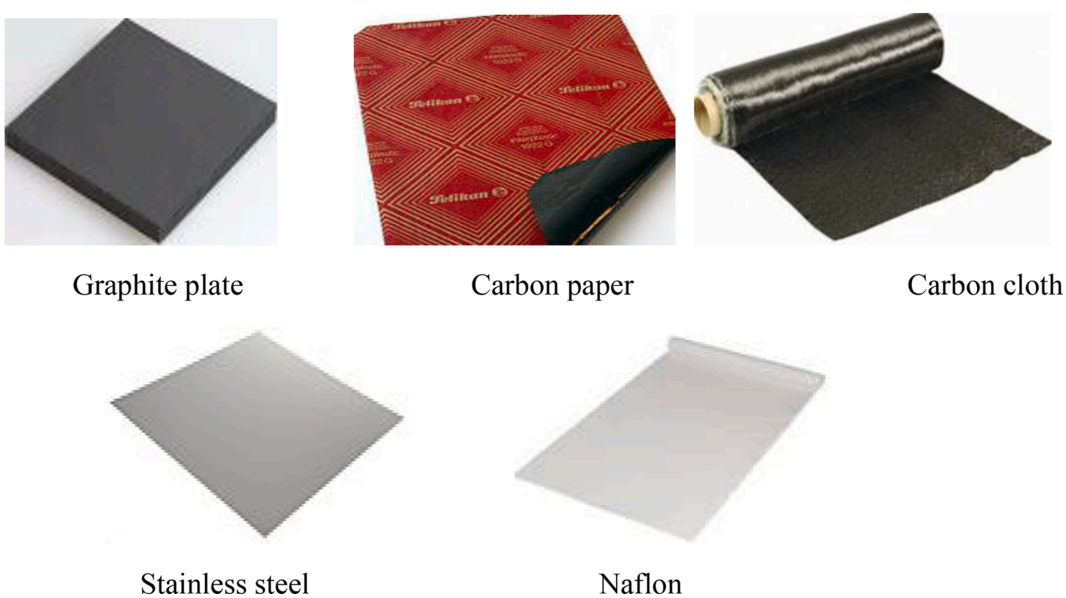

Fig. 8. Some materials used for MFC construction.

favourable at neutral pH while the micro-organism activities decrease at higher or lower pH. Jadhav and Ghangrekar [83] in Duteanu et al. [84] reported that higher current and voltage in the presence of higher electrochemical activity results in high pH difference across the membrane. An accumulation of protons makes the anode chamber more acidic and unfavourable for the growth of the bacteria [85]. At the cathode chamber, high pH reduces the current generation. Low pH enables oxygen reduction as well as achieves higher electric current from the MFCs [73,86,67]. The activities of the bacteria decrease as a result of the low pH in the anolyte, which has a tremendous effect on the biofilm formation and power output of the MFC. In Bermak et al. [87] study, it was discovered that a high rate of protons are exhibited at low anodic pH. This implies that a higher amount of protons accumulated at the cathode chamber reduces the power density. Considering the removal of COD during the wastewater treatment, this is favoured by higher pH in the anode chamber but reduces power. Interestingly, favourable pH and different pH between the anode and cathode depend on the type of species used in anode, the electron donor used as the substrate and catholyte used and proton flux through the membrane. The main effect of pH regarding the electrolyte has to deal with its influence on the bacterial metabolism and the cathodic oxygen reduction reaction rate [85]. Biffinger et al. [34] reported that an increase in the acidity of anode will increase the driving force for cathodic oxygen reduction by 59 Mv/pH unit provided that the catalyst activity remains high. In addition, to the pH parameter on the performance of MFC, selected works on the effect of pH has been briefly reviewed in section 4. In summary, pH of 6 to 9 is recommended for the microbial growth, resulting in higher power output.

4.5. Temperature

Similar to other energy production technology, MFC performance is affected by temperature. It affects microbial metabolism, mass transfer and thermodynamic. It has been found that MFCs operate best at the temperature range of 25° C to 30° C [88]. Studies have reported an efficient performance of MFCs in terms of power density and chemical oxygen demand removal at a higher temperature. This is because of the augmentation of the bacterial metabolism and membrane permeability [42]. To enhance the power output of MFC, the temperature must be increased, which will result to increased bacterial activities. Consequently, some studies have shown that at the start-up of the MFC, temperature contributes to the initial biofilm formation. In addition, at a higher temperature, the start-up time of the MFC operation decreases, which usually lead to stable biofilm formation [86]. Yong et al. [60] revealed that temperature of 30° C tends to be more beneficial for the operation of MFC to obtain a higher power output. This is because of the bacteria biofilms that show maximum catalyst activity between the aforementioned temperatures. However, variation in temperature can lead to different microbial communities in the anodic chamber of the MFC.

