Review Article

Nur Iman Syafiqah Muhammad Nasruddin, Mimi Hani Abu Bakar*

Mitigating membrane biofouling in biofuel cell system – A review

https://doi.org/10.1515/chem-2021-0111
received September 20, 2021; accepted November 26, 2021

Abstract: A biofuel cell (BFC) system can transform chemical energy to electrical energy through electrochemical reactions and biochemical pathways. However, BFC faced several obstacles delaying it from commercialization, such as biofouling. Theoretically, the biofouling phenomenon occurs when microorganisms, algae, fungi, plants, or small animals accumulate on wet surfaces. In most BFC, biofouling occurs by the accumulation of microorganisms forming a biofilm. Amassed biofilm on the anode is desired for power production, however, not on the membrane separator. This phenomenon causes severities toward BFCs when it increases the electrode’s ohmic and charge transfer resistance and impedes the proton transfer, leading to a rapid decline in the system’s power performance. Apart from BFC, other activities impacted by biofouling range from the uranium industry to drug sensors in the medical field. These fields are continuously finding ways to mitigate the biofouling impact in their industries while putting forward the importance of the environment. Thus, this study aims to identify the severity of biofouling occurring on the separator materials for implementation toward the performance of the BFC system. While highlighting successful measures taken by other industries, the effectiveness of methods performed to reduce or mitigate the biofouling effect in BFC was also discussed in this study.

Keywords: biofilm, membrane surface, nanoparticles, microorganisms, antibacterial

1 Introduction

Since decades ago, the energy crises worldwide have witnessed the decline of nonrenewable energy sources and inefficient utilization of renewable energy sources. One of the green technologies that can reduce organic pollution while simultaneously creating usable energy will be the biofuel cell (BFC). BFCs are an energy transformation technology that applies biological catalysts to a coupled redox reaction [1]. The system produced electric current by utilizing the bacteria or microorganisms, naturally consuming organic material from their ecosystem [2]. This action allows electrons to flow from anode to cathode compartment by converting chemical energy into electrical energy. In the anode compartment, power generates by electrochemical reactions from the process known as oxidation of fuels such as organic waste.

Meanwhile, at the cathode compartment, reduction of oxidant that is typically oxygen occurs [3]. BFC systems are easy to set up and do not require high temperatures to operate [4]. Active research is ongoing to improve this technology by manipulating new properties of unconventional materials at the atomic and molecular levels. This practice involves nanotubes [5], nanoparticles [6], and conductive polymers [7] for persuasive electricity generation from biological substrates through the use of various biocatalysts. The existence of nanotechnology has made it possible to achieve many important discoveries in the field of BFCs. The BFCs have the potential to be utilized as a primary and an alternate energy for stationary applications: commercial, industrial, and residential buildings, especially in remote or unreachable areas [8], and vehicles: apart from the stationary application, the BFC is also capable of propelling vehicles [9]. However, BFC faces constraints to provide sufficient energy for long-term applications and limited performance and single usability, which hinders it from commercializing green energy generation [10]. Due to the low power output, the BFCs gained interest as energy harvesters for low-powered probe sensors [11]. For instance, the BFC system can operate in human blood to power implanted medical devices, such as standard glucometer microelectronic devices, while consuming glucose and oxygen gas in human body fluids as fuel [12], apart from other various BFC devices (Table 1).

The importance of the development of BFC technology is due to its ability to generate electricity without
polluting the environment while simultaneously reducing the pollution impact in wastewater [13]. BFC can also function at higher competence than a combustion engine and can change the chemical energy in fuel directly into electrical energy with an ability capable of more than 60% [14]. Microbial fuel cell (MFC) is one of the systems listed as BFC, where the system aims to generate electricity by using electrons derived from biochemical reactions using bacterial catalysts [15]. The findings show that the power generated through this system is supposed to channel sufficient energy to meet some energy demand in the urban wastewater treatment plants [16]. In addition, BFC is a safe system where the power generated is environmentally friendly [17]. Among the BFCs listed in Table 1, only the MFC, microbial desalination cell (MDC), microbial electrosynthesis (MES), and microbial electrolysis cell (MEC) have reported on the biofouling effect. The typical biofouling formation occurs on the surface of the cathode [18] and membrane [19] during the long-term operation.

Biofouling incident resulted in the deterioration of system performance and a hike in internal resistance. For instance, biofouling adversely affects the MDC system. The developed biofilm on the surface of the membrane resulted in degradation of MDC performance as there is an excessive resistance to ion transport [20]. In addition, MESs and MECs also face similar biofouling issues [21]. Most BFCs use mixed culture as inoculation, thus facing the disadvantage of membrane biofouling [22]. Hishamaddah and Amanchogle mentioned that biofouling formed as early as 1 month and fully formed on the sixth month of continuous operation [23].

