Chapter

Progress in Domestic Wastewater Treatment, Resource Recovery and Energy Generation Using Microbial Fuel Cell

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Abstract

Microbial fuel cells (MFC) are emerging as a versatile eco-friendly bioelectrochemical system (BES) that utilizes microorganisms as biocatalysts to simultaneously convert chemical energy in the chemical bond of organic and inorganic substrates into bioelectricity and treat wastewater. The performance of MFC depends on the electroactive microorganisms, popularly known as exoelectrogens, the loading rate of organic substrate, pH, MFC configurations, hydraulic retention time, and temperature. In most cases, the performance of MFC can be evaluated by measuring chemical oxygen demand (COD) removal efficiency, Coulombic efficiency and MFC power density output. To date, the most common MFC's reactor designs are single-chamber MFC, double-chambers MFC, and stacked-MFC configurations. Generally, considerable developments in MFC systems for waste treatment, renewable energy generation and resource recovery have been made in the last two decades, despite critical challenges of capital cost investment, and low efficiency for large scale applications are impeding MFC from commercialization. This mini-review chapter provides a comprehensive assessment of principles and configurations of MFC, treatment of domestic wastewater, energy generation, and resource recovery by MFC and challenges of MFC. I believe the information provided in this chapter will enlighten the current and future prospects of versatile applications of MFC during domestic wastewater treatment.

Keywords: microbial fuel cell, MFC configuration, domestic wastewater, energy production, wastewater treatment, resource recovery

1. Introduction

The demand for sustainable resources and clean energy with minimal resource consumption is increasing because of rapid global population expansion, rising industrial development, high levels of environmental issues and energy insecurity. The world is confronting a climate change catastrophe and developing technologies that recycle wastes into value-added products, and renewable energy is a critical first step toward addressing the issues.

Waste flow is unending in today's dynamic world; hence, recycling and repurposing waste as a source of value-added materials and clean energy are

the comprehensive and intellectual strategy for the future. This optimistic approach of utilizing wastewater as a source of value-added products and clean energy would save society from energy insecurity and environmental resource depletion from the earth. Domestic or municipal wastewater and industrial wastewater are the two main types of wastewater generating every day. Domestic wastewater contains significant amounts of chemical oxygen demand (COD) with the range from 60 to 111,600 mg/L COD. Industrial wastewater, on the other hand, comprises a variety of nutrients depending on the source of the waste or the industry [1]. Water pollution and a lack of sufficient energy are the two most pressing issues today; however, a new technology known as the microbial fuel cell (MFC) can help address these issues in part. MFC is a versatile technology and can be used for a variety of applications, including Electric power generation, wastewater treatment, recovery of pure materials, removal of organic matters, water softening, bioremediations, dye decolorization and biosensor [2–5].

In this mini-review, the principle of MFC, evaluation of MFC's performance in domestic wastewater treatment, and varieties of MFC configurations are all explained. Moreover, the progress of domestic wastewater treatment, energy generation, and resource recovery simultaneously by MFC are all briefly summarized. In addition, the challenges encountered by MFC during the application of domestic wastewater treatment are thoroughly discussed. Finally, concluding remarks on domestic wastewater treatment by MFC are forwarded.

1.1 Fundamental principles of MFC

MFC is an ecofriendly bioelectrochemical system (BES) that utilizes microorganisms as biocatalysts to convert chemical energy in the chemical bond of organic and inorganic substrates into bioelectricity [6]. The organic and inorganic substrates used in MFC as the main feed to generate bioelectricity are low-grade biomasses like lignocellulose, artificial and real wastewaters which are all discharged to the environment every day as waste [7]. As a result, even while major technological challenges remain for its practical development and large-scale applications, MFC is becoming increasingly favorable in terms of environmental sustainability and alternative green electricity generation [8].

MFC mostly comprises anodic and cathodic chambers, and both are separated by proton exchange membrane (PEM). If one of the anodic or cathodic chambers in BES is triggered by microorganisms and produces electrical energy, the term Microbial Fuel Cell (MFC) is used. Microbial electrolysis (MEC) is employed when the system uses electrical energy to accelerate the electrochemical reactions (see **Figure 1**) [10].

1.2 Evaluation of MFC's performance during domestic wastewater treatment

In most cases, the performance of MFC can be evaluated by measuring three parameters: COD removal efficiency, Coulombic efficiency and MFC power density output.