From the above-mentioned factors affecting the performance of MFC, designing a MFC is possible. Interestingly, all the factors as discussed are important in one way or the other for the performance of the MFC technology. Considering the modification of electrode material surfaces, this proves to be an effective way to improve the performance of MFC because of its physiochemical properties of electrode to facilitate microbial attachment. However, the operating conditions such as temperature and pH might be referred as factors decisive associated to the performance of MFC, according to the authors views based on reviews. This is because the combination of optimum pH and temperature enhances bacterial growth and, therefore, improves MFC bacterial growth performance and, therefore, improves MFC's performance [65]. Previous studies relating to temperature and pH on MFC's improvement have been discussed earlier (section 4).

5. Applications, design and configuration of MFCs reactor

A reactor that provides anode with an anaerobic environment and cathode with an aerobic environment as well as having a pathway for charge exchange can operate as a MFC. MFCs are designed and configured either as single or double chamber reactor. These types of MFCs share the similar operating principles and also operate under different optimised conditions to increase power output.

5.1. Single chamber MFCs

The single-chamber MFC is a one-compartment consisting of the anode in a rectangular anode chamber coupled with the air cathode as shown in Fig. 6.

In this design, protons are made to be transferred from the anode solution to the porous air- cathode. The essence of the single chamber MFC is to eliminate the need for the cathodic chamber, thereby exposing the cathode directly to the air. The single chamber MFCs have many advantages over the double chamber MFCs, these includes low-cost, simple design (see Fig. 7), cathode chamber aeration and efficient power production. The disadvantage of this type of MFCs is associated with the back diffusion of oxygen from cathode to anode with PEM [89].

A single chamber MFC was designed by Tanikul and Pisutpaisal [90], for the treatment of distilled wastewater and bioelectricity generation. The result of the study revealed that voltage and current output increases with the distilled wastewater concentration as the COD varied in the range of 125 to 3000 mg COD L^{-1}. In addition, the COD removal and total solids reduction were found to be 29.5–56.7% and 35% respectively. Another study was conducted by Mardanpour et al. [91], on the design annular single chamber MFC. The fabricated MFC operated for 450 h for the treatment of wastewater. It was reported in the study that the open circuit voltage and maximum power densities obtained were 810 mV and 20.2 W/m^3 respectively. The maximum coulombic efficiency (CE) and COD removal were 26.87% and 91% respectively.

5.2. Double chamber MFCs

The double chamber MFCs is a two-compartment consisting of the anode and cathode separated by the proton exchange membrane, as shown in Fig. 7.

The double chamber is known for its low power generation because of the complex design and high internal resistance.

Kim et al. [92] designed and constructed a double anode chambered MFC to test its performance which was inoculated with *Shewanella oneidesis MR-1*. The MFC was fabricated using a transparent polycarbonate material as the anode and cathode while the Nafion material was used for the PEM. A maximum power and current density of 24 W/m^3 and 3.66 A/m^2 were obtained in the study. A similar study was conducted and reported by Miran et al. [93] on the fabrication of a rectangular double chamber. The PEM was made using Nafion, and the lemon peel substrate was agitated by a magnetic bar. It was revealed in the study that the voltage and power density generated were 0.58 V and 371 W/$m^{3,}$ respectively. In addition, the double chamber MFC has a coulombic efficiency and internal resistance of 32.3% and 143 O, respectively.

Studies have shown that the use of algae (seaweed) in this type of design enhances oxygen production as a result of the photosynthesis process in the plant [59]. The distinguishing feature of the double chamber MFC is the small membrane that separates the two chambers. De Juan [12], reported that the double chamber MFCs is commonly used in laboratory research such as examining power production using new substrates, electrodes material, membrane or types of microbial communities that are present during degradation of specific compounds or for MFC based sensor, however, it has the challenge of scaling up because of impractical configuration.

Considering the applications of MFCs, the health, sanitation and environmental hazards associated with wastewater disposal has made the technology a promising one for wastewater treatment. MFCs enhances the growth of bio-electrochemically active microbes during wastewater treatment. This is because of the high-level growth promoter present in some of the microbes used by MFCs. These microbes have the tendency to remove sulphides required for wastewater treatment. Some examples of MFC performance for wastewater treatment are presented in Table 5.

The application of MFCs in wastewater treatment decreases the energy demand involved in the treatment plant as well as eliminates the quantity of sludge produce by anaerobic production [98]. In addition, Fernarndez et al. [99] reported that the use of MFCs during wastewater treatment allows the cells to recover the chemical energy present in wastewater, thereby converting it into electrical energy. This phenomenon shows that the microorganism in the cell converts the chemical energy to electrical energy. Hence, MFCs can use wastewater (domestic, animal, brewery and food processing) to generate electricity. However, the treatment is not effective as the aerobic one, and will require further treatment.