### 2 Aim of the Study

Therefore, this research aims to understand biofilm and biofouling formation and the criticality of its impact on several industries. The study highlights several successful measures by industries to mitigate biofouling and the techniques redesigned in the BFC system. Consequently, the discussion in this study will give some insights on the BFC membrane biofouling, its consequences, and options to avoid it.

### 3 Biofouling mechanism

Nowadays, due to the increase in energy demand, researchers are conducting millions of studies to improve the BFC system to generate sustainable power to meet the demand. However, despite millions of studies, the problem of biofouling remains inevitable. Biofouling is the buildup of organisms (microorganisms) such as bacteria, fungi, and algae on the surface upon contact with water [24]. Biofouling is a common and natural phenomenon that occurs on the surface involving the interactions between microorganisms with organic matter. In BFCs, biofouling should thrive on the anode, however, not on the membrane. One of the negative impacts of membrane biofouling is the power performance deterioration of the BFCs [19]. Biofouling that forms on the surface of a membrane is a convoluted process involving association from bacterial adhesion (biofilm), species interactions, and extracellular polymeric substances (EPSs) excretion and utilization [25]. EPSs and soluble microbial products are the usual compounds discharged by microbes. The compounds are deposited on the surface of the membrane at the early stage of biofouling formation [26]. Biofilm contains tightly packed microorganisms in a matrix form that functions as their boundary to purification and disinfection [27]. As shown in Figure 1, at bacteria first contact with a membrane surface (stage 1), the bacteria will make an irreversible interaction. Once the bacteria are attached to the membrane surface (stage 2), the bacteria will produce and excrete the EPSs that allows cells to become cemented on the surface. Continual bacterial growth on the surface

| Type of BFC systems       | Functions of BFC systems                                                      | References |
|---------------------------|-------------------------------------------------------------------------------|------------|
| Microbial fuel cell       | Generating electric current and treating wastewater                          | [112]      |
| MDC                       | Wastewater treatment, water desalination, and production of electrical energy  | [113]      |
| MEC                       | Generating hydrogen or methane                                               | [114]      |
| MES                       | Produce sustainable energy and carbon source (organic molecule) at biocathode | [115, 116] |
| Biological photovoltaics  | Capturing sustainable energy and generating electrical energy                | [117]      |
| Up-flow MFC               | Generating power and wastewater treatment                                    | [118]      |
| Enzymatic BFC             | Catalyze the conversion of chemical energy into electrical energy             | [119]      |
causes the development of microcolonies (stage 3). The microcolonies will continue to increase in size (stage 4); thus, the interior cells will become overcrowding, increase in concentrations of waste products, decrease in nutrients, which later leads to a change in the physicochemical environment. Finally, digestion of the matrix within the microcolony will occur due to source food depletion (stage 5) [28]. This act will free the cells from the matrix and allow active mobility for the cells. The formation of a biofilm layer on the membrane surface causes the membrane to become thicker, upturning the resistance and making it harder for mass transfer and ion transport [29]. Biofouling formation causes limitations to the operating efficiency of the BFC system. Adverse biofilm interaction on the membrane surface leads to mass transfer and charge transfer reduction [30].

Since decades ago, due to this issue, researchers have sought to conduct many experiments to achieve membrane with antibiofouling features to inhibit or diminish the unfavorable outcome of this phenomenon.

In wastewater systems, biofouling is considered an unwanted deposition of micro and macroorganisms. Membranes clogged through biofouling will result in the gradual deterioration of system performance [32]. Ashfaq et al. showed that biofouling consists of proteins, polysaccharides, and lipids [33]. During long-term operations, biofouling showed capability in deterring the ions flux in the membrane [34]. In the BFC system, biofouling will occur on electrodes during electricity generation. It is essential for biofouling to occur on the anode electrode to avoid a phenomenon called electrode passivation [35], which leads to system failure. Electrode passivation has not been widely inspected, although microbe–electrode connections are essential for electricity generation [36]. The high concentration of organic matter and bacteria encouraged biofouling on the surface of the membrane, which reduced the performance of BFC system [37]. Therefore, there are studies conducted to mitigate the biofouling formation [38] such as decreasing the bacterial attachment by $\beta$-amino acids [39] and improving biofilm cleaning by manually scraping the surface of the membrane in ultrafiltration [40] to get clean water.

## 4 Biofouling on BFC

In a BFC system, biofilm is necessary to grow on the anode electrode to supply electrons from the oxidation of the organic substrate. It is, however, a significant drawback when biofilm forms on other parts of the system, which later leads to biofouling [41]. Flimban et al. studied the effect of Nafion membrane fouling on the power generation of MFC. They reported that biofouling affected the coulombic efficiencies and the maximum power densities of the MFC after 2 months while...
the system started showing decline after 6 months of operations [42].