The COD removal efficiency (η_{COD}) of MFC indicates the total energy produced by microorganisms from the substrates (mostly organic matters). It can be estimated by using the following equation:

$$\eta_{COD} = \frac{\left(COD_{inf} - COD_{eff}\right)}{COD_{inf} * 100\%} \quad (1)$$

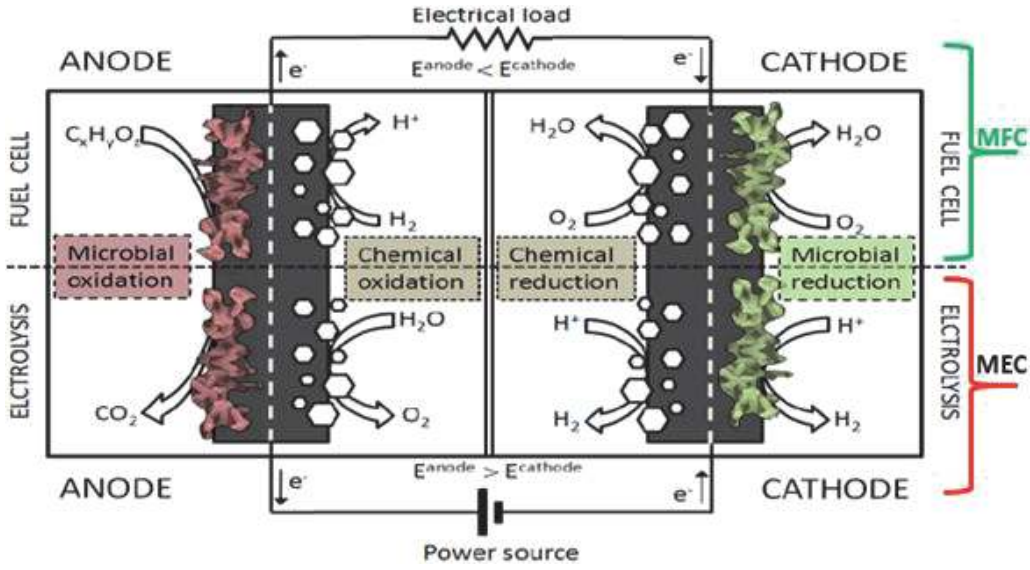

Figure 1.
Schematic overview of the possible combination of microbial and chemical analysis in BESs. Energy is harvested in MFCs if $E_{anode} < E_{cathode}$, *and energy is consumed in MECs if* $E_{anode} > E_{cathode}$ *[9].*

where, COD_{inf} and COD_{eff} are the influent and effluent COD (mg/L) respectively.

All organic matters cannot be converted to useful energy in MFC. This is because the biofilm formed on the MFC's anode or/and cathode chamber needs the energy to grow and maintain itself. As a result, some energy is dissipated as unrecoverable low-grade heat due to overpotentials such as pH gradient across PEM, ionic loss, activation overpotential, concentration overpotential, anode and cathode overpotentials, and ohmic loss due to internal resistance. Therefore, the real potential generated by the closed-circuit MFC is significantly lower than the energy produced from the theoretical open circuit potential. Thus, the performance of MFC is evaluated by calculating the real closed-circuit potential by using the standard potential as follow [8]:

$$U_{output} = E_{cathode} - E_{anode} - \sum \eta_j + I * R_i \tag{2}$$

where $\sum \eta_j$ is the sum of both activation and concentration overpotentials, I is the current flow, R_i is the internal resistance in the circuit. $E_{cathode}$ and E_{anode} are electrode potentials for cathode and anode, respectively which can be calculated by Nernst equation [6]:

$$E_{cathode} = E^o_{cat} - \frac{RT}{nF}\left[\ln\left(\frac{[R]}{[O]}\right)\right], E_{anode} = E^o_{an} - \frac{RT}{nF}\left[\ln\left(\frac{[R]}{[O]}\right)\right] \tag{3}$$

where, E^o_{cat} and E^o_{an} are standard electrode potentials for cathode and anode, respectively, O is the oxidized species, R is the reduced species and n is the number of electrons that transfers during reaction. R is the universal gas constant (8.314 J/mol K), F is Faraday's constant (9.64853 * 104 C/mol) and T (K) is the absolute temperature.

