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Economic benefit analysis of typical microbial fuel cells based on a cost–benefit analysis model

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ABSTRACT

A cost–benefit analysis model was developed using the full microbial fuel cell (MFC) lifecycle costs and benefits to improve the efficiency with which MFCs are used to generate power and purify wastewater. The cost per unit power and revenue per unit power for typical MFCs were calculated from the investment cost and revenue from generating power during the wastewater treatment process. The cost–benefit ratio (CBR), calculated from the cost per unit power and revenue per unit power, was used to describe the comprehensive benefits offered by MFCs. The model indicated that revenue per unit power increased faster as the cost per unit power increase for a constructed wetland MFC (CW–MFC) than for the other MFCs that were assessed. The CW–MFC gave the best comprehensive benefits of the MFCs that were assessed, the lg(CBR) values being 2.7238 ± 0.1504 under experimental conditions and 2.4910 ± 0.0584 under practical conditions. The constructed wetland MFC lg(CBR) values were significantly lower than the lg(CBR) for the other MFCs ($p < 0.05$). The microalgae MFC (MA-MFC) gave the poorest comprehensive benefits, and the lg(CBR) values for experimental and practical conditions were both significantly higher ($p < 0.05$) than the lg(CBR) values for the other MFCs.

Keywords: Microbial fuel cells; Cost–benefit analysis model; Comprehensive benefit

1. Introduction

Socio-economic development and dramatic population increases in China are causing increasingly severe environmental problems and increasing demand for energy. China used more energy than any other country in 2010, 2011, and 2012 (previously the USA used more than any other country) [1]. Total energy consumption in China in 2016 was ~4.36 × 10^9 t standard coal equivalents, and energy consumption has increased by 1.4% each year on average [2]. Traditional fossil fuels such as coal and petroleum are non-renewable and will eventually run out. Water pollution is an increasingly serious problem in China and directly leads to water shortages. It has been found that almost half of all water bodies in China are polluted to some degree and that almost 200 × 10^6 people in China have contaminated drinking water [3]. Conventional water supply and wastewater treatment processes require high energy inputs, and this can aggravate water shortages.

It is important to develop ways to use energy sustainably, decrease energy use, and decrease environmental pollution. Microbial fuel cells (MFCs), which use electrode reactions to take advantage of metabolic processes in microbes, are new systems allowing renewable energy to be produced while treating waste material. MFCs are considered to be promising ways of producing energy while treating wastewater [4,5]. MFCs generate electricity through electro-active bacteria consuming organic pollutants [6].

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MFCs produce electricity and purify wastewater, but currently available MFCs produce much less energy than can be produced by chemical fuel cells. High installation and operating costs (because expensive proton exchange membranes and Pt-catalytic cathodes are used) make currently available MFCs unattractive [7]. The benefits of MFCs therefore need to be explored in detail.

Many previous studies of MFCs have been focused on MFC design and configuration and the electrode materials, operating parameters, and bacteria used. Little effort has been put into performing cost–benefit analyses (CBAs) for MFCs, and no complete accounting systems have been performed. A CBA model based on a comprehensive analysis of various MFCs is established here. The CBA was validated using MFC test cases to allow the comprehensive benefits offered by different MFCs to be analyzed and compared and the best operating mode to be identified.

2. MFC devices

Classic MFCs are usually composed of anode and cathode chambers separated by proton exchange membrane [8]. The schematic structure is shown in Fig. 1. Substrate in the anode chamber is oxidized under catalytic actions of microorganisms to produce electrons and protons. The electrons are transferred to the anode surface before they reach the cathode through wires which connect the cathode and the anode. The protons migrate to the cathode through the proton exchange membrane residing between the cathode and anode chambers. Protons and electrons react with the oxidizing materials in the cathode chamber on the cathode surface, which makes MFC to output electrical energy.

There are a number of ways, using different standards, of classifying MFCs. MFCs of the types described below are currently available.

2.1. Single-chamber and double-chamber MFCs

Most MFCs currently used in laboratories are double-chamber MFCs. Such a MFC has an anode chamber and a cathode chamber separated by a proton-exchange membrane [9–11]. Electrolyte solutions in the cathode and anode chambers are independent of each other and the cathode and anode act as electron acceptors and electron donors, respectively. Double-chamber MFCs are airtight, which guarantees an anaerobic environment in the anode chamber and protects the anode chamber from contamination. Double-chamber MFCs are often used to separate electrogenic bacteria and to test the electrogenic performances of individual bacteria species [12].

A double-chamber MFC will have a high internal resistance, as high as 900–1000 Ω [13], which will restrict the electrogenic performance of the MFC. Double-chamber MFCs have complex structures and are expensive and large. These disadvantages can be avoided in single-chamber MFCs, which were developed from double-chamber MFCs [14,15]. A single-chamber MFC does not have a cathode chamber, meaning the cathode and anode are closer than in a double-chambered MFC. This design is cheaper than a double-chambered MFC because no proton exchange membrane is used, and the internal resistance is somewhat lower in a single-chambered MFC than in a double-chambered MFC. However, it is easier for oxygen to reach the anode of a single-chambered MFC than the anode of a double-chambered MFC, meaning it is difficult to maintain an anaerobic environment at the anode of a single-chambered MFC.

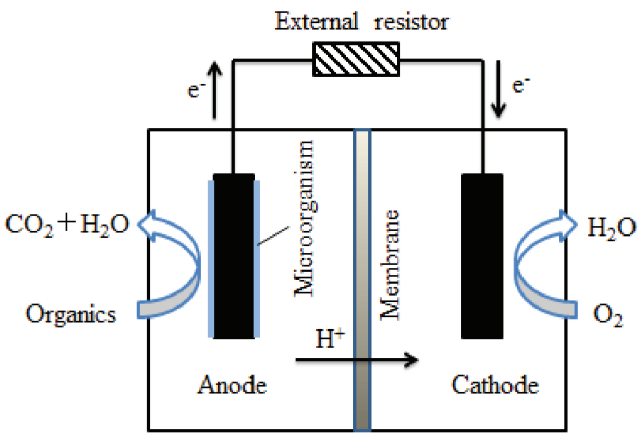

Fig. 1. Schematic diagram of a microbial fuel cell.

2.2. MFCs with different electrode materials

The electrodes determine the performance and cost of an MFC, and the biggest challenge to producing a cost-effective and extendable MFC is designing suitable electrodes [16]. The electrogenic bacteria in an MFC reside on the anode, and the catalytic reactions occur at the anode–solution interface. A good anode should be conductive, chemically stable, biocompatible, and have a large specific surface area. Carbon paper, carbon cloth, graphite sheets, and graphite plates are often used as electrodes in the laboratory [17]. Carbon-based materials are cheap, conductive, and corrosion resistant. Bacteria easily become attached to the surfaces of carbon-based materials and grow. However, carbon-based anodes generally give poor electrogenic performances. The electrogenic performance of a carbon-based anode can be improved by ammoniating the anode at a high temperature, treating the anode with acid, or adding a small amount of metal ions to the carbon material. Granular activated carbon has been successfully used in MFCs because it has a large specific surface area and is cheap and easy to handle [18]. Carbon nanotubes have stable pore structures, and the pores are conducive to microorganism growth. Graphene has a high catalytic activity because of its unique honeycomb lattice structure. Carbon nanotubes and graphene are widely used in MFC anodes because of the advantages they offer, and they have been found to improve the electrogenic performances of MFCs relative to previously available anodes. Composite materials prepared by combining conductive polymers with carbon nanotubes or graphene give higher MFC power densities than can be achieved using carbon nanotubes or graphene alone.

The cathode accepts protons and electrons and determines the redox reaction rate. The cathode should have a high redox potential and be stable. A catalyst often needs to be added to the cathode to give a good electrogenic performance. Most MFCs use air cathodes, which are generally made from carbon-based materials. Activated carbon cathodes have been found to give comparable performances to Pt-loaded cathodes in MFCs [19,20]. Foamed nickel and stainless steel can also be used in MFC cathodes because they are cheap, very conductive, and physically strong [21]. The catalyst used in the cathode is critical to the MFC performance. Pt and Pt alloys give satisfactory catalytic effects. However, the price of Pt limits the use of Pt and Pt alloys. Transition metal oxides are widely used as cathodes because they are cheap and widely available. MnO_2 and TiO_2 are considered to be ideal cathode catalysts. Conductive polymers such as polyaniline and polypyrrole are easy to synthesize and have good electrical conductivities and stabilities. Polyaniline and polypyrrole used either alone or in composites with other materials (e.g., carbon nanotubes or V_2O_5) are good catalysts. Marked progress has been made in developing materials with performances comparable to the performance of Pt in the short term and even longer term [6].

2.3. Microalgae MFCs

It has been found that microalgae–microbial fuel cells (MA–MFCs) combining photosynthetic microorganisms with MFCs can generate electricity efficiently using light and carbon dioxide and also purify water. Research into MA–MFCs was first performed in 1964. However, the energy utilization rate was too low for early MA–MFCs to be of practical use [22]. Improvements in the structures and performances of MFCs have allowed MA–MFCs to once again attract interest. The use of algae biocathodes in MA–MFCs has been studied by many researchers [23–25]. It has been shown that useful MA–MFCs may now be created and that many pollutants that can be removed by MFCs may be able to be removed by MA–MFCs. However, a MA–MFC requires a large surface area to allow an appropriate amount of light to enter the cathode chamber, and it is expensive to harvest and process the used algal cells [7]. The electricity generation mechanism and factors affecting the electrogenic performances of MA–MFCs are not well understood and need to be studied further.

2.4. Single substrate/mixed wastewater MFCs

The substrate is one of the most important biological factors affecting electricity generation in a MFC [26]. A wide range of substrates, from pure compounds to wastewater containing a complex mixture of organic compounds, can be used in MFCs to generate power [27]. Pure compounds such as acetic acid, butyric acid, and glucose have low molecular masses and simple molecular structures. Chae et al. assessed the electrogenic performances of MFCs using acetic acid, butyric acid, glucose, and propionic acid as substrates when the MFCs were operated for a year [28]. The MFC using acetic acid had the highest coulombic efficiency, and the MFC using glucose had the highest power density. MFCs can also use complex mixtures such as domestic wastewater [29,30], dye wastewater [31,32], electroplating wastewater [33], swine wastewater [34], and brewery wastewater [35–37] as substrates. These types of wastewater have complex compositions and high organic contents and the components can be resistant to degradation and can therefore be used as electron donors and carbon sources in MFCs. Using wastewater in an MFC allows the wastewater to be decontaminated while power is generated.