4.1 Biofouling effect on membranes of BFC

Membranes are the crucial parts of BFCs as the function is to retain desirable hydrophilic characters to ensure electrolyte penetration [43]. Usually, biofouling on the membrane of MFC can happen in a wide range of situations. Microorganisms that cause biofouling will only attach to hydrophobic and positively charged membrane surfaces [44]. Several reports mentioned that most bacteria involved in biofilm formation are known as negatively charged [45]. The most suitable conditions for the development of microorganisms depend on sufficient carbon sources as their food and nutrients in order for the microorganisms to trigger their particular reaction, such as oxidation and reduction [46]. There are several types of the membrane that have been used widely in BFCs that facing biofouling issues, such as cation exchange membrane (CEM) [47], anion exchange membrane (AEM) [48], proton exchange membrane (PEM) [49], and ceramic membrane [50].

The MDC differs from other BFCs, due to its application of two membranes: CEM and AEM (Figure 2). Fouling on the CEM and AEM comes from salt composition and microbes, respectively [52]. The main biofouling factor is the permanent attachment of uncontrollable biofilms caused by bacteria and their EPSs on the membrane surface. Crucial initiator in membrane biofouling is the acidic polysaccharides produced by phytoplankton and bacteria, also known as transparent exopolymer particles, produced by saltwater bacteria [53], and proto biofilms. The power generation will gradually drop when the salt composition begins to scale on CEM [54]. The salt composition from ions, such as \( \text{Mg}^{2+}, \text{Ca}^{2+}, \) and \( \text{PO}_4^{3-} \), is more likely to be deposited on CEM and form a scaling layer. At the same time, biofouling was more prone to grow on AEM in MDC [55]. AEM is a membrane with good thermal stabilities, high ionic conductivities, and excellent chemical stabilities. AEM is compatible with an alkaline fuel cell system, as the performance after about 5 days revealed maximum power density up to 124.8 mW/cm² at 60°C and open-circuit voltage (OCV) of 1.08 V [56]. AEM functions by moving the hydroxide anions, inhibiting fuel from reaching the oxygen [57], giving fast cathode reactions, and lowering the cost for electrocatalysts [58]. In BFC, however, biofouling formation on AEM is an issue as recorded by Elangovan and Dharmalingam. The power density of the MFC system with AEM deteriorated up to 2.3% from 918 to 897 mW/m² in 30 days [59]. Another study conducted by Ping et al. in the long-term investigation of AEM in MDCs showed biofouling formation by fungi on the AEM surface as it turned black. The initial power density reported of the system was 990 mW/m². However, after 80 days of operation, the power density dropped about 16.2% to 830 mW/m² and further reduced about 32.5% to 560 mW/m² after

![Figure 2: Schematic of an MDC [51].](image-url)
250 days [60]. To prolong the membrane life in operational plants, it is crucial to discharge old, uncontrollable growth of biofilms as one of the methods that may help prevent membrane biofouling. Other methods used to prevent biofouling are broad-spectrum biocides and chemicals targeting bacterial cells to discharge matured biofilms [61]. However, this method is not suitable for MDC as the MDC system requires a large amount of seawater. Biofouling formation on the membrane is a critical problem the desalination industry faces worldwide, and biofouling control remains a challenge in MDC systems.

One of the most reported membranes affected by biofouling is PEM. Biofouling in the MEC system is usually formed on the PEM. It is a major flaw when biofouling is spotted on PEM as it limits the proton migration [62,63]. The accumulation of bacteria and their products formed a thick biofilm on the surface of PEM and led to the decline of power generation. This thick biofilm prevents the passage of protons from the anode side toward the cathode side. The biofouling formation reduced the flux of ions on the membrane of MEC. This condition will raise the internal resistance and cause disturbance toward flowing in and flowing out of the ions on the membrane [54]. The internal resistance is related to severe membrane fouling, which hinders substrate transportation [21]. For instance, Nafion is known to be the most favored PEM in the BFC system. The reported power generation via biofouled Nafion was 20.9 mW/m², which is 79% lesser than the power generated by pretreatment Nafion (100 mW/m²) [63]. Flimban et al. reported that their MFC reached the highest OCV of about 700 mV within 6 months before it started to decline continuously until almost zero [42]. The researchers, however, did not report on PEM cleaning nor the thickness of the biofilm formed that may have affected their system. In terms of chemical oxygen demand (COD), Kardi et al. reported that their MFC system faced decreased COD removal percentage until 18% in the first 5 days and later increased from 89 to 92% [64]. This behavior shows that COD removal gradually increases throughout the operation [42]. Percentage of COD removal indicates the existence of microbial in the wastewater to metabolize the carbon source or organic pollution [65]. Moreover, biofouling formed by these microbes causes an immediate damaging and harmful effect on a system’s membrane, such as preventing the proton transfer and raising the ohmic resistance, thus giving swift deterioration in MFC performance [66]. In continuous long-term research on PEM, its performance gradually decreased due to low proton conductivity, which degrades the electricity generation and increases MFC operational cost because of membrane replacement [67].