Another study on the application of MFCs on wastewater treatment was conducted by Rodrigo et al. [100]. The findings showed that using anaerobic pre-treatment of activated sludge, electricity generation can be obtained within 8 – 10 days. The maximum power density reported in the study was 25 W/m^3 with a voltage of 0.23 V using domestic wastewater.

Zhou et al. [76], mentioned that the measure of treatment efficiency of the MFCs before and after operation depends on the basic wastewater treatment parameters such as the COD, BOD, total solids and nitrogen removal etc. It is reported that the operation of MFC in a fed-batch mode is advantageous to obtain a high COD removal rate. Therefore, coulombic efficiency obtained in such case is quite low varying from 10 to 30%, according to Liu et al. [97].

Another application of MFCs as pointed out by Bose [98] has to deal with biosensors, for the online monitoring of organic matter and detection of water toxicity. Studies have shown that the usual methods used to calculate the total organic content and detection of biological oxygen demand in wastewater treatment are not suitable for online screening and control of biological wastewater treatment. For the detection of the toxic content in water which is necessary for providing safe water for human, animal and crops consumptions, MFCs can act as a possible biological oxygen demand sensor because of the linear correlation of MFC with the strength of organic matter in wastewater.

More also, the presence of toxicants in fluent water can be easily detected by monitoring the perturbations in the electric current that is generated by MFCs. Fluent water is the term used to describe the water that can easily move, that is having the capacity to flow. It is sometime refers as a current of water or a stream. The use of MFCs as a biosensor will affect the metabolic activities of microbes present in any toxic element in any aqueous feedstock [101]. There is the possibility of using MFCs as biological oxygen demand (BOD) sensor. The MFCs used for this purpose has excellent operational sustainability's as well as reproducibility, which can operate for up to 5 years [45,71].

A typical double chamber MFC can be amended to microbial electrolysis cell for hydrogen production [67] as an alternative to electricity. This process occurs through the production of protons and electrons present in the anodic chamber, which are transferred to the cathode, thereby combining with oxygen to form water. Studies conducted by Trchounian and Trchounian [102], Rodriguez et al. [104] have reported the production of hydrogen with the help of microbial electrolytic cells using MFCs with external potential at the cathode terminal for the purpose of electricity generation. According to Logan [78], the generation of hydrogen gas must be accompanied by an increased additional voltage of 0.23 V or more at the anode as well as the vanished of oxygen at the cathode chamber.

Bosa [98] reported that the main application of MFCs is in generation of electricity. Some example of MFC performance for electricity from literature is presented in Table 6.

The MFC for electricity generation is made possible through the specific microbes that have the potential to convert chemical energy to electrical energy as well as the reduction of CO_2 to biomass by the application of mediator. Over 70% efficiency is obtained by MFCs, just like other chemical fuels [45]. Furthermore, electricity generation by MFC is as a result of the microorganism that oxidizes the substrate into protons and electron at the anode chamber, which passes through the PEM and electrical connection respectively, to the cathode [67]. The anode and cathode chamber of the MFC is said to be connected electrically to the multimeter, with an external resistor as to measure the voltage and power based on Ohm's law. The higher coulombic efficiency and power output of the MFCs is attributed to the substrate that oxidized into electrons. Reguera et al. [53], conducted a study in which a microorganism *Geobacter sulfurreducens* reduced acetate completely into electrons and protons. Compounds that are metabolized by bacteria have the potential to be converted into electricity. However, the main objective of MFCs is to achieve a more suitable current and power which are necessary for small electrical devices applications. Based on this, Rahimnejad et al. [107] conducted a study where ten light-emitting diode (LED) lamps were turned and one digital clock with fabricated stacked MFC. The finding revealed that both devices were successfully operated for the desired time.

Several factors are responsible for the electrical output of the MFC, such as the design of the MFC, electrode materials, pure culture or mixed culture inoculum, proton exchange membrane and operation condition (pH and temperature). Selected factors affecting the performance of the MFCs been presented and discussed in Section 6.

Table 6
Common materials used for MFC.