2.5. Constructed wetland MFCs

A MFC has an aerobic cathode and an anaerobic anode, which is consistent with the natural stratification of a constructed wetland (CW), which will be aerobic at the top and anaerobic at the bottom [38]. This has led CW–MFCs to be constructed. Plant roots in the cathode chamber release oxygen, which acts as an electron acceptor, and a biocathode is formed at the top of a CW. CW–MFCs are much cheaper to construct than MFCs that use a noble metal such as Pt as a catalyst. CW–MFCs are new environmentally benign wastewater treatment systems that are regarded as economical and effective systems for harvesting bioenergy [39]. A CW–MFC can also limit greenhouse gas emissions by acting as a carbon sink. Many studies aimed at improving the electricity generation and wastewater treatment performances of CW–MFCs have been performed in recent years [40–42].

3. Cost–benefit analysis model

A cost–benefit analysis (CBA) is a systematic evaluation of the strengths and weaknesses of alternatives. CBA is used to identify the best approach to achieving benefits while preserving savings [43]. CBA is also defined as a systematic process for calculating and comparing the costs and benefits of a decision, policy, or project. For instance, a CBA has been performed to assess biofuel consumption targets in Spain [44]. CBAs have also been performed for wastewater treatment plant investment in Serbia [45] and solar water heater development in Taiwan [46].

It is complex, time consuming, and expensive to perform a CBA. The aim of this study was not to undertake a comprehensive feasibility analysis of the extension of MFCs to practical projects but simply to use cost and benefit accounting and perform comprehensive benefit evaluations for different MFC devices. A simplified CBA model based on existing CBAs was developed to allow the costs and benefits of different MFCs to be calculated.

3.1. Cost model

3.1.1. Net investment cost

The investment cost when creating a MFC will be dominated by the procurement costs of the materials (electrodes, epoxy resin, reactors, wires, etc.). MFC reactors are generally made of Plexiglas or polyethylene and are typically cuboid or cylindrical. The electrodes can be made of carbon-based materials, metals, or composite materials, and can be of various shapes and sizes depending on the reactor structure. The wires (for conducting electricity) are usually made of Cu or Ti but are occasionally Pt. Epoxy resin is used to insulate and seal the links between the electrodes and wires.

Different materials have different life spans, and only some materials (e.g., Plexiglas reactors, wires, and some electrode materials) can be recycled after being used in an MFC. It has been found that Cu, Pt, Plexiglas, stainless steel, and Ti can have service lives of 10 years or more and that these materials will have depreciated to 90% of the original price at the end of their service lives. A Nafion membrane will have a service life of ~2 years [47] and will depreciate to 50% of the original price. The depreciated value is the price obtained for a material minus the recycling cost. Some materials used in a MFC can simply be removed and cleaned before being used again, so the recycling cost will be dominated by the cost of the labor involved. A labor cost of $4.7 for recycling all materials in a MFC was used in the CBA.

The net investment cost (Ci) for a MFC was defined as the difference between the investment cost and the depreciated value.

3.1.2. Operating and maintenance costs

The operating and maintenance costs (Cm) will include labor costs, daily operating and maintenance costs of devices, water quality monitoring costs, and routine maintenance costs. The materials need to be processed and assembled before the MFC can be operated, and a trial run needs to be performed to ensure that the MFC has been correctly assembled. The main costs during the trial will be labor costs ($158 in our assessment). Routine maintenance after operating the MFC normally will mainly involve replacing the reaction fluid and checking that the MFC is operating normally. The routine maintenance costs will include labor costs and device and instrument maintenance costs ($15.8 per operating cycle in our assessment). The costs of the reagents used in the reaction solution can be calculated from the doses used and the operating cycle. The water quality is monitored twice each month to assess how effectively the MFC is treating the wastewater. The water quality monitoring costs include reaction solution costs, instrument and equipment use fees, and labor costs. Chemical oxygen demand, ammonia nitrogen, total phosphorus, and total nitrogen monitoring were each assumed to cost $24.5. Each part of the MFC is inspected and repaired once every three months at a cost of $15.8 per item. The cost of replacing a material will be determined by the lifespan of the material and the actual condition of the material. For example, metals have long lifespans and will not be replaced every year, whereas carbon-based materials such as carbon cloth and carbon paper will break easily and should be replaced every six months. Some reactors will require energy-consuming instruments such as fluorescent lamps and peristaltic pumps to be used constantly for a long time, and the electricity used was assumed to cost $0.13/kW·h).

3.1.3. Cost per unit power

The cost per unit power (Cu) is the cost of a unit area (1 m^2) of electrode material generating a unit power (1 W) of electricity and processing wastewater for 1 d,

$$Cu = Ci/(P \times 360) + Cm/360 \tag{1}$$

where Cu is in units of $/((W/m^2)d), Ci is the net investment cost in $/a, P is the power density of the device in W/m^2, and Cm is the operating and maintenance cost in $/a.

3.2. Benefit model

3.2.1. Revenue from electricity production

The annual power output of the MFC (for an operating year of 360 d) and the revenue brought in can be calculated from the power density of the MFC and the electrode area. The electricity price was assumed to be $0.13/(kW·h) . The revenue from electricity production (Re) can be calculated using the equation

$$Re = P \times A \times 360 \times 24 \times 0.13 \tag{2}$$

where Re is the revenue from power generation in $/a , P is the power density of the device in W/m^2, A is the electrode area in m^2, 360 × 24 is the time the MFC operates each year in h, and 0.13 is the price of electricity in $/(kW·h) .

3.2.2. Revenue from wastewater treatment

The wastewater treatment capacity of a MFC for one year and the revenue for treating wastewater (for an operating year of 360 d) can be calculated from the effective volume and operating cycle of the MFC. The revenue from treating wastewater (Rw) was assumed to be $0.13/m^3 [48]. The revenue from wastewater treatment was calculated using the equation.

$$Rw = V \times (360/T) \times 0.13 \times 10^{-6} \tag{3}$$

where Rw is the annual revenue from wastewater treatment in $/a, V is the effective volume of the MFC in mL, T is the operating cycle of the device in d, and 0.13 is the revenue from treating wastewater in $/m^3.

3.2.3. Revenue per unit power produced

Revenue per unit power produced (Ru) was calculated for a year because the revenue from a MFC will be low. Revenue per unit power means the revenue for a unit area (1 m^2) of electrode material generating a unit of electricity (1 W) and processing wastewater for a year. The revenue per unit power can be calculated using the equation

$$Ru = (Re + Rw)/P \tag{4}$$

where Ru is in $/((W/m^2)a), Re is the annual revenue from electricity generated by the MFC in $/a, Rw is the annual revenue from treating wastewater in $/a, and P is the power density of the device in W/m^2.

3.3. Cost–benefit ratio

The cost–benefit ratio (CBR) [49] is an indicator used in CBA to summarize the overall value for money of a project or proposal. The CBR is the ratio between the cost of the project or proposal in monetary terms and the benefit given by the project or proposal in monetary terms. The CBR takes into account the cost of executing the project and the monetary gain arising from the project. The lower the CBR the better the investment. The inverse of the CBR is the benefit–cost ratio [50].

The electrode areas, effective volumes, and operating cycles of MFCs can vary widely, so the CBR can be used to consistently evaluate the overall benefits of different MFCs after the costs and benefits have been estimated, and will allow the costs and benefits of different MFCs to be compared fairly. The CBR can be calculated using the equation

$$CBR = Ci/(Re + Rw) \tag{5}$$

where Ci is the investment cost in \$/a, and Re and Rw are the revenues from generating electricity and treating wastewater, respectively, in \$/a.

3.4. Sensitivity analysis

Sensitivity analysis is a common method for analyzing uncertainty when evaluating the economics of an investment project [44]. Sensitivity analysis involves identifying which of multiple factors most strongly affect the economic benefit index of the project and analyzing the effects of variations in these factors on the economic benefit indicators for the project.

4. Discussion

Typical MFCs were studied. These were an anode-material-changing MFC (AC–MFC), a cathode-material-changing MFC (CC–MFC), a raw water MFC (RW–MFC), a microalgae MFC (MA–MFC), and a constructed wetland MFC (CW–MFC). The net investment cost, operating and maintenance costs, and revenues from generating electricity and treating wastewater were estimated for each MFC using the CBA model.

The MFC operating parameters are shown in Table 1. The costs (see Appendices A and B for calculations of the costs of specific items), benefits (see Appendix C for specific calculations), and CBRs for the MFCs are shown in Table 2.

The results for each MFC are shown in Fig. 2, with the Cu and Ru on the horizontal and vertical axes, respectively. It can be seen that the Ru increased as the Cu increased. The Cu values were \$5 – \$40/((W/m^2)d), but the Ru values varied over a broader range . The rate at which the Ru increased as the Cu increased was highest for the CW–MFC, next highest for the RW-MFC, then the CC–MFC, then the MA–MFC, and lowest for the AC–MFC.

The lg(CBR) values for the MFCs are shown as a histogram in Fig. 3. The lg(CBR) reference value was 0, which meant that the costs and benefits were equal. The CW–MFC gave the best comprehensive benefits of the MFCs that were assessed ($p < 0.05$), the CW–MFC lg(CBR) values being 2.7238 ± 0.1504 for experimental conditions and 2.4910 ± 0.0584 for practical conditions. The MA–MFC lg(CBR) values were 5.0079 ± 0.1068 for experimental conditions and 4.9993 ± 0.1091 for practical conditions, both of which were significantly higher than

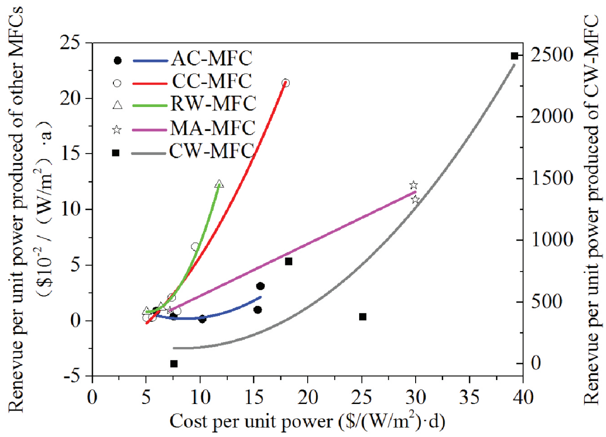

Fig. 2. Cost–benefit curves for typical microbial fuel cells.