Ceramics application as a membrane in the fuel cell system has become a favorite because of its relatively lower cost than polymeric membranes [68]. In addition, ceramic improves power and treatment efficiencies, electroactive bacterial surroundings [69], mechanical stability, and thermal and chemical resistivity [70]. Ceramic has various pore sizes (0.14, 0.2, and 0.45 µm) formed by controlling the sintering temperature. The pore size of a membrane plays an essential role in the critical ion flux [71]. The determination of biofilm on ceramic membrane depends on the concentration of the microorganisms and the feeding concentrations – thin biofilm forms when the feeding concentration is low [72]. Gajda et al. conducted a 1 year study to compare the biofouling effect between ceramic membrane and PEM. Their results showed that ceramic membrane experienced power loss earlier on day 350, up to 20%, whereas PEM experienced 20% power loss on day 446 [73]. The results proved that PEM is the best. However, the ceramic membrane is cheap, easy to get, and easier to clean compared to PEM.

Miskan et al. reported the detection of biofouling and categorized the formation into three different stages within 6 months of the system operations. They found a biofouling layer accumulated on the studied membrane with a thickness up to 14.7 ± 0.4 µm in 2 months after start-up. In the fourth month, the result showed the biofouling layer increased by 11-fold (165.1 ± 22.4 µm) and 17-fold after 6 months (250.1 ± 10.7 µm) [74]. Fouling on the membrane increases the system’s operating pressure, decrease ions flux, and shortens the membrane life span [75]. Thus, there are approaches to using positively charged surfaces to defeat biofouling. The dilemma of biofouling formation created a significant obstacle to the water industry [76] since the unwanted organism growth can stain the water and block the surface and host pathogens [77].

5 Membrane biofouling prevention measures

Laqbaqbi et al. reported that the biofilm hydraulic permeability and membrane surface coverage hold the most significant consequences on water flux in the marine industry. This biofilm affected the process efficiency and increased the operational efficiency cost [78]. Biofouling also gives some mining difficulties in marine science, especially on the alternative method to conduct amidoxime-based polymeric or uranium adsorption [79]. Since biofouling is an inevitable issue in various activities, many adverse effects
indirectly encourage researchers to study the measures in controlling its formation.

### 5.1 Quorum sensing (QS) disruption

Based on Figure 3, membrane bioreactors (MBRs) are reported as the most efficient technology in advanced wastewater treatment. However, the MBRs also faced with membrane biofouling issues. In MBR, biofouling starts when cell-to-cell communication occurs, which allows bacteria to accumulate. Mobile entrapping elements such as the rotary microbial carrier frame, cell entrapping beads (CEB), and macrocapsules for methods in quorum quenching (QQ) were analyzed to disrupt QS, which is a cell-to-cell means of communication in biofilm. Results showed that the application of QQ reduced up to 60% of biofouling [100]. Irreversible biofouling, which often occurs in reverse osmosis membrane, is challenging to eliminate using the physical method. Thus, the researcher had applied the quorum-sensing inhibitor as the biofouling prevention and successfully reduced up to 46–91% of biofouling growth [80].

### 5.2 Quaternary ammonium compounds (QACs)

Another finding reported to reduce biofouling is through polyvinylidene fluoride (PVDF) membrane on the activated carbon air cathode [82]. Ping et al. grafted QACs on PVDF membrane. The method was through electron transfer atom-transfer radical-polymerization (ARGET ATRP), with the M0 representing unmodified membrane and MQ representing a QAC-grafted modified membrane (Figure 4). During the experiment, the water flux declined due to bacterial adhesion and biofilm growth on the membrane surface. Membrane modification showed improvement to water flux up to 50%. They discovered that the QAC-modified membrane had antimicrobial potential with the inhibition rate ~98.3% of *Escherichia coli* and ~98.5% of *Staphylococcus aureus*, respectively; the total of dead cells was present more than alive cells on the membrane surface [83]. Their study was later testified by Zhen et al. when the PVDF membrane loaded with QACs and silica nanopollen. The results are almost similar to Ping et al. though silica nanopollen was added to the mixture: *E. coli* ~98.2% and *S. aureus* ~99.9% [84].

The presence of antimicrobial agents often interfered with the potential biofouling on the membrane surface. For instance, Zhang et al. applied a carbon carrier to assemble the QAC carbon blended and mixed with PVDF membrane. They found that the modified membrane’s surface was improved in biofouling mitigation due to hydrophilic carbon material. The results show that the carbon carrier could upgrade QAC stability and anti-biofouling effectiveness for engineering operation [86]. However, there was no information on the inhibition rate toward bacteria. Although PVDF is common in the membrane industry, PVDF itself is toxic to bacteria [87].