The second parameter used for evaluating the performance of MFC is done by estimating the Coulombic efficiency. Coulombic efficiency explains the ratio of numbers of electrons transfer vial external resistance, R (ohms), which generates

electricity, to the total number of electrons generated from the organic substrate by microorganisms. Therefore, the Coulombic efficiency (CE) of MFC can be calculated as follow [11]:

$$CE = \frac{\left(\int_{t_1}^{t_2} Udt\right)/R}{F * b(\Delta COD)V} * MW \tag{4}$$

where U is the output voltage as a function of time (t), R is external resistance in ohms, b is the number of electrons exchanged per mol of O_2, equal to 4, COD is the removal of chemical oxygen demand, V is the volume of wastewater in litter in the anodic chamber, and MW is the molecular weight of O_2. The last parameter used for measuring the performance of MFC is power density based on electrode projected surface area (PA) or/and power density based on the liquid volume in the anodic or cathodic chamber (PV) and it can be calculated as follow:

$$\mathrm{P} = \mathrm{IU}, \mathrm{PA} = \mathrm{P/A}, \mathrm{PV} = \mathrm{P/V} \tag{5}$$

where, A is the surface area of an electrode and V-the liquid volume anolyte in the anodic or catholyte in the cathodic chamber.

2. Domestic wastewater treatment and energy harvesting simultaneously by MFC

Domestic wastewater is any waste that has been used and then discharged into the environment by consumers in any community. It consists of all types of waste materials, such as feces and urine which are added to the water during flushing toilets, personal washing, laundry, food preparation and kitchen cleaning [12].

Domestic wastewater is one of the sources of water, energy and value-added chemicals and nutrients for plant fertilizers, among other things. As a result, it is critical to the process and converts domestic wastewater into renewable energy, value-added products and reduces sludge generation. The aerobic wastewater treatment technique, which is one of the conventional and common treatment methods, faces obstacles such as high operating costs and energy-intensive [1]. Therefore, biological wastewater treatment employing MFC is considered as an alternative technique due to water treatment by removing chemical oxygen demand (COD), recovery of value-added chemicals and electricity generation simultaneously [2, 13].

2.1 Principle of wastewater treatment and energy generation by MFC

The principle of wastewater treatment using MFC is that electrochemical reactions are taking place inside the chamber of MFC and pollutants are removed by exoelectrogenic microorganisms. As the result of these reactions, Gibbs free energy (negative free reaction energy) and release energy (electric or electron release) are spontaneously released. The electromotive force (emf), ΔE^0, can be calculated from the standard free energy as follow [2]:

$$\Delta E^0 = -\left[\sum v_i \Delta G^0_{i,products} - \sum v_i \Delta G^0_{i,reactants}\right]/nF - \frac{\Delta G}{nF} \tag{6}$$

where, $\Delta G^0_{i,products}$ and $\Delta G^0_{i,reactants}$ are the negative free energies of formation of products and reactants (J/mol), respectively, n (moles) of stoichiometry factors of the redox reaction, and F—Faraday's constant (96,485 C/mol).

The useful energy that can be extracted from the reaction of thermodynamic is measured by Gibbs free energy of the reaction. If the system of MFC is generating electricity from wastewater, the theoretical cell voltage of MFC (or emf) can be calculated from the difference between anode and cathode potentials as follow:

$$\Delta E^0_{cell} = \Delta E^0_{cathode} - \Delta E^0_{anode} \tag{7}$$

The cell voltage of MFC will be positive if the Gibbs free energy is negative, indicating that electrical energy generation from the reaction in MFC is spontaneous. For instance, if the wastewater with high content of acetate is used as the organic substrate in MFC, and assume that the concentration of acetate ($[CH_3COO^-]$ = $[HCO_3{}^-]$ = 10 mM, pH = 7 at 298 K, pO_2 = 0.2 bar), with oxygen reduction, the combined redox reaction will be as follow [14]:

$$\text{Ande} : CH_3OO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^- \left(E^0 = -0.289 \text{ V vs.SHE}\right) \tag{8}$$

$$\text{Cathode} : 2O_2 + 8H^+ \rightarrow \left(E^0 = -0.85 \text{ V vs.SHE}\right) \tag{9}$$

$$\text{Total} : CH_3OO^- + 2O_2 \rightarrow 2HCO_3^- + H^+ \left(\Delta G = -847.6 \frac{\text{kJ}}{\text{mol}}; \text{emf} = 1094 \text{ V}\right) \tag{10}$$

The effective mechanisms and treatment of domestic wastewater by MFC are mainly influenced by several factors such as the configuration of MFC, pH of the electrolyte, the temperature of the electrolyte, electrodes configuration, substrate concentrations, biofilm formation, hydraulic retention time and types of microorganisms [1, 15–18]. Some of the parameters and their effect on the operational performance of MFC are briefly summarized in **Table 1**.

From the different operation parameters affecting the performance of MFC during wastewater treatment, only three configurations of MFC are summarized in the following sections.