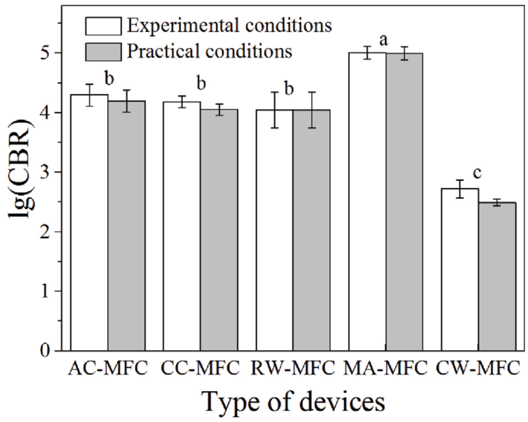

Fig. 3. Cost–benefit ratios (CBRs) for typical microbial fuel cells under different conditions (different letters (a, b, and c) indicate the values were significantly different at the $p = 0.05$ level).

the lg(CBR) values for the other MFCs ($p < 0.05$), meaning the MA–MFC comprehensive benefits were worse than the comprehensive benefits of the other MFCs. The lg(CBR) values for the other MFCs (4.0–4.3) were between the CW–MFC and MA–MFC lg(CBR) values. MA–MFCs generally have high investment costs and high operating and maintenance costs because such systems require lighting equipment or photobioreactors and have low wastewater treatment capacities, meaning they have poor efficiencies. CW–MFCs are large but have high wastewater treatment capacities and generally use inexpensive electrodes and recycled materials. The roots of the wetland plants used in CW–MFCs can increase the oxygen concentration in the system, improving the water treatment effect, and the biomass produced by the plants can be harvested. These factors mean that CW–MFCs offer considerable comprehensive benefits.

The MFCs described here are mostly used in experiments and few full-scale MFCs have been built. The costs of experimental and full-scale MFCs will be different. For example, the influent of a full-scale MFC will be natural sewage, so the costs of reagents used in experimental MFCs will not apply. The differences in costs of experimental and

Table 1
Operating parameters for typical microbial fuel cells

Serial No.	Reactor type	Electrode materials			Anode area (cm^2)	Type of substrate	Volume of anode chamber (mL)	Power density (mW/m^2)	Cycle (d)	References
		Anode materials	Cathode materials	Membrane						
1	Single chamber	Activated carbon	Pt-loaded carbon paper	Cation exchange membrane	6.25	Wastewater from food factory	84	338	6	[51]
2	Single chamber	Carbon cloth	Pt-loaded carbon paper	Cation exchange membrane	6.25	Wastewater from food factory	84	78	6	[51]
3	Single chamber	Graphite felt	Pt-loaded carbon cloth	–	12	Acetate	225	1256	3	[37]
4	Single chamber	Graphene-polyaniline modified carbon cloth	Pt-loaded carbon cloth	–	7	Synthetic wastewater containing sodium acetate	28	831	2	[52]
5	Single chamber	Carbon paper	Pt-loaded carbon cloth	–	20	Synthetic wastewater containing sodium acetate	80	378.13	1.25	[53]
6	Double chamber	Carbon paper	Pt-loaded carbon paper	Proton exchange membrane	11.25	Domestic wastewater with the medium ingredients	250	38	10	[54]
7	Single chamber	Graphite felt	Pt-loaded carbon cloth	–	12	Glucose	225	1519	5	[37]
8	Single chamber	Graphite felt	Carbon paper (MnO_2/CNTs as catalyst)	–	7	Synthetic wastewater containing glucose	58	210	6	[55]
9	Single chamber	Graphite felt	Carbon paper (Pt/C as catalyst)	–	7	Synthetic wastewater containing glucose	58	229	5	[55]
10	Double chamber	Graphite felt	Carbon paper	–	7	Synthetic wastewater containing glucose	58	32.7	4	[55]
11	Double chamber	Graphite felt	Graphite felt	–	7	Synthetic wastewater containing glucose	58	109.5	3	[55]
12	Single chamber	Graphite felt	Carbon paper (CNTs as catalyst)	–	7	Synthetic wastewater containing glucose	58	8	5	[55]
13	Double chamber	Graphite felt	Stainless steel mesh	–	7	Synthetic wastewater containing glucose	58	3.1	4	[55]

Table 1 (*Continued*)

Serial No.	Reactor type	Electrode materials			Anode area (cm^2)	Type of substrate	Volume of anode chamber (mL)	Power density (mW/m^2)	Cycle (d)	References
		Anode materials	Cathode materials	Membrane						
14	Single chamber	Graphite felt	Pt-loaded carbon cloth	–	12	Brewery wastewater	225	251	6	[37]
15	Single chamber	Carbon paper	Pt-loaded carbon paper	Cation exchange membrane	6.25	Wastewater from food factory	84	56	6	[51]
16	Single chamber	Graphite flake	Graphite rod	–	30	Surplus sludge	230	44	2	[56]
17	Double chamber	Graphite felt	Graphite felt	Proton exchange membrane	30	Synthetic wastewater containing glucose added Chlorella	256	82.6	25	[57]
18	Double chamber	Graphite felt	Pt-loaded carbon paper	Proton exchange membrane	49.5	Synthetic wastewater containing glucose added Chlorella	500	24.4	8	[58]
19	Double chamber	Carbon felt	Pt-loaded carbon paper	Proton exchange membrane	49.5	Synthetic wastewater containing glucose added Chlorella	500	27.5	8	[58]
20	Single chamber	Granular activated carbon	Granular graphite	–	254.34	Synthetic wastewater containing glucose	2540	19.7	2	[59]
21	Single chamber	Activated carbon	Stainless steel mesh coupled with activated carbon	–	706.5	Synthetic wastewater containing glucose	7000	74.447	2	[60]
22	Single chamber	Stainless steel mesh coupled with activated carbon	Stainless steel mesh coupled with activated carbon	–	254.34	Synthetic wastewater containing sodium acetate.	2544	9.3	1	[61]
23	Single chamber	Titanium mesh coupled with activated carbon	Titanium mesh coupled with activated carbon	–	268.67	Synthetic wastewater	4850	3714.08	3	[62]

Table 2
Results of the cost–benefit analysis of typical microbial fuel cells

Type of MFC	Serial No.	Cost per unit power (Cu) ($/(W/m^2) d)	Revenue per unit power produced (Ru) ($10^{-2}/(W/m^2) a)	Annual net investment cost (Ci)($ /a)		Annual revenue ($10^{-3}/a)	Cost–benefit ratio (CBR)		References
				Under experimental conditions	Under practical conditions		Under experimental conditions	Under practical conditions	
AC–MFC	1	5.12	0.26	29.26	29.26	0.88	33250	33250	[51]
	2	5.93	0.89	29.62	29.62	0.69	42928	42928	[51]
	3	7.55	0.41	18.88	13.46	5.17	3652	2603	[37]
	4	10.20	0.16	15.07	12.69	1.31	11504	9687	[52]
	5	15.34	1.00	61.61	47.27	3.79	16256	12472	[53]
	6	15.59	3.12	74.69	39.33	1.19	62765	33050	[54]
CC–MFC	7	5.44	0.27	16.67	13.46	4.15	4017	3243	[37]
	8	5.04	0.29	11.88	9.45	0.61	19475	15492	[55]
	9	5.56	0.31	12.87	9.90	0.71	18127	13944	[55]
	10	7.36	2.10	13.62	9.91	0.69	19739	14362	[55]
	11	7.87	0.88	14.38	9.52	0.97	14825	9814	[55]
	12	9.55	6.67	12.10	9.13	0.53	22830	17226	[55]
	13	17.92	21.40	13.18	9.47	0.66	19970	14348	[55]
RW–MFC	14	5.03	0.82	13.46	13.46	2.05	6566	6566	[37]
	15	6.35	1.21	29.84	29.84	0.68	43882	43882	[51]
	16	11.76	12.24	25.82	25.82	5.39	4790	4790	[56]
MA–MFC	17	7.19	0.94	127.61	126.39	0.77	165727	164143	[57]
	18	29.80	12.22	224.52	218.61	2.99	75090	73114	[58]
	19	29.96	10.91	254.68	248.77	3.00	84893	82923	[58]
CW–MFC	20	18.16	834.80	90.59	72.30	164.45	551	440	[59]
	21	25.08	387.27	400.19	71.83	288.31	1388	249	[60]
	22	39.11	2498.77	70.60	58.71	232.39	304	253	[61]
	23	7.56	5.10	64.05	62.95	189.42	338	332	[62]

full-scale MFCs can be determined by comparing the CBRs of different MFCs under different conditions. No significant differences were found between the CBRs for different MFCs under practical and experimental conditions. However, there will be some hidden costs and benefits related to factors such as the sewage components, development of new materials, and government support. It was therefore necessary to perform sensitivity analyses.

The amounts of power produced by the different MFCs, the processing costs, and the material replacement cycle will be different for wastewater with different compositions, such as different chemical oxygen demands and ammonia nitrogen and nutrient concentrations. For example, MFCs treating pure acetate acid [63] and glucose [64] will produce electricity more effectively in the early processing stages than will MFCs treating water containing complex mixtures of pollutants. Water quality strongly affects the costs and benefits of MFCs. The MFC size also affects the benefits. Addressing all the matters described above will require data from future studies.

Developing new materials may decrease the costs of electrodes. Graphene quantum dots are biocompatible. Microorganisms can adhere to and multiply on graphene quantum dots and become a good source of electrons and give a good current through an MFC [65]. Graphene quantum dots may therefore be used in improved anode materials in an MFC to increase the output efficiency. Plant fibers treated with poly (3,4-ethylenedioxythiophene) can form large directional channel conductors, which can be cheaper than conventional metal electrodes [66]. The manual maintenance costs will be different in different parts of the world. Manual labor costs, for example, are different in Mexico and Brazil [67].