### 5.3 Chitosan–graphene oxide

In the marine field study, biofouling has become a global problem affecting cost and maintenance impacts for the
restoration process. It affects the environment of marine life because of cross-contamination from the invasive species collected across the world from the river to pond [88]. A chitosan–graphene oxide (GCZ8A) foam was used for uranium recovery in seawater with anti-biofouling ability. GO can increase the hydrophilicity of the thin-film composite membrane and transmit antimicrobial activity to the membrane without amending the transporting features [89]. Results showed that GCZ8A displayed more than 70% cell death rate in the seawater, which simultaneously prevented cell adhesion on the surface [90]. Thus, this method is most suitable to use on membranes that work in seawater.

5.4 Metal oxide

Next, in medical field research, the isoporous silica-micelle membrane was applied on indium tin oxide (ITO) glass using the modified Stöber method as an electrode. The produced electrode provides an antibiofouling layer for electrochemical detection of drug molecules in human blood without the blood going for pretreatment [91].

Biofouling is harmful to the system and the building facade; this phenomenon has been studied with different intrinsic characteristics such as porosity and the roughness of the surface. Some researchers are working on an antibiofouling structure for placement on any surfaces exposed to flooded environments. The structures must be mixed or added to the antibiofouling agents, thus protecting biofouling from plant and animal species accumulation. In this case, the antibiofouling element utilized was titanium dioxide (TiO2) [92]. TiO2 as antibiofouling is due to the benefits of providing opacity and durability, which aid in ensuring the longevity of the paint or coating and protects the membrane surface [93].

In the natural environment, algae can produce an antifouling (AF) mechanism to protect them from biofouling by producing reactive oxygen species such as hydroxyl radicals and peroxides. The ability of the organism to safeguard themselves in an eco-friendly way inspired researchers to fabricate zinc oxide (ZnO), a photocatalytic nanocoating substance, for surface fishing net. After a month, the result showed a reduction in the abundance of microfouling organisms within 22.69% [94] (Figure 5).

5.5 Silver ions

Dolina et al. reported that soaking a hollow fiber polyethersulfone membrane into silver ion solution and the modified membrane demonstrated a lower propensity against biofouling. Their results showed that when filtering the real wastewater for 8 h, modified membrane gives 15% higher permeability than unmodified membrane [95]. In a continuous cross-flow membrane module study, silver nanoparticles (AgNP) impregnated on sulfonated polyethersulfone showed suitability for antibiofouling membrane in a continuous operational mode [96]. Their results showed complete E. coli cell killing in E. coli flowing contaminated water.

Although manual cleaning can restore the system's performance to 100% [29], the method is very time and energy-consuming and costly. Therefore, chemicals and nanomaterials are applied to make membranes resistant to biofouling formation. However, physical and chemical
cleaning is not enough to eliminate biofouling from the membrane surface since it is a living organism with uncontrollable growth [97]. Biofouling mitigation strategies are needed as an alternative to the conventional cleaning approach. For instance, there are several ways to prepare a hydrophilic membrane, including membrane surface modifications and nanocomposite membranes such as AgNP. Likewise, various ways to eliminate organic matter that causes biofouling, using chemicals or physical cleaning. Also, choosing suitable nanomaterial properties based on material type, surface area, membrane size, hydrophilic and hydrophobicity is crucial to achieving a high-performance membrane with good antibiofouling resistance.

Many experiments are being conducted widely using silver. The main reason for the preference is the characteristic of the AgNP as antibacterial, antifungal, antioxidants, and improved physicochemical properties such as optical and thermal, electrical, and catalytic properties [98]. For instance, silver showed a successful antimicrobial agent against uropathogenic E. coli biofilms [99] and gram-positive and gram-negative bacteria [100]. In marine studies, PVDF is often used as the membrane because of its superior thermal stability, chemical resistance, and outstanding mechanical strength [101].

5.5.1 Forward osmosis (FO)

FO has the potential to treat and prevent fouling [102]. This performance can further be improved by introducing graphene oxide-silver nanocomposites on the membrane surface. The result showed that the modified membrane gave an 80% restriction rate toward Pseudomonas aeruginosa cells.

6 Recent advancements in biofouled membrane mitigation in the BFC system

Similarly, like other industries, the formation of biofouling causes many problems to BFC. Some researchers have adopted the AgNP method, as there is evidence that this element can prevent biofouling formation on the membrane surface. For instance, a report on AgNP accumulated on polydopamine (pDA) coated on PEM of MEC showed a possible method to overcome this biofouling effect [103]. They found an increase in power density from 0.9 to 1.0 W/m². Power density gaining might be due to the decreasing internal resistance, from 54 to 52 Ω in 2 months after biofouling removal.