2.2 Configurations of MFCs for wastewater treatment

It is very important to evaluate the configurations and designs of MFC for domestic wastewater treatment and power generation simultaneously. This is because configurations can alter the reactor volume, the presence or absence of proton exchange membrane or porous spacer, oxygen supply into cathode chamber and electrode spacing. The most common MFC configurations include single-chamber MFC, double chambers MFC, and stacked MFC configurations [15].

2.2.1 Single chamber MFC

Single chamber MFC (SCMFC) contains only one chamber, which anode chamber, with a proton exchange membrane (PEM) or gas diffusion layer (GDL) which separates anode chamber and cathode electrode [19]. In some cases, SCMFC can be designed without a membrane [20]. During operation, the wastewater to be treated and the biocatalysts, which are microorganisms, are added to the SCMFC's anode chamber. For microorganism's survival and to degrade/oxidize organic sources in the water, the environment of MFC should be anaerobic. Anode and cathode of SCMFC are connected by external wire and electrical ions are transferred through it

Parameter	Effect in the performance of MFC
pH	• Increasing the acid level in the anode chamber inhibits the growth of microorganisms. • Increasing the pH level in the cathode chamber decreases the reduction of O_2 potential. • The average optimal pH is between 8 and 11.
Substrate concentration	• A high level of COD enhances the removal of COD in the wastewater and generates higher power density until the optimum point where microorganisms are inhibited. • A high level of COD decreases the average recovery efficiency of NH_4^+-N and PO_4^{3-}-P.
Temperature	• The optimum temperature for the biofilm formation is between 30 and 45°C. • The lower temperature needs a longer start-up time.
Hydraulic retention time	• Energy generation and COD removal are directly proportional to hydraulic retention time.
Resistance	• The lower the external resistance, the higher generation of energy and removal efficiency of COD. • The higher external resistance delays the time for substrate degradation and reduces electron transport.
Aeration	• Increasing the oxygen in the anode chamber inhibits the COD removal. • The higher the oxygen level in the cathode chamber enhances COD removal and power generation.
Configuration of MFC	• Different configurations, single chamber, double chamber, and stacked MFC have different performances in energy generation.

Table 1.
Different parameters affecting the performance of MFC in wastewater treatment [1, 16–18].

from anode to cathode. The air-porous cathode is directly exposed to oxygen from the atmosphere and electrons are transferred from the anode to it via an external wire to complete the circuit. Oxygen is then serves as an electron acceptor and reduces to produce water after reaction with hydrogen ion. The most common configuration of SCMFC is shown in **Figure 2**.

The electrolyte in the anode chamber serves as a separator in SCMFC without membrane. The efficiency of SCMFC without membrane, on the other hand, is lower than that of SCMFC with a membrane. The reason of decreasing efficiency is that degradation of substrates in the anode chamber occurs aerobically as a result of oxygen diffusion into the anode chamber, leaking of the anolyte, and evaporation [21, 22]. Some of these challenges can be prevented or reduced by utilizing polytetrafluoroethylene (PTFE) diffusion layers on the cathode, which improve oxygen diffusion and water loss [21]. Because there is no cost for the membrane, and if the efficiency of SCMFC without a membrane is enhanced, it will be more advantageous economically than SCMFC with membrane. Moreover, since there is no need for aeration in the cathode chamber, SCMFC is more cost-effective [15, 19].

Using glucose as substrate, graphite carbon brush as anode and 30% Pt coated carbon cloth as a cathode [23], the SCMFC configuration can generate power density up to 2400 mW/m^2 over 50 Ω external resistance. Whereas, when SCMFC is employed for domestic wastewater treatment (pH of 7.3–7.6, and chemical oxygen demand (COD) of 200–300 mg L^{-1}), 766 mW/m^2 power density was generated over 1000 Ω external resistance and from 90–95% COD was removed using carbon cloth as the anode, and 0.5 g/cm^2 Pt coated wet-proof carbon cloth with four PTFE layers on the airside as a cathode [24]. In another report, the domestic wastewater