Governments may support the development of "clean energy" sources such as solar energy by providing subsidies [68]. Such national policies can decrease equipment costs and can improve social acceptance of "clean energy" production systems, making it relatively easy to develop new facilities. Increased demand promotes large-scale production, decreasing the unit cost.

Different types of MFCs will offer different benefits, and this will be reflected in the ecological services offered. Installing ecological wastewater treatment plants using MFCs to treat urine in developing countries offers social benefits that are more important than the power generated

[69]. In countries with scarce freshwater resources, it is cheaper to use microbial fuel techniques to dilute seawater than to produce potable water by reverse osmosis [70].

There can be great differences between experimental conditions and practical conditions, and further studies will be needed to investigate the effects of these differences.

5. Conclusions

A CBA model and a detailed economic benefit analysis for typical MFCs are presented here. As the costs increase, the revenue per unit power produced was found to increase faster for CW–MFC than the other MFCs, next fastest for RW-MFC, then CC–MFC, then MA–MFC, and then AC–MFC. CW–MFC was found to offer the best comprehensive benefits of the MFCs that were assessed ($p < 0.05$), the CW-MFC lg(CBR) values being 2.7238 ± 0.1504 for experimental conditions and 2.4910 ± 0.0584 for practical conditions. The MA–MFCs lg(CBR) values were 5.0079 ± 0.1068 for experimental conditions and 4.9993 ± 0.1091 for practical conditions. These were both significantly higher than the lg(CBR) values for the other MFCs ($p < 0.05$), meaning the MA–MFCs offered the poorest comprehensive benefits of the MFCs that were assessed. The results indicated that CW–MFCs are most appropriate for practical applications but that further research is required to assess various aspects of the costs and benefits offered.

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Appendix A: Calculations of the costs of specific items

The lifespan of the device counts for one year but the actual operating time is 360 days because the device needs to be overhauled and maintained several times during the period.

Reference [51]

1. Investment costs

Table A.1
Investment costs

Materials	Price	Costs ($)
Single-chamber plexiglass reactor (84 mL)	–	8.5
Carbon cloth, 6.25 cm^2	$15.4/32 × 16 cm^2	0.2
Carbon paper, 6.25 cm^2	$75.8/40 × 40 cm^2	0.3
Cocoanut active charcoal	$2.4/kg	0.005
Pt-loaded carbon paper (0.5 mg/cm^2), 6.25 cm^2	$104.3/10 × 10 cm^2	6.5
Cation exchange membrane, 6.25 cm^2	$36.3/80 × 40 cm^2	0.07
316 Stainless steel plates, 6.25 cm^2	$56.9/$m^2$	0.04

2. Reagent costs

$0 (Using wastewater from a local food factory as reaction fluid does not require adding other reagents.)

Reference [37]

1. Investment costs

Table A.2(a)
Investment costs

Materials	Price	Costs ($)
Single-chamber plexiglass reactor (225 mL)	–	15.8
Graphite felt, 12 cm^2	$36.3/$m^2$	0.04
Hydrophobic carbon cloth, 12 cm^2	$16.2/32 × 16 cm	0.4
10%C/Pt, 6 mg	$27.2/g	1.6

2. Reagent costs

The working volume of the anode chamber is 225 ml which is calculated to be 250 ml.

The MFC based on brewery wastewater: 6 days per cycle, 60 cycles per year, 15 L in total (Raw water without any regents); the MFC based on synthetic wastewater containing glucose: 5 days per cycle, 72 cycles per year, 18 L in total; the MFC based on synthetic wastewater containing acetate: 3 days per cycle, 120 cycles per year, 30 L in total.

Table A.2(b)
Reagent costs

Reagents	Concentration (g/L)	Price ($/500 g)	Annual costs ($)	
			Synthetic wastewater containing glucose	Synthetic wastewater containing acetate
K_2HPO_4	3.40	12.0	1.5	2.4
KH_2PO_4	4.35	9.3	1.5	2.4
NH_4Cl	0.20	3.8	0.03	0.05
NaCl	0.04	5.4	0.008	0.01
$MgSO_4·7H_2O$	0.01	5.4	0.002	0.003
$CaCl_2·H_2O$	0.02	5.1	0.003	0.006
$NaHCO_3$	0.25	5.9	0.05	0.09
KCl	0.02	5.9	0.005	0.006
Yeast extract	0.01	$27.8/100 g	0.05	0.08
Glucose	0.48	7.4	0.1	–
Acetate	0.65	7.4	–	0.3
Total			3.2	5.4

Reference [52]

1. Investment costs

Table A.3(a)
Investment costs

Materials	Price	Costs ($)
Single-chamber plexiglass reactor (28 mL)	–	8.2
Hydrophilic carbon cloth, 7 cm^2	$13.3/20*21 cm	0.2
Hydrophobic carbon cloth, 7 cm^2	$13.3/20*21 cm	0.2
Crystalline flake graphite (300 item), 0.5 g	$3.2/500 g	0.003
Phenylamine, 1.8 mL	$36.2/100 mL	0.7
10%C/Pt, 35 mg	$27.2/g	1.0

2. Reagent costs

The working volume of the anode chamber is 28 ml which is calculated to be 50 ml. There are 2 days per cycle, 180 cycles per year, 9 L in total.

Table A.3(b)
Reagent costs

Reagents	Concentration (g/L)	Price ($/500g)	Annual costs ($)
CH_3COONa	1.00	7.4	0.1
$NaH_2PO_4{\cdot}2H_2O$	2.77	6.5	0.3
$Na_2HPO_4{\cdot}12H_2O$	11.40	5.1	1.0
NH_4Cl	0.31	3.8	0.02
KCl	0.13	5.9	0.01
Vitamins	12.5 mL/L	$0.08/L	0.7
Trace elements	5 mL/L	$0.02/L	0.1
Total			2.4

Reference [53]

1. Investment costs

Table A.4(a)
Investment costs

Materials	Price	Costs ($)
Single-chamber plexiglass reactor (80 mL)	–	8.4
Carbon paper (HCP030N) 20 cm²	$75.9/10 × 10 cm	15.2
Carbon cloth (50% wet-proof) 20 cm²	$15.4/32 × 16 cm	0.6
10%Pt/C, 100 mg	$27.2/g	2.7
Nafion ethanol solution (5%) 0.70 mL	$1169/1000 mL	0.8
PTFE (60 wt% dispersion) 480 mg	$24.5/100 g	0.02

2. Reagent costs

The working volume of the anode chamber is 80 ml which is calculated to be 100 ml. There are 30 hours per cycle, 288 cycles per year, 28.8 L in total.

Table A.4(b)
Reagent costs

Reagents	Concentration (g/L)	Price ($/500g)	Annual costs ($)
CH_3COONa	0.64	7.4	0.3
$NaHCO_3$	3.13	5.9	1.1
NH_4Cl	0.31	3.8	0.07
$NaH_2PO_4{\cdot}H_2O$	0.75	40.9	8.8
KCl	0.13	5.9	0.04
NaH_2PO_4	4.22	7.1	1.7
Na_2HPO_4	2.75	11.6	1.8
$(NH_4)_2SO_4$	0.56	6.8	0.2
$MgSO_4{\cdot}7H_2O$	0.2 mg/L	5.4	0
$CaCl_2$	0.015	7.4	0.006
$FeCl_3{\cdot}6H_2O$	0.001	10.4	0
$MnSO_4{\cdot}H_2O$	0.02	7.4	0.008
Metal elements and trace elements		$0.009/L	0.3
Total			14.3

Reference [54]

1. Investment costs

Table A.5(a)
Investment costs

Materials	Price	Costs ($)
Double-chamber, two 250-mL bottles with a glass bridge	$55.3/set	55.3
Carbon paper 11.25 cm²	$13.3/20 × 21 cm	0.4
Pt-loaded carbon paper (1 mg/cm²) 11.25 cm²	$112.2/10 × 10 cm	12.6
Nafion117 membrane 0.71 cm²	$366.5/40 × 40 cm	0.2

2. Reagent costs

The working volume of the anode chamber and the cathode chamber is 250 ml. There are 10 days per cycle, 36 cycles per year, 9 L in total for each.

Table A.5(b)
Reagent costs

Electro-lyte	Reagents	Concen-tration (g/L)	Price ($/500g)	Annual costs ($)
Anolyte	CH_3COO-Na	1.64	7.7	0.2
	NH_4Cl	0.31	3.8	0.02
	NaH_2PO_4·-H_2O	0.75	$40.9/100g	2.8
	KCl	0.13	5.9	0.01
	NaH_2PO_4·-H_2O	4.22	$40.9/100g	15.5
	Na_2HPO_4	2.75	11.6	0.6
	Metal elements and vitamins	–	–	0. 1
Catholyte	NaH_2PO_4·-H_2O	4.22	$40.9/100g	15.5
	Na_2HPO_4	2.75	11.6	0.6
Total				35.4

Reference [55]

1. Investment costs

Table A.6(a)
Investment costs

Items	Materials	Price	Costs ($)
Research on different cathode materials	Double-chamber plexiglass reactor (58 mL for each)	–	16.4
	Graphite felt 7 cm²	$36.3/m²	0.03
	Carbon paper 7cm²	$13.3/ 20 × 21 cm	0.2
	Stainless steel mesh	$6.4/30 m²	The cost is negligible.
Research on different catalysts	Single-chamber plexiglass reactor (58 mL)	–	8.2
	MnO_2/ CNTs 15 mg	Made by oneself	0.2
	CNTs 15 mg	$67.9/50 g	0.02
	Pt/C 15 mg	$27.2/g	0.4
	Graphite felt 7 cm²	$36.3/m²	0.03
	Carbon paper 7 cm²	$13.3/20 × 21 cm	0.2

2. Reagent costs

The double-chamber plexiglass reactor was used in the research on different cathode materials. The working volume of the anode chamber and the cathode is 58 ml which is calculated to be 100ml. The MFC used graphite felt as cathode: 3 days per cycle, 120 cycles per year, 12 L in total for each; the MFC used carbon paper and stainless steel mesh as cathode: 4 days per cycle, 90 cycles per year, 9 L in total for each.