Additionally, a study was conducted on AgNP in MFC system with different loadings such as 5 and 10%. The result showed that 7 days after start-up, the polyamide membrane without using AgNP recorded a charge of transfer resistance increased by 32%. The AgNP modified membrane with either 5 and 10% AgNP load showed that the charge of transfer resistance increased by only 5% [104]. Reducing as much resistance in a BFC system if necessary to boost the BFC performance [105]. While, a report on MEC revealed the failure of using AgNP on PEM as sterilizing agents as the silver leached into the electrolyte and interfered with proton transfer (Figure 6). Later, they coated the PEM with AgNP and PDA, and this action gave better power results: 68.12% higher than PEM modified with only AgNP, which was 5.69% [49]. They mentioned that the PDA was able to hold the AgNP securely on the surface of the PEM. Their finding shows that the silver ions are poisonous toward

Figure 5: ZnO effect on biofilm adhered onto the fishing net [102].
the microorganism. These silver ions disrupt the growth of microbes in several ways, such as creating pores in the microbes’ cytoplasm membrane, allowing the outflow of ions and other materials, eventually causing imbalance toward the electrical potential in the microbes [106]. Without silver ions, the membrane surface will start to foul after a long continuous operation, thus reducing the system’s performance [107]. Although the silver ions have low toxicity toward mammalian cells [108] compared to the microbes, the leaching of these ions into the anolyte will harm the electroactive bacteria on the anode, which leads to the drop in BFC power generation.

Other established BFC procedures to mitigate biofouling include alkaline lysis in biofilm removal and the chemical compounds formed on the membrane surface. As a result, the performance in terms of electric current was increased compared to before using the alkaline lysis procedure [109]. Replacing the outer layer of the BFC cathode is another additional step that resulted in the further increase of current from 378.6 ± 108.3 to 503.8 ± 95.6 µA [110]. Bakonyi et al. reported that choosing a suitable membrane type can avoid biofouling. Their study utilized ceramic mixture barium–cerium–gadolinium oxides (BCGO) powders doped with lithium (Li) membrane and compared to Nafion 117 membrane. The obtained results showed that BCGO doped with Li gives better permeability than Nafion 117. The biofouling formation on BCGO doped with Li surface also reduced more than 10% compared to Nafion 117 due to the unique surface of the BCGO powders [111].

7 Conclusion

Manual cleaning can restore performance to 100%; however, it is time consuming and costly. Studies using chemical solutions such as silver and QAC showed almost 100% of biofouling elimination. However, the studies were done on specific microorganism cultures, such as E. coli. Since BFC inoculum is also involved in mixed culture microorganisms, continuous studies are ongoing in mitigation membrane biofouling, not just targeting single culture. This article discussed biofouling in several systems while highlighting the main challenges and
possible ways to overcome them. Exploring other systems other than BFC is necessary as these systems experienced many critical challenges with biofouling while considering the effect on the environment. Various adjustment on the available measures suits the BFC requirement, including increasing power production while suppressing biofouling. For further improvements, research needs to focus more on mitigation strategies such as delaying the biofilm formation, reducing the effect of biofouling on systems performance, and removing biofouling using advanced controlling strategies.

**Acknowledgements:** The authors appreciate the financial support offered by the Ministry of Education Malaysia through a research grant of FRGS/1/2018/TK10/UKM/03/2.

**Funding information:** FRGS/1/2018/TK10/UKM/03/2.

**Author contribution:** N.I.S.M.N.: writing – original draft; M.H.A.B.: writing – proofread, review and editing, conceptualization, funding acquisition, supervision, validation.

**Conflict of interest:** The authors state no conflict of interest.

**Ethical approval:** The conducted research is not related to either human or animal use.

**References**

[1] Gonzuelo F, Marković N, Ruff A, Schuhmann W. The open circuit voltage in biofuel cells: nernstian shift in pseudocapacitive electrodes. Angew Chem - Int Ed. 2018;57(41):13681–5.

[2] Hernández-Fernández FJ, Pérez De Los Ríos A, Salar-García MJ, Ortiz-Martínez VM, Lozano-Blanco LJ, Godínez C, et al. Recent progress and perspectives in microbial fuel cells for bioenergy generation and wastewater treatment. Fuel Process Technol. 2015;138:284–97. doi: 10.1016/j.fuproc.2015.05.022.

[3] Cosnier S, Gross AJ, Giroud F, Holzinger M. Beyond the hype surrounding biofuel cells: What’s the future of enzymatic fuel cells? Curr Opin Electrochem. 2018;12:148–55. doi: 10.1016/j.coelec.2018.06.006.

[4] Cosnier S, Gross AJ, Le Goff A, Holzinger M. Recent advances on enzymatic glucose/oxygen and hydrogen/oxygen biofuel cells: achievements and limitations. J Power Sources. 2016;325(November):252–63.