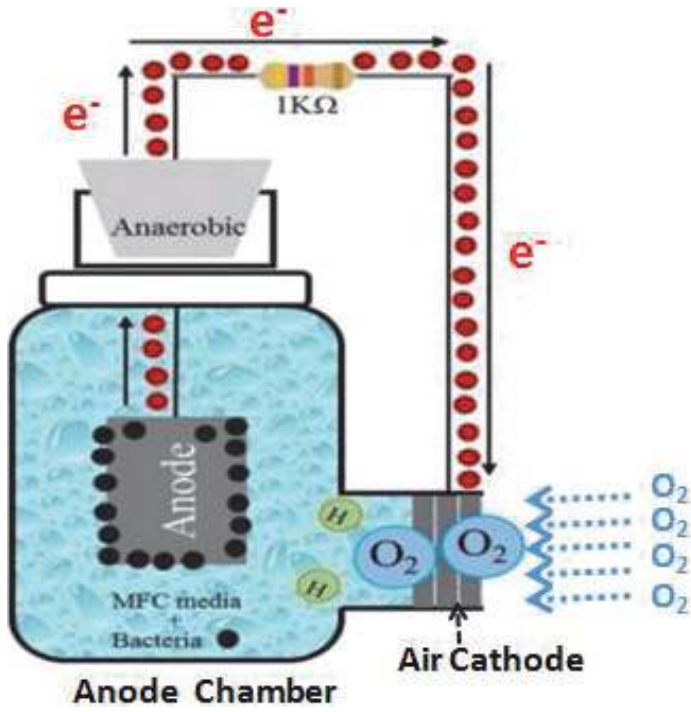

Figure 2.
Configuration of single-chamber MFC (modified from [21]).

(COD = 1010 ± 30 mg L^{-1}) can be modified with acetate and treated by using SCMFC with a single (two-sided) cathode module with a specific surface area of 29 m^2 m^{-3}, two brush anode module and a wire spacer as a separator. The results reveal a higher power density of 1100 mW/m^2 with an average COD removal of 57% [25] than the aforementioned system.

2.2.2 Double chamber MFC

Double chamber MFC (DCMFC) contains anode and cathode chambers which are separated by proton exchange membrane (PEM). PEM allows the transfer of a proton from the anode chamber to cathode chamber while preventing the diffusion of oxygen from cathode chamber to anode chamber (see **Figure 3**). DCMFCs are often used to cleanse wastewater and generation of electricity from the waste simultaneously. Although the cathode and anode chambers are different compartments and separated by PEM, anode and cathode electrodes from each chamber are connected by an external wire through which electrons from the anode are delivered to the cathode [21].

Flat plate MFC [27], bottle MFC [28], miniature MFC [29], and up-flow MFC [30, 31] are examples of DCMFC configurations. The up-flow MFC configurations are thought to be particularly well suited to scaling-up for high larger volume domestic wastewater treatment. However, pumping fluids and recirculation of the waste inside the up-flow MFC systems consume more energy than the system's output, indicating that the primary function of the up-flow MFC is used mainly for wastewater treatment than energy generations. Moreover, another drawback of the DCMFCs configuration is that the catholyte in the cathode chamber must be supplied with new electrolytes regularly or with aeration to provide oxygen to the cathode [21].