The single-chamber plexiglass reactor was used in the research on different catalysts. The working volume of the anode chamber is 58 ml which is calculated to be 100 ml. The MFC used MnO_2/CNTs as catalyst: 6 days per cycle, 60 cycles per year, 6 L in total; the MFCs used CNTs and Pt/C as catalyst: 5 days per cycle, 72 cycles per year, 7.2 L in total.

Table A.6(b)
Reagent costs (research on different cathode materials)

Reagents	Concentration (g/L)	Price ($/500g)	Annual costs ($)		
			Used graphite felt as cathode	Used carbon paper as cathode	Used stainless steel mesh as cathode
NH_4Cl	0.34	3.8	0.03	0.02	0.02
$NaH_2PO_4 \cdot 2H_2O$	3.312	7.4	0.6	0.4	0.4
$Na_2HPO_4 \cdot 12H_2O$	10.311	5.1	1.3	1.0	1.0
KCl	0.130	5.9	0.02	0.01	0.01
$MgSO_4 \cdot 7H_2O$	0.492	5.4	0.06	0.05	0.05
$CaCl_2$	0.0113	7.4	0.002	0.002	0.002
Vitamin H	0.002	$16.2/5 g	0.02	0.001	0.01
Vitamin B_{12}	0.0001	$ 88.8/5 g	0.005	0.003	0.003
Folic acid	0.002	$69.6/100 g	0.003	0.003	0.003
Nicotinic acid	0.005	29.6	0	0	0
Vitamin B_6	0.01	92	0.005	0.003	0.003
DL-Pantothenic acid	0.0001	$59.9/100 g	0	0	0
Vitamin B_1	0.005	$128.5/10 g	0.2	0.1	0.1
4-aminobenzoic acid	0.005	53.3	0.002	0.002	0.002
Vitamin B_2	0.005	$59.9 /100 g	0.008	0.006	0.006
$NTAN(CH_2COOH)_3$	1.5	$7.7 /250 g	0.1	0.09	0.09
$FeSO_4 \cdot 7H_2O$	0.1	5.9	0.003	0.002	0.002
NaCl	1	5.4	0.03	0.02	0.02
$CuSO_4 \cdot 5H_2O$	0.1	8.7	0.005	0.003	0.003
$MnCl_2 \cdot 4H_2O$	0.53	5.3	0.01	0.01	0.01
$ZnSO_4 \cdot 7H_2O$	0.18	7.1	0.006	0.005	0.005
$CaCl_2$	0.076	7.4	0.003	0.002	0.002
$AlK(SO_4)_2 \cdot 12H_2O$	0.184	6.2	0.005	0.005	0.005
$CoCl_2 \cdot 6H_2O$	0.1	32.1	0.02	0.01	0.01
H_3BO_3	0.01	5.4	0	0	0
$NiCl_2 \cdot 6H_2O$	0.024	17.6	0.002	0.002	0.02
$NaMoO_4 \cdot 2H_2O$	0.012	7.4	0	0	0
Glucose	1	7.4	0.2	0.1	0.1
Total			4.9	3.7	3.7

Table A.6(c)
Reagent costs (research on different catalysts)

Reagents	Concentration (g/L)	Price ($/500 g)	Annual costs ($)		
			Used MnO_2/CNTs as catalyst	Used Pt/C as catalyst	Used CNTs as catalyst
NH_4Cl	0.34	3.8	0.02	0.02	0.02
$NaH_2PO_4·2H_2O$	3.312	7.4	0.3	0.4	0.4
$Na_2HPO_4·12H_2O$	10.311	5.1	0.6	0.8	0.8
KCl	0.130	5.9	0.009	0.01	0.01
$MgSO_4·7H_2O$	0.492	5. 4	0.03	0.04	0.04
$CaCl_2$	0.0113	7.4	0.002	0.002	0.002
Vitamin H	0.002	$16.2/5 g	0.008	0.01	0.009
Vitamin B12	0.0001	$88.8/5 g	0.002	0.003	0.003
Folic acid	0.002	$69.6/100 g	0.002	0.002	0.002
Nicotinic acid	0.005	29.6	0	0	0
Vitamin B6	0.01	92.0	0.002	0.003	0.003
DL-Pantothenic acid	0.0001	$59.9/100 g	0	0	0
Vitamin B1	0.005	$128.5/10 g	0.08	0.1	0.1
4-aminobenzoic acid	0.005	53.3	0	0.002	0.002
Vitamin B2	0.005	59.9$/100 g	0.003	0.005	0.005
$NTAN(CH_2COOH)_3$	1.5	$7.7/250 g	0.06	0.07	0.07
$FeSO_4·7H_2O$	0.1	5.9	0.002	0.002	0.02
NaCl	1	5.4	0.01	0.02	0.02
$CuSO_4·5H_2O$	0.1	8.7	0.002	0.003	0.003
$MnCl_2·4H_2O$	0.53	5.3	0.006	0.008	0.008
$ZnSO_4·7H_2O$	0.003	7.1	0.03	0.003	0.003
$CaCl_2$	0.012	7.4	0.02	0.002	0.002
$AlK (SO_4)_2·12H_2O$	0.03	6.2	0.003	0.003	0.003
$CoC_{12}·6H_2O$	0.02	32.1	0.008	0.009	0.009
H_3BO_3	0.002	5.4	0	0	0
$NaSeO_3$	0.003				
$NiC_{12}·6H_2O$	0.004	17.6	0.002	0.002	0.002
$NaMoO_4·2H_2O$	0.002	7.4	0	0	0
Glucose	0.2	7.4	0.09	0.1	0.1
Total			2.4	3.0	3.0

Reference [56]

1. Investment costs

Table A.7
Investment costs

Materials	Price	Costs ($)
Single-chamber plexiglass reactor (230 mL)	–	9.8
Graphite flakes 30 cm^2	$12.6/0.8*10*10 cm	3.8
Graphite rods	$4.7/ 2 cm in diameter, 10 cm in length	4.7

2. Reagent costs

0 $ (The use of surplus sludge as reaction fluid does not require adding other reagents.)

Reference [57]

1. Investment costs

Table A.8(a)
Investment costs

Materials	Price	Costs ($)
Double-chamber plexiglass reactor (256 mL for each)	$31.6/set	31.6
Two fluorescent lamps	$4.3 for each	8.5
Graphite felt 5*6 cm	$36.3/$m^2$	0.1
Nafion117 membrane 6 × 6 cm	$366.5/40 × 40 cm	8.2

2. Reagent costs

The volume of the anode chamber and the cathode is 256 ml which is calculated to be 300 ml. There are 25 days per cycle, 15 cycles per year, 4.5 L in total for each.

Table A.8(b)
Reagent costs

Electrolyte	Reagents	Concentration (g/L)	Price ($/500 g)	Annual costs ($)
Common nutritive medium for anode and cathode	NaH_2PO_4	0.458	7.1	0.06
	$NaH_2PO_4\cdot$–$2H_2O$	6.64	7.4	0.9
	NH_4Cl	0.31	3.8	0.02
	$MgSO_4\cdot$–$7H_2O$	0.075	5.4	0.008
	$CaCl_2\cdot$2–H_2O	0.036	4.8	0.003
	KCl	0.13	5.9	0.01
	Citric Acid	0.006	10.1	0.002
	Ferric citrate	0.006	13.2	0.002
	$Na_2\cdot$EDTA	0.001	$56.9/–100 g	0.005
Anolyte	Glucose	0.469	7.4	0.03
	Congo red	0.3	59.1	0.2
Catholyte	$NaHCO_3$	0.4	5.9	0.02
	$NaNO_3$	0.2	6.0	0.01
Chlorella			$47.4	47.4
Total				6.0

Reference [58]

1. Investment costs

Table A.9(a)
Investment costs

Materials	Price	Costs ($)
Double-chamber plexiglass reactor		
(500 mL for the anode chamber, 300 mL for the cathode chamber)	–	19.4
Two fluorescent lamps	$4.3 for each	8.5
Carbon felt (9 × 5.5 cm)	$36.3/$m^2$	0.2
Pt-loaded carbon paper (0.6 mg/cm^2) 20 × 3 cm	$105.8/10 × 10 cm	63.5
Nafion117 membrane 7 cm^2	$366.5/40*40 cm	1.6

2. Reagent costs

The volume of the anode chamber is 500 ml. There are 8 days per cycle, 45 cycles per year, 22.5 L in total. The volume of the cathode chamber is 300 ml. There are 8 days per cycle, 45 cycles per year, 13.5 L in total.

Table A.9(b)
Reagent costs

Electrolyte	Reagents	Concentration (g/L)	Price ($/500 g)	Annual costs ($)
Anolyte	Glucose	1	7.4	0.3
	NH_4Cl	0.31	3.8	0.05
	NaH_2PO_4	2.452	7.1	0.8
	Na_2HPO_4	4.576	11.6	2.4
	KCl	0.13	5.9	0.03
Catholyte	NaH_2PO_4	2.452	7.1	0.5
	Na_2HPO_4	4.576	11.6	1.4
	KCl	0.13	5.9	0.02
BG11–medium	$NaNO_3$	1.5	6.0	0.2
	K_2HPO_4·–$3H_2O$	0.04	7.4	0.008
	$MgSO_4$·–$7H_2O$	0.075	5.4	0.01
	$CaCl_2{\cdot}2H_2O$	0.036	4.8	0.005
	Na_2CO_3	0.02	7.4	0.005
	Citric Acid	0.006	10.1	0.002
	Ferric citrate	0.006	13.2	0.002
	Na_2·EDTA	0.001	$56.9/100 g	0.008
	H_3BO_3	0.061	5.4	0.009
	$MnSO_4{\cdot}H_2O$	0.169	7.4	0.03
	$ZnSO_4{\cdot}7H_2O$	0.287	7.1	0.06
	$CuSO_4{\cdot}5H_2O$	0.0025	8.7	0
	Ammonium molybdate	0.0125	$20.2/100 g	0.03
Chlorella			$47.4	47.4
Total				53.3

Reference [59]

1. Investment costs

Table A.10(a)
Investment costs

Materials	Price	Costs ($)
Plexiglass reactor (18 cm in diameter and 52 cm in height)	27.8	27.8
Active carbon 1.5 kg	$2.4/kg	3.6
Granular graphite 5 kg	$1.6/kg	8.1
Gravels 1.2 kg	$0.08/kg	0.09
Volcanic rocks 7.2 kg	$0.5/kg	3.4
Fiberglass 254.34 cm^2	$13.9/1020 × 1220 mm	0.3
Five shoots of bulrush	$0.3/shoot	1.3

2. Reagent costs

The systems are operated in a continuous mode by using a peristaltic pump at flow rate of 2.5 mL/min, resulting in a hydraulic retention time of 2 d. The volume of the reaction liquid is 7.2 L. There are 2 days per cycle, 180 cycles per year, 1296 L in total.