[5] Yin S, Liu X, Kobayashi Y, Nishina Y, Nakagawa R, Yanai R, et al. A needle-type biofuel cell using enzyme/mediator/carbon nanotube composite fibers for wearable electronics. Biosens Bioelectron. 2020;165:112287. doi: 10.1016/j.bios.2020.112287.

[6] Inamuddin Shakeel N, Imran Ahamed M, Kanchi S, Abbas Kashmery H. Green synthesis of ZnO nanoparticles decorated on polyindole functionalized-MCNTs and used as anode material for enzymatic biofuel cell applications. Sci Rep. 2020;10(1):1–10.

[7] Kang Z, Jiao K, Cheng J, Peng R, Jiao S, Hu Z. A novel three-dimensional carbonized PANi600@CNFs network for enhanced enzymatic biofuel cell. Biosens Bioelectron. 2018;101(September 2017):60–5. doi: 10.1016/j.bios.2017.10.008.

[8] Gao M, Wang P, Jiang L, Wang B, Yao Y, Liu S, et al. Power generation for wearable systems. Energy Environ Sci. 2021;14(4):2114–57.

[9] Abdellouai H, Ghedamsi K, Mecharek A. Performance and lifetime increase of the PEM fuel cell in hybrid electric vehicle application by using an NPC seven-level inverter. J Eur Des Syst Autom. 2019;52(3):325–32.

[10] Yun S, Zhang Y, Xu Q, Liu J, Qin Y. Recent advance in new-generation integrated devices for energy harvesting and storage. Nano Energy. 2019;60:600–19.

[11] Ancona V, Caracciolo AB, Borello D, Ferrara V, Genni P, Pietrelli A. Microbial fuel cell: an energy harvesting technique for environmental remediation. Int J Environ Impacts Manag Mitig Recover. 2020;3(2):168–79.

[12] Cadet M, Gounel S, Stines-Chaumel C, Brilland X, Rouhana J, Louerat F, et al. An enzymatic glucose/O2 biofuel cell operating in human blood. Biosens Bioelectron. 2016;83:60–7. doi: 10.1016/j.bios.2016.04.016.

[13] Sun J, Li N, Yang P, Zhang Y, Yuan Y, Lu X, et al. Simultaneous antibiotic degradation, nitrogen removal and power generation in a microalgae-bacteria powered biofuel cell designed for aquaculture wastewater treatment and energy recovery. Int J Hydrogen Energy. 2020;45(18):10871–81. doi: 10.1016/j.ijhydene.2020.02.029.

[14] Hosseini SE, Butler B. An overview of development and challenges in hydrogen powered vehicles. Int J Green Energy. 2020;17(1):13–37. doi: 10.1080/15435075.2019.1685999.

[15] Obileke KC, Onyeaka H, Meyer EL, Nwokolo N. Microbial fuel cells, a renewable energy technology for bio-electricity generation: A mini-review. Electrochem commun. 2021;125:107003. doi: 10.1016/j.elecom.2021.107003.

[16] He Y, Zhu Y, Chen J, Huang M, Wang P, Wang G, et al. Assessment of energy consumption of municipal wastewater treatment plants in China. J Clean Prod. 2019;228:399–404. doi: 10.1016/j.jclepro.2019.04.320.

[17] Suzuki R, Shitanda I, Aikawa T, Tojo T, Kondo T, Tsujimura S, et al. Wearable glucose/oxygen biofuel cell fabricated using modified aminoferrocene and flavin adenine dinucleotide-dependent glucose dehydrogenase on polyglycidyl methacrylate-grafted MgO-templated carbon. J Power Sources. 2020;479(September 2019):1–10. doi: 10.1016/j.jpowsour.2020.228807.

[18] Al Lawati MJ, Jafary T, Baawain MS, Al-Mamun A. A mini review on biofouling on air cathode of single chamber microbial fuel cell; prevention and mitigation strategies. Biocatal Agric Biotechnol. 2019;22:101370. doi: 10.1016/j.bcab.2019.101370.
[19] Noori MT, Tiwari BR, Mukherjee CK, Ghangrekar MM. Enhancing the performance of microbial fuel cell using Ag–Pt bimetallic alloy as cathode catalyst and anti-biofouling agent. Int J Hydrogen Energy. 2018;43(42):19650–60. doi: 10.1016/j.ijhydene.2018.08.120.

[20] Rahman S, Jafary T, Al-Mamun A, Bawaain MS, Choudhury MR, Alhaimali H, et al. Towards upsocaling microbial desalination cell technology: A comprehensive review on current challenges and future prospects. J Clean Prod. 2021;288(March):125597. doi: 10.1016/j.jclepro.2020.125597.