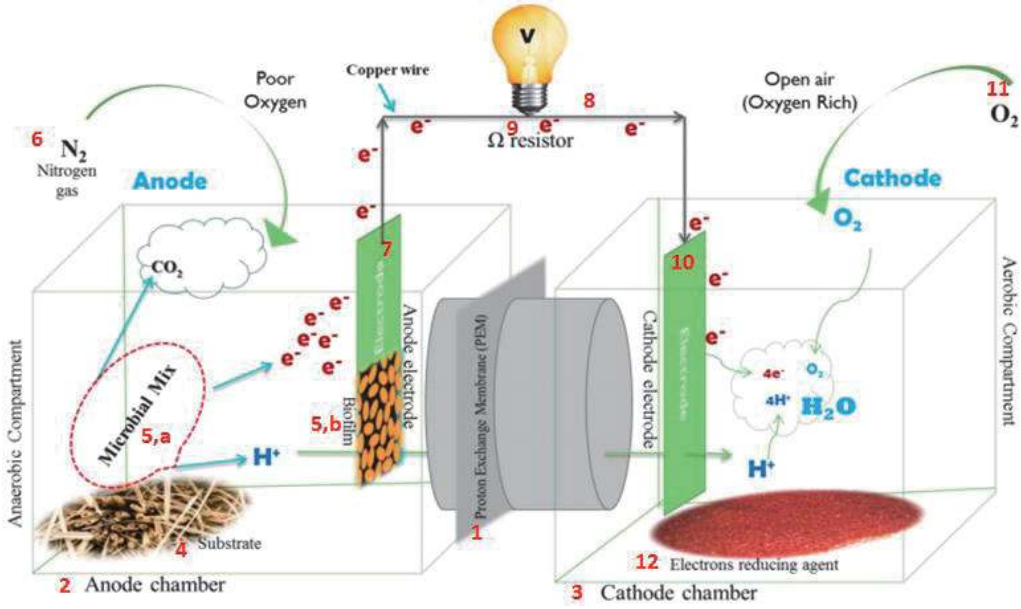

Figure 3.
Major components of double chamber MFC: 1. proton exchange membrane (PEM) selective to H^+ cation and separating the two chambers; 2. anode chamber (anaerobic conditions); 3. cathode chamber under aerobic (open-air) conditions; 4. substrate or biomass for bacteria to feed on; 5. pure or mixed bacterial culture (a) and biofilm (b); 6. nitrogen gas to remove oxygen and maintain the anaerobic condition; 7. anode electrode, on which microorganisms are attached; 8. copper wire for transferring electrons from anode to the cathode; 9. external resistor; 10. cathode electrode; 11. air oxygen; 12. electrons reducing agent [26].

Due to differences in biofilm growth on the anode chamber, treatment of domestic wastewater with DCMFC over different seasons results in variable treatment performances. For example, during the summer season, domestic wastewater treatment generates a higher power density (209 mW/m^2) than during the winter water sample, which generates only 107 mW/m^2. The COD removal efficiency for summer season wastewater was 72%, while there was no significant COD removal for a winter sample of domestic wastewater [32].

2.2.3 Stacked MFC

To scale up the voltage, stacked MFCs combine multiple MFCs in series and parallel. Both connections can be utilized to treat wastewater and generate electricity at the same time. In a series stacked MFC connection, the higher power density and current density can be generated than in a parallel stacked MFC connection [33]. For instance, E.B. Estrada-Arriaga et al. used series and parallel connections of stacked MFCs for domestic wastewater MFC. The results revealed the higher power density (2500 mW/m^2) and current density (500 mA/m^2) in series connection than that of power density (5.8 mW/m^2) and current density (24 mA/m^2) in parallel connection. Moreover, the efficiency of COD removal is also higher in series connection (>80%) than that of the efficiency (>78%) in parallel stacked MFC [34]. The increase of power density and efficiency of COD removal caused by however, in some situations, stacking MFC in series connection faced a challenge due generating negative voltage (voltage reversal), indicating that the system's complex bioreaction resulted in a loss of microbial activity. The challenge can be partially solved by installing diodes in the stacked MFC in order to consume unbalanced electrons and reduce the variation of electrode potentials. On the other hand, for power and wastewater generation, pluggable stacked MFC designs are preferable due to their benefit of off-line capacity for repairs (**Figure 4**) [15].

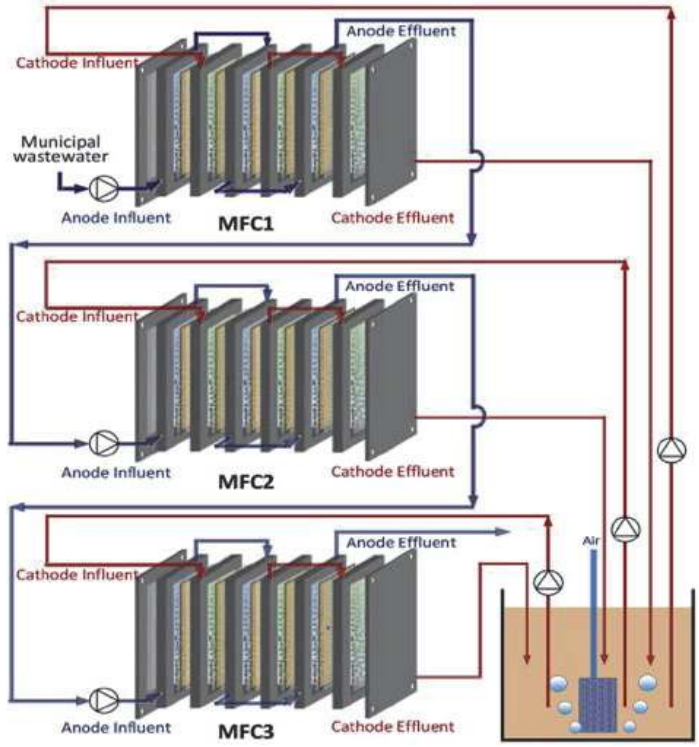

Figure 4.
Water flow connection for treating the municipal wastewater with high COD concentration using stacked MFC. Every three MFC modules were assembled to achieve step-wise COD removal [33].