Table A.10(b)
Reagent costs

Reagents	Concentration (g/L)	Price ($/500g)	Annual costs ($)
Glucose	0.19	7.4	3.6
NaH_2PO_4	0.032	7.1	0.6
Na_2HPO_4	0.018	11.6	0.5
$NaHCO_3$	0.336	5.9	5.1
NaCl	0.33	5.4	4.6
$MgSO_4{\cdot}7H_2O$	0.20	5.7	2.9
$CaCl_2$	0.015	7.4	0.3
$FeCl_3 \cdot 6H_2O$	0.001	10.6	0.03
$MnSO_4 \cdot H_2O$	0.028	7.7	0.6
$CoCl_2 \cdot 6H_2O$	0.24mg	33.8	0.02
$Na_2MoO_4{\cdot}2H_2O$	0.04mg	31.0	0.003
Total			18.3

Reference [60]

1. Investment costs

Table A.11(a)
Investment costs

Materials	Price	Costs ($)
A polyacrylic plastic cylinder (30 cm in diameter)	12.2	12.2
Active carbon 5.3 kg	$2.4/kg	12.6
Stainless steel mesh 1 m^2	$276.5/36.6 m^2	7.6
Gravels (3–6 mm) 39.22 kg	$0.08/kg	3.1
Ipomoea aquatica (seeds)	$0.5	0.5

2. Reagent costs

The volume of the reaction liquid is 12.4 L. There are 2 days per cycle, 180 cycles per year, 2232 L in total.

Table A.11(b)
Reagent costs

Reagents	Concentration (g/L)	Price ($/500 g)	Annual costs ($)
NH_4Cl	0.31	3.8	5.2
NaH_2PO_4	2.452	7.1	77.3
Na_2HPO_4	4.576	11.6	236.2
KCl	0.13	5.9	3.4
Glucose	0.19	7.4	6.2
Total			328.4

Reference [61]

1. Investment costs

Table A.12(a)
Investment costs

Materials	Price	Costs ($)
An acrylic column (18 cm in diameter, 75 cm in height)	37.4	37.4
Active carbon 1.5 kg	$2.4/kg	3.6
Stainless steel mesh 254.34 cm²	$276.5/36.6 m²	0.2
1000 glass beads	$5.7/1000 grains	5.7
Gravels 13.4 kg	$0.08/kg	1.1
Two shoots of *T. latifolia*.	$0.4/shoot	0.8

2. Reagent costs

Table A.12(b)
Reagent costs

Reagents	Concentration (mg/L)	Price($/500 g)	Annual costs ($)
C_6H_5COONa	107.1	10.6	4.2
CH_3COONa	204.9	7.7	5.8
NaCl	7	5.4	0.1
$MgCl_2·6H_2O$	3.4	6.2	0.08
$CaCl_2·2H_2O$	4	4.8	0.07
K_2HPO_4	36.7	12.0	1.6
Total			11.9

The peristaltic pump (4.048 mL/min) and air pump were operated with 3 h on followed by 0.5 h off cycles, which maintained the hydraulic retention time (HRT) at 1 day. The volume of the reaction liquid is 5.1 L. There is 1 day per cycle, 360 cycles per year, 1836 L in total.

Reference [62]

1. Investment costs

Table A.13(a)
Investment costs

Materials	Price	Costs ($)
Plexiglass reactor (20 cm in diameter and 60 cm in height)	–	28.4
Active carbon 1.6 kg	$2.4/kg	3.8
Titanium mesh	$15.8/sheet (customized)	64.8
Gravels 2 kg	$20.5/t	0.04
Coarse sand 8 kg	$0.6/kg	4.8
Ceramsite 5 kg	$0.6/kg	3.1
Six shoots of bulrush	$0.3/shoot	1.5

2. Reagent costs

The systems are operated in a continuous mode by using a peristaltic pump, resulting in a hydraulic retention time of 3 d. The volume of the reaction liquid is 4.85 L. There are 3 days per cycle, 120 cycles per year, 582 L in total.

Note: the price information of the plexiglass used in the experiment is from a plastic products Co., Ltd in Guangzhou, China. The price information of the chemical reagent is from the Chinese reagent network (http://www.labgogo.com/).

Table A.13(b)
Reagent costs

Reagents	Concentration (mg/L)	Price ($/500 g)	Annual costs ($)
Sucrose	53.438	6.0	0.4
$(NH_4)_2SO_4$	37.714	6.2	0.3
KNO_3	50.500	7.7	0.5
KH_2PO_4	6.581	6.3	0.07
Total			1.2

Appendix B. Specific calculation of cost per unit power of each device

1. Cost per unit power (Cu)

The cost per unit power (Cu) is the cost of a unit area (1 m^2) of electrode material generating a unit power (1 W) of electricity and processing wastewater for 1 d,

$$Cu = Ci/(P \times 360) + Cm/360 \quad (B.1)$$

where Cu is in units of $/((W/$m^2$)d), Ci is the net investment cost in $/a, P is the power density of the device in W/m^2, and Cm is the operating and maintenance cost in $/a.

The lifespan of the device counts for one year but the actual operating time is 360 days because the device needs to be overhauled and maintained several times during the period. The annual net investment cost of the device under the practical conditions refers to that except the costs of the reagents.

2. Specific calculations

Reference [51]

Table B.1(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/ time	158	–	
Costs of routine maintenance	15.8/cycle	947.9	6 days per cycle, 60 cycles per year	1756.7/a
Costs of water quality monitoring	24.5/time	587.7	Twice a month	4.88/d
Costs of overhaul	15.8/time	63.2	Once every three months	

Table B.1(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	7.7	4.7	71.3
Cation exchange membrane	0.04		
Stainless steel plates	0.03		
Wires	68.2		

Table B.1(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	8.5	Single-chamber, plexiglass, 84 cm^3
Electrode materials	13.2	Activated carbon (AC) sheets (6.25 cm^2) were used as the anode, Pt-loaded carbon paper (0.5 mg/cm^2) was used as the cathode, cation exchange membrane 6.25 cm^2. (1st)
	13.5	Activated carbon (AC) sheets and the Pt-loaded carbon paper were replaced once. Carbon cloth (6.25 cm^2) was used as the anode, Pt-loaded carbon paper (0.5 mg/cm^2) was used as the cathode, cation exchange membrane 6.25 cm^2. (2nd). The carbon cloth and the Pt-loaded carbon paper were replaced once.
	13.7	Carbon paper (6.25 cm^2) was used as the anode, Pt-loaded carbon paper (0.5 mg/cm^2) was used as the cathode, Cation exchange membrane 6.25 cm^2. (15th), Carbon paper and Pt-loaded carbon paper were replaced once.
Wires and epoxy resin	78.8	Pt wires 1 m, epoxy resin 25 mL
Costs of reagents	0	Real wastewater from a local food factory
Depreciated income	71.3	
Operating and maintenance	1756.7	6 days per cycle, 60 cycles per year

Using wastewater from a local food factory as reaction fluid does not require the addition of other reagents. So the costs under the experimental conditions are the same as the costs under the practical conditions.

Table B.1(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/$m^2$)·d)	Annual net investment cost under practical conditions ($/a)
1	338	29.3	0.081	4.88	5.12	29.3
2	78	29.6	0.082		5.93	29.6
15	56	29.8	0.082		6.34	29.8

Here follows the calculation process of the Cost per unit power:

Device 1: Power density: 338 mW/m^2

Costs of investment and reagents: $0.081/d ÷ 0.338W/$m^2$ = $0.24/(W/$m^2$) · d

Costs of operation and maintenance (except reagents): $4.88/d, do not change with the power of the device.

Cost per unit power = $0.24 + $4.88 = $5.12/(W/$m^2$) · d

Device 2: Power density: 78 mW/m^2

Costs of investment and reagents: $0.082/d ÷ 0.078W/$m^2$ = $1.05/(W/$m^2$) · d

Costs of operation and maintenance (except reagents): $4.88/d do not change with the power of the device.

Cost per unit power = $1.05 + $4.88 = $5.93/(W/$m^2$) · d

Device 15: Power density: 56 mW/m^2

Costs of investment and reagents: $0.082/d ÷ 0.056W/$m^2$ = $1.46/(W/$m^2$) · d

Costs of operation and maintenance (except reagents): $4.88/d do not change with the power of the device.

Cost per unit power = $1.46 + $4.88 = $6.34/(W/$m^2$) · d

Annual net investment cost under practical conditions is to subtract the costs of reagents from annual net investment cost.

The calculation method and process of cost per unit power of other devices are the same as this reference, and the following will not repeat.