Anode materials	Advantages	Disadvantages	References
Carbon paper	High conductivity	Low specific area and expensive	[20]
Stainless steel	High conductivity and low cost	Poor bacteria attachment and low power generation	[20]
Carbon cloth	Flexible, large specific area	Brittle	[20]
Graphite fibre brush	High porosity and conductivity	Expensive	[20]
Graphite rod	High conductivity and defined surface area	Low strength	[20]
Conductive polymer	Large surface area	Low conductivity	[20]
Graphite granules bed	Low cost, high porosity and large specific area	High contact resistance	[20]
Cathode materials	Advantages	Disadvantages	References
Platinum	Excellent catalyst ability	Expensive	[78]
Graphite and carbon material	–	Poor catalyst for oxygen reduction	[78]
Manganese oxide; lead dioxide and cobalt complexes	High power density	Short longevity	[79]
Proton exchange membranes	Advantages	Disadvantages	References
Nafion	Ability to allow ion transfer, Excellent ionic conductivity	Oxygen leakages from cathode to anode; substrate crossover and loss	[20,22]

6. Prospects of MFCs technology

The main drawback in the use of MFC technology is associated with insufficient power output. Secondly, the issue of the high cost of electrode materials, membranes, and cathode catalyst poses a further limitation to the technology. Providing an electrode material of high surface area to improve the power output is a direction this technology should focus on in the future. Doing this in the absence of PEM in futuristic MFC (at large scale) can make the technology more economical.

From literature, MFC technology uses the same biomass present in anaerobic digestion technology in many cases for energy production. MFCs are capable of converting biomass at a temperature below 20 °C and with low substrate concentration, which tends to be problematic for methanogenic digester in both technologies [108]. As a result of the over-reliance on biofilms for mediator less electron transport associated with MFCs which is a disadvantage to the technology, while anaerobic digester such as the up-flow anaerobic sludge capacity to reduce or eliminate this, by reusing the microbial consortium without cell immobilization in an anaerobic digester, there is the possibility for the MFC technology to co-exist with the anaerobic digestion in the coming days.

As earlier stated on the application of MFCs, especially in wastewater treatment, a large surface area is needed for the biofilm to build upon the anode chamber. Therefore, creating a low-cost electrode capable of resisting fouling could be a novel research. According to Du et al. [45], it is unrealistic to expect that power density output from an MFC to compete with a conventional chemical fuel cell (hydrogen-powered fuel cell). Hence, the fuel in MFC is said to be dilute biomass located in the anode chamber that has limited energy.

Having reviewed the waste to energy technology in relation to MFC, Table 7 summarises major areas of successful application of the study (Tables 8 and 9).

Further research is needed in the area of scaling up MFC for large-scale application, though some knowledge has been gained regarding MFC. This is important because of the low reaction rate associated with over coulombic efficiency of 90%, which has been achieved in previous studies.

7. Conclusion and recommendation

Due to the high demand for energy, and environmental pollution

Table 7
Performance of wastewater treatment from MFC from selected authors.

Design of MFC	Wastewater/heavy metal	COD removal (%)	References
Single chamber MFC	Oliver mill wastewaters	65	[15]
	Biodiesel waste	90	[94]
	Chromium (VI)	99	[91]
	Cadmium	90	[95]
Double chamber MFC	Domestic wastewater	88	[96]
	Chemical wastewater	63	[77]
	Food wastewater	85	[97]
	Real urban wastewater	70	[76]

Table 8
Performance of electricity generation from MFCs from selected authors [98].

MFC Design	Substrate	Power density (W/m^3)	References
Single chamber	Glucose	68	[103]
	Acetate	835	[104]
	Ethanol	820	[23]
	Domestic wastewater	114	[105]
Double chamber	Glucose	855	[89,106]
	Acetate	1926	
	Wastewater	2485	[88]

Table 9
Areas of application of MFCs.

Application of MFC technology	References
Wastewater treatment	[99,109]
Electricity generation	[9,28,30]

associated with the production of energy from fossil fuels using conventional conversion, there is the need for an alternative source of energy and conversion technologies. Energy source for microbial fuel cells (MFCs) promises to be a clean one without pollution, which can substitute traditional fossil fuels. MFC is one of the technologies capable of producing energy from different sources of substrates. From the review, it was found that higher power density can be achieved through the use of a proper selection of microorganism, a suitable mode of operation and improved type of MFCs as well as effective use of materials. To optimise the efficiency of the MFC, different configurations and modes of operation have been developed.

Having reviewed the materials for construction of MFC, the study recommends further studies on it. This will help to reduce the internal resistance and corrosion as regards to the technology. In addition, the replacement of PEM as a result of its cost needs to be considered. The development of proton specific membrane is recommended to alleviate this problem associated with high internal resistance.

CRediT authorship contribution statement

KeChrist Obileke: Conceptualization, Formal analysis, Writing - original draft, Data curation, Methodology. **Helen Onyeaka:** Conceptualization, Formal analysis, Writing - original draft, Methodology. **Edson L Meyer:** Project administration, Supervision, Validation, Resources. **Nwabunwanne Nwokolo:** Data curation, Writing - review & editing .

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.

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