The largest volume (1000 L) of modularized stacked MFC was assembled and operated for more than a year for municipal wastewater treatment with lower (average 80 mg L^{-1}) and higher initial COD concentrations (average 250 mg L^{-1}). The result showed that the COD removal efficiency was 74% and 70–80% for lower and higher initial COD treatment, respectively. Moreover, the power density was varied in the range from 7 to 60 W m^{-3} (0.42–0.64 W m^{-2}) [33].

3. Resource Recovery from domestic wastewater by MFC

Currently, there is an urgency of closing the cycle of resources for more sustainable development and resource efficiency of current domestic wastewater treatment practices. The effluent of domestic wastewater contains high contents of fat, food residues, detergents, feces, and pharmaceuticals. Thus, in the form of chemicals and value-added compounds, domestic wastewater contains different chemicals presented in **Table 2** [35]. If domestic wastewater is discharged untreated into the water body, the nutrients found in it will be the main potential of causing eutrophication and hypoxia. Therefore, MFCs are useful technologies to recover nutrients from domestic wastewater before its discharge to the environment.

Recovery of these valuable resources presents in domestic wastewater using MFC increases its economic viability. Especially, nitrogen and phosphorous are highly important in the agricultural process due to their use as fertilizers [1].

Nitrogen in domestic wastewater can be removed or recovered using MFC in the form of NH_4^+-N by the processes of ammonification, nitrification and denitrification. Microorganisms in the anode chamber of MFC are the main agents to remove/recover NH_4^+-N and then transport it to the cathode chamber by diffusion and migration. For the diffusion of ammonium, the concentration gradient is the main driver, while

Value-added chemical compounds	Amounts of chemicals
Carbon-rich organic matter (carbonaceous chemical oxygen demand, or COD)	300–600 g
Nitrogen (from ammonium and organic compounds)	40–60 g
Phosphorus (from phosphates and organic compounds)	5–20 g
Sulfur (mainly sulfate) and other traces of heavy metal ions	10–20 g

Table 2.
Different resources from domestic wastewater [35].

electricity is the main parameter in migration. In this case, the content of ammonium in the catholyte is comparative to electricity production by MFC [36–38].

Similarly, phosphorus from domestic wastewater can be precipitated in the form of struvite ($NH_4MgPO_4{\cdot}6H_2O$) on the surface of the cathode [39]. Struvite is a slow-release fertilizer and has many commercial values if it is recovered efficiently including reuse as fertilizers, substituting the demand for phosphorus rock and reducing eutrophication in the water body [40, 41]. The content of phosphorus in struvite is found in the range of 13% and 14% by weight. Since phosphorous is involved in the redox reaction, it can be recovered as struvite according to the following equation.

$$Mg^{+2} + NH_4{}^{+} + PO_4{}^{3-} + 6H_2O \rightarrow NH_4MgPO_4 \cdot 6H_2O\downarrow \qquad (11)$$

The precipitation of struvite occurs near or on the surface of the cathode electrode. This is because the solubility of struvite is decreased at higher pH and in MFC, the pH is higher at the cathode surface due to the reaction producing more OH^- ions as shown in Eq. (12) [17].

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \qquad (12)$$

Generally, it is estimated that the availability of total phosphorous in the sewage could supply 15–20% of the world's demand for phosphorous, provided that recovered fully [17].

Therefore, there is now a recommendation of shifting from pollutant removal to resource recovery from domestic wastewater which is now considered as a source rather than a waste [42]. With this regard, MFC is the key technology for resource recovery and energy generation simultaneously from domestic wastewater. For instance, ammonia was recovered with a recovery rate of 3.29 gN d^{-1} m^{-2} and with simultaneous surplus energy generation of 3.46 kJ gN^{-1} from urine by using MFC technology [4].

The loading rate of organic substrates in wastewater significantly affects the recovery/removal of nutrients and electric generation by MFC. This is because, the content of organic substrates in the waste influences the metabolism activities of microorganisms, growth of microorganisms, hence biofilm formation on the surface of electrodes, and the ability of substrate degradation by microorganisms [17]. Yuanyao Y. et al., reported in their experiment that when the loading rate of organic substrate in domestic wastewater is increased, power generation and COD removal are decreased but the recovery efficiency of $PO_4{}^{3-}$-P and $NH_4{}^{+}$-N by MFC are increased. For instance, the maximum power density and COD removal efficiency by MFC at 435 and 870 mg COD/L day loading rate of the organic substrate is 253.84 mW/m^2 with 90% COD removal efficiency and 71.66 mW/m^2 with 70%, COD removal, respectively. On the contrary, when the loading rate of the organic