Reference [37]

Table B 2(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	1756.71/a 4.88/d
		948	Brewery wastewater, 6 days per cycle, 60 cycles per year	
Costs of routine maintenance	15.8/cycle	1137	Glucose, 5 days per cycle, 72 cycles per year	1946.29/a 5.41/d
		1896	Acetate, 3 days per cycle, 120 cycles per year	2704.58/a 7.51/d
Costs of water quality monitoring	24.5/time	588	Twice a month	
Costs of overhaul	15.8/time	63	Once every three months	

Table B 2(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	14.2	4.74	9.76
Wires	0.28		

Table B 2(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	15.80	Single-chamber, plexiglass, 5*9*6 cm, working volume 225 mL
Electrode materials	4.11	Graphite felt (12 cm^2) was used as the anode
		Pt-loaded carbon cloth was used as the cathode
		The graphite felt and the Pt-loaded carbon cloth were replaced once
Wires and epoxy resin	3.32	Copper wires 1m, epoxy resin 25 mL
Costs of reagents	5.42	Acetate (3rd)
	3.20	Glucose (7th)
	0	Brewery wastewater (14th)
Depreciated income	9.76	
Operating and maintenance	1756.71	Brewery wastewater, 6 days per cycle, 60 cycles per year
	1946.29	Glucose, 5 days per cycle, 72 cycles per year
	2704.58	Acetate, 3 days per cycle, 120 cycles per year

Table B 2(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/$m^2$)·d)	Annual net investment cost under practical conditions ($/a)
3	1256	18.88	0.05	7.51	7.55	13.46
7	1519	16.67	0.05	5.41	5.44	13.46
14	251	13.46	0.04	4.88	5.03	13.46

Reference [52]

Table B 3(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/ time	158	–	3652.45 /a
Costs of routine maintenance	15.8/ cycle	2843.60	2 days per cycle, 180 cycles per year	
Costs of water quality monitoring	24.5/ time	587.68	Twice a month	10.15/d
Costs of overhaul	15.8/ time	63.19	Once every three months	

Table B 3(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	7.39	4.74	2.94
Wires	0.28		

Table B 3(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	8.21	Single-chamber, plexiglass, working volume 28 mL.
Electrode materials	4.09	Graphene - polyaniline modified carbon cloth was used as the anode, Pt-loaded carbon cloth (7 cm^2) was used as the cathode. The graphene - polyaniline modified carbon cloth and the Pt-loaded carbon cloth were replaced once.
Wires and epoxy resin	3.32	Copper wires 1 m, epoxy resin 25 mL.
Costs of reagents	2.38	Synthetic wastewater containing sodium acetate.
Depreciated income	2.94	
Operating and maintenance	3652.45	2 days per cycle, 180 cycles per year

Table B.3(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/$m^2$)·d)	Annual net investment cost under practical conditions ($/a)
4	703	15.07	0.04	10.15	10.20	12.69

Reference [53]

Table B.4(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/ time	158	–	5358.61/a
14.88/d				
Costs of routine maintenance	15.8/ cycle	454.76	30 h per cycle, 288 cycles per year	
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.4(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	7.54	4.74	3.29
Wires	0.50		

Table B.4(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	8.37	Single-chamber, plexiglass, 20 cm^2 in cross-sectional area and 4 cm in length, working volume 80 mL.
Electrode materials	38.64	Carbon paper (20 cm^2) was used as the anode, Pt-loaded carbon cloth (0.5 mg/cm^2) was used as the cathode. The carbon paper and the Pt-loaded carbon cloth were replaced once.
Wires and epoxy resin	3.55	Titanium wires 1 m, epoxy resin 25 mL.
Costs of reagents	14.33	Synthetic wastewater containing sodium acetate
Depreciated income	3.29	
Operating and maintenance	5358.61	30 hours per cycle, 288 cycles per year

Table B.4(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/$m^2$)·d)	Annual net investment cost under practical conditions ($/a)
5	378.13	61.61	0.17	14.88	15.34	47.27

Reference [54]

Table B.5(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	1377.6/year
Costs of routine maintenance	15.8/cycle	568.72	10 days per cycle, 36 cycles per year	3.83/day
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.5(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	49.76	4.74	45.39
Proton exchange membrane	0.08		
Wires	0.28		

Table B.5(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	55.29	Double-chamber, two 250-mL bottles with a glass bridge.
Electrode materials	26.11	Carbon paper (11.25 cm^2) was used as the anode, Pt-loaded carbon
		Paper (1 mg/cm^2) was used as the cathode, Nafion117 0.71 cm^2
		The carbon paper and the Pt-loaded carbon paper were replaced once.
Wires and epoxy resin	3.32	Copper wires 1 m, epoxy resin 25 mL.
Costs of reagents	35.36	Domestic wastewater with the medium ingredients
Depreciated income	45.39	
Operating and maintenance	1377.57	10 days per cycle, 36 cycles per year

Table B.5(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/$m^2$)·d)	Annual net investment cost under practical conditions ($/a)
6	38	74.69	0.21	3.83	15.59	39.33

Reference [55]: Research on different cathode materials

Table B.6(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total($)
Costs of labor	158/time	158	–	
Costs of routine maintenance	15.8/cycle	1895.73	Graphite felt was used as the cathode.	2704.58/year
			3days per cycle, 120 cycles per year	7.51/day
		1421.80	Carbon paper was used as the cathode.	2230.65/year
			4 days per cycle, 90 cycles per year	6.20/day
		1421.80	Stainless steel mesh was used as the cathode.	2230.65/year
			4 days per cycle, 90 cycles per year	6.20/day
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.6(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	14.79	4.74	10.33
Stainless steel mesh	The cost is negligible with the less use.		
Wires	0.28		

Table B.6(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	16.43	Double-chamber, plexiglass, 3 cm in length and 5 cm in diameter, 58 mL
Electrode materials	0.49	Graphite felt was used as the anode, carbon paper was used as the cathode.
The graphite felt and the carbon paper were replaced once. (10th)	0.10	Graphite felt was used as the anode and the cathode.
The graphite felt was replaced once. (11th)	0.05	Graphite felt (7 cm^2) was used as the anode, stainless steel mesh was used as the cathode. The graphite felt was replaced once. (13th)
Wires and epoxy resin	3.32	Copper wires 1m, epoxy resin 25 mL.
Costs of reagents (synthetic wastewater containing glucose)	3.71	Graphite felt was used as the anode, carbon paper was used as the cathode.
	4.86	Graphite felt was used as the anode and the cathode.
	3.71	Graphite felt was used as the anode, stainless steel mesh was used as the cathode.
Depreciated income	10.33	
Operating and maintenance	2230.65	Carbon paper was used as the cathode, 4 days per cycle and 90 cycles per year.
	2704.58	Graphite felt was used as the cathode, 3 days per cycle and 120 cycles per year.
	2230.65	Stainless steel mesh was used as the cathode, 4days per cycle and 90 cycles per year.

Table B.6(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/($W/m^2$)·d)	Annual net investment cost under practical conditions ($/a)
10	32.7	13.62	0.04	6.20	7.36	9.91
11	109.5	14.38	0.04	7.51	7.87	9.52
13	3.1	13.18	0.04	6.20	17.92	9.47

Research on different catalysts

Table B.7(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	
Costs of routine maintenance	15.8/cycle	947.87	MnO_2/CNTs were used as the catalyst, 6 days per cycle and 60 cycles per year	1756.71/year 4.88/day
		1137.44	Pt/C was used as the catalyst, 5 days per cycle and 72 cycles per year.	1946.29/year 5.41/day
		1137.44	CNTs were used as the catalyst, 5 days per cycle and 72 cycles per year.	1946.29/year 5.41/day
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.7(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	7.39	4.74	2.94
Wires	0.28		

Table B.7(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	8.21	Double-chamber, plexiglass, 3 cm in length and 5 cm in diameter, 58 mL.
Electrode materials		
(The graphite felt, the carbon paper and the catalysts were replaced once.)	0.85	Graphite felt (7 cm^2) was used as the anode, carbon paper was used as the cathode. MnO_2/CNTs were used as the catalyst. (8th)
	1.31	Graphite felt (7 cm^2) was used as the anode, carbon paper was used as the cathode. Pt/C was used as the catalyst. (9th)
	0.53	Graphite felt (7 cm^2) was used as the anode, carbon paper was used as the cathode. CNTs were used as the catalyst. (12th)
Wires and epoxy resin	3.32	Copper wires 1 m, epoxy resin 25 mL.
Costs of reagents (synthetic wastewater containing glucose)	2.43	MnO_2/CNTs were used as the catalyst.
	2.97	CNTs were used as the catalyst.
	2.97	Pt/C was used as the catalyst.
Depreciated income	2.94	
Operation and maintenance	1756.71	MnO_2/CNTs were used as the catalyst, 6 days per cycle and 60 cycles per year.
	1946.29	Pt/C was used as the catalyst, 5 days per cycle and 72 cycles per year.
	1946.29	CNTs were used as the catalyst, 5 days per cycle and 72 cycles per year.

Table B.7(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/m^2)·d)	Annual net investment cost under practical conditions ($/a)
8	210	11.88	0.03	4.88	5.04	9.45
9	229	12.87	0.04	5.41	5.56	9.90
12	8	12.10	0.03	5.41	9.55	9.13

Reference [56]

Table B.8(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	3652.45/year
Costs of routine maintenance	15.8/cycle	2843.60	2 days per cycle, 180 cycles per year	10.15/day
Costs of water quality monitoring	24.5/ time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.8(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	8.82	4.74	4.36
Wires	0.28		

Table B.8(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	9.79	Single-chamber, plexiglass, working volume 230 mL.
Electrode materials	17.06	Graphite flakes (30 cm^2) were used as the anode, graphite rods were used as the cathode. The graphite flakes and the graphite rods were replaced once.
Wires and epoxy resin	3.32	Copper wires 1 m, epoxy resin 25 mL.
Costs of reagents	0	Surplus sludge without any reagents.
Depreciated income	4.36	
Operation and maintenance	3652.45	2 days per cycle, 180 cycles per year

Table B.8(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operating and maintenance cost ($/d)	Cost per unit power ($/(W/m^2)·d)	Annual net investment cost under practical conditions ($/a)
16	44	25.82	0.07	10.15	11.76	25.82

Reference [57]

Table B.9(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	1045.81/ year
Costs of routine maintenance	15.8/cycle	236.97	25 days per cycle, 15 cycles per year	2.91/day
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.9(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	28.44	4.74	33.69
Proton exchange membrane	4.12		
Fluorescent lamps (The life span is 24,000 hours. Depreciate to 63% of original price.)	5.37		
Wires	0.50		

Table B.9(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	31.60	Double-chamber, plexiglass, 8*8*4 cm for each.
Artificial light source	8.53	2 fluorescent lamps
Electrode materials	8.68	Graphite felt (5*6 cm) was used as the anode and the cathode.
		Proton exchange membrane:6*6 cm
		The graphite felt was replaced once.
Wires and epoxy resin	3.55	Titanium wires 1 m, epoxy resin 25 mL.
Costs of reagents	48.61	Synthetic wastewater containing glucose added Chlorella.
Costs of power consumption for the artificial light source	60.33	26W*2 (The price of electricity is $0.13/degree.)
Depreciated income	33.69	
Operation and maintenance	1045.81	25 days per cycle, 15 cycles per year

Table B.9(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operation and maintenance cost ($/d)	Cost per unit power ($\$/(W/m^2)\cdot d$)	Annual net investment cost under practical conditions ($/a)
17	82.6	127.61	0.35	2.91	7.19	126.39

Reference [58]

Table B.10(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	1519.75/year
Costs of routine maintenance	15.8/cycle	710.90	8 days per cycle, 45 cycles per year	4.22/day
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.10(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	17.49	4.74	19.21
Fluorescent lamps (The life span is 24000 h. Depreciate to 63% of original price.)	5.37		
Proton exchange membrane	0.80		
Wires	0.28		

Table B.10(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	19.43	Double-chamber, 500 mL for the anode chamber and 300 mL for the cathode chamber. The material is unknown, and it is assumed to be plexiglass.
Artificial light source	8.53	2 fluorescent lamps
Electrode materials	128.98	Carbon felt (49.5 cm^2) was used as the anode, Pt-loaded carbon paper was used as the cathode. Proton exchange membrane 7 cm^2. The carbon felt and the Pt-loaded carbon paper were replaced once.
Wires and epoxy resin	3.32	Copper wires 1 m, epoxy resin 25 mL.
Costs of reagents	53.30	Synthetic wastewater containing glucose added Chlorella.
Costs of power consumption	30.16	Intermittent illumination 26W*2 (The price of electricity is $0.13/degree.)
For the artificial light source	60.33	Continuous illumination 26W*2 (The price of electricity is $0.13/degree.)
Depreciated income	19.21	
Operation and maintenance	1519.75	8 days per cycle, 45 cycles per year

Table B.10(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operation and maintenance cost ($/d)	Cost per unit power ($/(W/$m^2$)·d)	Annual net investment cost under practical conditions ($/a)
18	24.4	224.52	0.62	4.22	29.80	218.61
19	27.5	254.68	0.71	4.22	29.96	248.77

Reference [59]

Table B.11(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/ time	158	–	3652.45/ year
Costs of routine maintenance	15.8/ cycle	2843.60	2 days per cycle, 180 cycles per year	10.15/ day
Costs of water quality monitoring	24.5/ time	587.68	Twice a month	
Costs of overhaul	15.8/ time	63.19	Once every three months	

Table B.11(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	25.02	4.74	24.05
Fillers	2.08		
Plants	1.26		
Wires	0.42		

Table B.11(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	27.80	Plexiglass, 18 cm in diameter and 52 cm in height.
Electrode materials	23.22	Granular active carbon was used as the anode, granular graphite was used as the cathode. The granular active carbon and the granular graphite were replaced once.
Fillers	3.99	Gravels, volcanic rocks and fiberglass.
Plants	1.26	Bulrush
Wires and epoxy resin	5.28	Copper wires 1.5 m, epoxy resin 40 mL.
Costs of reagents	18.28	Synthetic wastewater containing glucose.
Costs of power consumption for the peristaltic pump	34.81	The power of the peristaltic pump is 30W. The price of electricity is $0.13/ degree.
Depreciated income	24.05	
Operation and maintenance	3652.45	2 days per cycle, 180 cycles per year

Table B.11(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operation and maintenance cost ($/d)	Cost per unit power ($/(W/ m^2)·d)	Annual net investment cost under practical conditions ($/a)
20	19.7	90.59	0.25	10.15	18.16	72.30

Reference [60]

Table B.12(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total($)
Costs of labor	158/ time	158	–	3652.45/ year
Costs of routine maintenance	15.8/cycle	2843.60	2 days per cycle, 180 cycles per year	10.15/ day
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.12(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	10.95	4.74	17.02
Stainless steel mesh	6.80		
Wires	0.75		
Fillers	2.79		
Plants	0.47		

Table B.12(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	12.16	A polyacrylic plastic cylinder (30 cm in diameter).
Electrode materials	32.67	Granular activated carbon was used as the anode (706.5 cm^2), the stainless steel mesh (12 mesh) coupled with GAC was used as the cathode. The granular activated carbon was replaced once.
Fillers	3.10	Gravels (3–6 mm)
Plants	0.47	Ipomoea aquatica
Wires and epoxy resin	5.63	Titanium wires 1.5 m, epoxy resin 40 mL.
Costs of reagents	328.36	Synthetic wastewater containing glucose.
Costs of power consumption for the peristaltic pump	34.81	The power of the peristaltic pump is 30 W.
Depreciated income	17.02	The price of electricity is $0.13/degree.
Operation and maintenance	3652.45	2 days per cycle, 180 cycles per year

Table B.12(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operation and maintenance cost ($/d)	Cost per unit power($/($W/m^2$)·d)	Annual net investment cost under practical conditions ($/a)
21	74.447	400.19	1.11	10.15	25.08	71.83

Reference [61]

Table B.13(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	6496.05/year 18.04/day
Costs of routine maintenance	15.8/cycle	5687.20	One day per cycle, 360 cycles per year.	
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.13(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	33.63	4.74	36.48
Stainless steel mesh	0.35		
Fillers	6.07		
Plants	0.75		
Wires	0.42		

Table B.13(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	37.36	An acrylic column (18 cm D×75 cm H)
Electrode materials	14.60	Activated carbon with stainless steel was used as the anode and the cathode. The activated carbon was replaced once.
Fillers	6.75	Gravels and glass beats.
Plants	0.75	Cattail, 2 strains.
Wires and epoxy resin	5.28	Copper wires 1.5 m, epoxy resin 40 mL.
Costs of reagents	14.34	Synthetic wastewater containing sodium acetate.
Costs of power consumption for the peristaltic pump	30.45	The power of the peristaltic pump is 30 W.
Depreciated income	36.48	The price of electricity is $0.13/degree.
Operation and maintenance	6496.05	One day per cycle, 360 cycles per year.

Table B.13(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operation and maintenance cost ($/d)	Cost per unit power ($/($W/m^2$)·d)	Annual net investment cost under practical conditions ($/a)
22	9.3	70.60	0.20	18.04	39.11	58.71

Reference [62]

Table B.14(a)
Operating and maintenance costs other than reagents

Items	Unit cost ($)	Annual cost ($)	Remarks	Total ($)
Costs of labor	158/time	158	–	2704.58/year 7.51/day
Costs of routine maintenance	15.8/cycle	1895.73	3 days per cycle, 120 cycles per year	
Costs of water quality monitoring	24.5/time	587.68	Twice a month	
Costs of overhaul	15.8/time	63.19	Once every three months	

Table B.14(b)
Depreciated income

Depreciated items	Depreciated value ($)	Costs of labor ($)	Total ($)
Reactor	25.59	4.74	87.64
Titanium mesh	58.29		
Wires	0.57		
Fillers	6.41		
Plants	1.52		

Table B.14(c)
Summaries of various costs

Investment items	Costs ($)	Remarks
Reactor	28.44	Single-chamber, plexiglass, 20 cm in diameter and 60 cm in height.
Electrode materials	72.35	Titanium mesh coupled with activated carbon was used as the anode (268.67 cm^2) and the cathode. The activated carbon was replaced once.
Fillers	7.97	Coarse sand, ceramsite and gravels
Plants	1.52	Bulrush
Wires and epoxy resin	5.43	Copper wires 2 m, epoxy resin 40 mL.
Costs of reagents	1.17	Synthetic wastewater
Costs of power consumption for the peristaltic pump	34.81	The power of the peristaltic pump is 30W.
		The price of electricity is $0.13/degree.
Depreciated income	87.64	
Operation and maintenance	2704.58	3 days per cycle, 120 cycles per year

Table B.14(d)
Cost per unit power

Serial numbers of the devices	Power density (mW/m^2)	Annual net investment cost ($/a)	Daily net investment cost ($/d)	Daily operation and maintenance cost ($/d)	Cost per unit power ($/(W/m^2)·d)	Annual net investment cost under practical conditions ($/a)
23	3714.08	64.05	0.18	7.51	7.56	62.95

Appendix C. Calculation of electricity production, wastewater treatment revenue and annual total revenue of each device

Table C.1
Annual total revenue

Serial No.	Power density (mW/m^2)	Annual electricity production (10^{-5} kW·h)	Annual revenue from electricity production (10^{-5} \$)	Annual wastewater treatment (10^{-3} m^3)	Annual revenue from wastewater treatment (10^{-3} \$)	Annual total revenue (10^{-3} \$)	References
1	338	183	24.64	5.04	0.64	0.88	[51]
2	78	42	5.69	5.04	0.64	0.69	[51]
3	1256	1302	174.88	27.00	3.41	5.16	[37]
4	831	503	67.61	5.04	0.64	1.31	[52]
5	378.13	653	87.68	23.00	2.91	3.78	[53]
6	38	37	4.90	9.00	1.14	1.19	[54]
7	1519	1575	211.53	16.20	2.05	4.16	[37]
8	210	127	17.06	3.48	0.44	0.61	[55]
9	229	138	18.48	4.18	0.53	0.71	[55]
10	32.7	20	2.69	5.22	0.66	0.69	[55]
11	109.50	66	8.85	6.96	0.88	0.97	[55]
12	8	5	0.63	4.18	0.53	0.53	[55]
13	3.10	2	0.32	5.22	0.66	0.66	[55]
14	251	260	34.91	13.50	1.71	2.06	[37]
15	56	30	4.11	5.04	0.64	0.68	[51]
16	44.00	114	15.32	41.40	5.23	5.39	[56]
17	82.60	214	28.75	3.84	0.48	0.77	[57]
18	24.40	104	13.90	22.50	2.84	2.98	[58]
19	27.50	118	15.80	22.50	2.84	3.00	[58]
20	19.70	433	58.14	1296	163.82	164.45	[59]
21	74.447	4544	610.11	2232	382.15	288.31	[60]
22	9.30	204	27.33	1836	232.07	232.39	[61]
23	3714.08	86215	11577.09	582	73.62	189.42	[62]