substrate was 435 mg COD/L day, the average efficiency in removing NH_4^+-N and PO_4^{3-}-P in the anode effluent was 14% and 12.43%. When the loading rate of organic substrate was increased to 870 mg COD/L day, the average efficiency in removal of PO_4^{3-}-P and NH_4^+-N in domestic wastewater by using MFC were also increased to 71.5% and 75.13%, respectively. However, for the recovery of NH_4^+-N from domestic wastewater using MFC, the average recovery reduced from 85.11% to 24.34% while increasing the loading rate of organic substrates from 435 to 870 mg COD/L day, respectively. Similarly, the recovery rate of PO_4^{3-}-P was decreased from 83.23% to 24.4% while increasing the loading rate of the organic substrate from 435 to 870 mg COD/L day, respectively [16]. These results strictly showed that the loading rate of organic substrate significantly affects the removal of COD, generation of power and nutrient recovery from domestic wastewater using MFC technology.

4. Challenges of MFC for domestic wastewater treatment

The main drawback of MFC technologies for large-scale applications is the capital cost investment, hence making the technology not feasible for large-scale wastewater treatment and other applications. The costs are mainly associated with electrodes materials, membranes, separators, current collectors and the addition of expensive Pt catalysts [1, 19, 43]. The operational cost for the treatment of domestic wastewater by MFC is as high as 30 times that of the conventional activated sludge treatment of domestic wastewater [44]. However, operational costs can be minimized with the power output of MFC that can be reused for domestic wastewater treatment associated with heating, despite power production is not higher compared with the power input. In addition, the process of domestic wastewater treatment by MFC does not produce a high quantity of sludge, indicating less treatment process of sludge before it is discharged to the environment [1, 19].

Another challenge of MFC for domestic wastewater treatment is scaling-up the size and its treatment efficiency. Scaling-up is mainly expressed in terms of increasing capacity and size of MFC that facilitate and enhance electron transport efficiency. This challenge can be partially solved by large stacked MFC systems with 250–1000 L [33, 45]. Moreover, the distance between anode and cathode also affects the efficiency of MFC because of an increment of resistance. Minimizing the distance between electrodes can solve the issue partially. The electrode stability during domestic wastewater treatment is a very important factor for the performance of MFC. Thus, developing low-cost, high current density output, and carbon-rich anode materials from waste tires are of high importance for solving the problem [43, 46].

5. Conclusion

Domestic wastewater, if left untreated, can be the main source of pollution in the environment, but it can also be used as a raw material for energy production and nutrient recovery. Domestic wastewater treatment, bioelectricity generation and resource recovery simultaneously by using MFC is an eco-friendly strategy and provides many benefits. These include one, it helps the direct generation of renewable electric power from waste. The power generated can be reused for wastewater treatment processes and thus minimizes costs associated with the energy consumption for heating the process. Second, it treats domestic wastewater

by removing COD and releases good quality effluents before discharging it to the environment, thus achieving a low environmental footprint. Third, it assists resource recovery like phosphorus, carbon-rich compounds and nitrogen from domestic wastewater because of the effective combination of biological processes and electrochemical processes in bioelectrochemical systems. Especially, nitrogen and phosphorous are highly important in the agricultural process due to their use as fertilizers.

However, the performance of MFC depends on the electroactive microorganisms, commonly known as exoelectrogens. Moreover, the operating parameters such as loading rate of organic substrate, pH, MFC configurations, hydraulic retention time, and temperature all have an impact on MFC performance during domestic wastewater treatment. In most cases, the performance of MFC can be evaluated by measuring three parameters: COD removal efficiency, Coulombic efficiency and MFC power density output. One of the elements in the success of MFC is its design. To date, the most common MFC reactor designs have been single-chamber MFC, double chambers MFC, and stacked MFC configurations. The size of each type of reactor design greatly varies with some MFCs having sizes of a few square centimeters and others having up to a square meter with volumes ranging from milliliters to thousands of liters, respectively. Considerable developments in MFC systems for waste treatment, renewable energy generation and resource recovery have been made in the last two decades, despite critical challenges of capital cost investment, and low efficiency for large-scale applications are impeding MFC from commercialization. Therefore, improving these technical challenges must pave the way for making economically feasible large-scale MFC. Further research will suggest reasonable design, and size of reactors for the multi-purpose MFC to efficiently treat domestic wastewater, generate renewable energy and resource recovery.

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Conflict of interest

The authors declare no conflict of interest.

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