[21] Ding A, Fan Q, Cheng R, Sun G, Zhang M, Wu D. Impacts of applied voltage on microbial electrolysis cell-anaerobic membrane bioreactor (MEC-AnMBR) and its membrane fouling mitigation mechanism. Chem Eng J. 2018;333(September 2017):630–5. doi: 10.1016/j.cej.2017.09.190.

[22] Dessi P, Rovira-Alsina L, Sánchez C, Dinesh GK, Tong W, Chatterjee P, et al. Microbial electroosmosis: Towards sustainable biorefineries for production of green chemicals from CO2 emissions. Biotechnol Adv. 2021;46(July):107675.

[23] Maddah H, Chogle A. Biofouling in reverse osmosis: phenomena, monitoring, controlling and remediation. Appl Water Sci. 2017;7(6):2637–51.

[24] Yebra DM, Kili S, Dam-Johansen K. Antifouling technology - past, present and future steps towards efficient and environmentally friendly antifouling coatings. Prog Coatings. 2004;50(2):75–104.

[25] Lu H, Xue Z, Saikaly P, Nunes SP, Bluver TR, Liu WT. Membrane biofouling in a wastewater nitrification reactor: Microbial succession from autotrophic colonization to heterotrophic domination. Water Res. 2016;88:337–45.

[26] Li H, Xing Y, Cao T, Dong J, Liang S. Evaluation of the fouling potential of sludge in a membrane bioreactor integrated with microbial fuel cell. Chemosphere. 2021;262:128405. doi: 10.1016/j.chemosphere.2020.128405.

[27] Achinas S, Charalamposiannis N, Euverink GJW. A brief recap of microbial adhesion and biofilms. Appl Sci. 2019;9(14):1–15.

[28] Mikhaylin S, Bazinet L. Fouling on ion-exchange membranes: Classification, characterization and strategies of prevention and control. Adv Colloid Interface Sci. 2016;229(December):34–56. doi: 10.1016/j.cis.2015.12.006.

[29] Sulonen MLK, Lakaniemi AM, Kokko ME, Puhakka JA. Long-term stability of bioelectricity generation coupled with tetra-rationate disproportionation. Bioresour Technol. 2016;216:876–82. doi: 10.1016/j.biortech.2016.06.024.

[30] Amaral G, Bushee J, Cordani UG, Kawashita K, Reynolds JH, Almeida FFEMDE, et al. Biofouling of membranes in microbial electrochemical technologies: Causes, characterization methods and mitigation strategies. J Petrol. 2019;369(1):1689–99. Available from: http://dx.doi.org/10.1016/j.jsames.2011.03.003%0Ahttps://doi.org/10.1016/j.gr.2017.08.001%0Ahttps://doi.org/10.1016/j.precamres.2014.12.018%0Ahttps://doi.org/10.1016/j.precamres.2011.08.005%0Ahttps://doi.org/10.1080/00206814.2014.90275%0Ahttps://dx.

[31] Monroe D. Looking for chinks in the armor of bacterial biofilms. PLoS Biol. 2007;5(11):e307. doi: 10.1371/journal.pbio.0050307. https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.0050307.

[32] Rao TS. Chapter 6 – Biofouling in industrial water systems. In: Amjad Z, Demadis KD, editors. Mineral scales and deposits. Amsterdam: Elsevier B.V; 2015. p. 123–40. https://www.sciencedirect.com/science/article/pii/B9780444632899000617v1?via%3Dihub.

[33] Ashfaq MY, Al-Ghouti MA, Qjlawweh H, Zouari N. Evaluating the effect of antiscalants on membrane biofouling using FTIR and multivariate analysis. Biofouling. 2019;35(1):1–14.

[34] Atkinson AJ. Development and performance evaluation of an innovative antibiofouling reverse osmosis membrane for water purification applications. Gillings School of Global Public Health: University of North Carolina at Chapel Hill; 2017. https://cdr.lib.unc.edu/downloads/j9602082m.

[35] Mazerie I, Didier P, Razan F, Hapiot P, Coulon N, Girard A, et al. A general approach based on sampled-current voltammetry for minimizing electrode fouling in electroanalytical detection. ChemElectroChem. 2018;5(1):144–52.

[36] Pandit S, Shanbhag S, Mauter M, Oren Y, Herzberg M. Influence of Electric Fields on Biofouling of Carbonaceous Electrodes. Environ Sci Technol. 2017;51(17):10022–30.

[37] Bogler A, Lin S, Bar-Zeev E. Biofouling of membrane distillation, forward osmosis and pressure retarded osmosis: Principles, impacts and future directions. J Membr Sci. 2017;542(July):378–98. doi: 10.1016/j.memsci.2017.08.001.

[38] Zoubouis AI, Gkotsis PK. Chapter 7 – Fouling challenges in ceramic MBR systems. In: Basile A, Ghasemezadeh K, Jailinejad E, editors. Current trends and future developments on (bio-) membranes. Elsevier; 2020. p. 199–217. https://www.sciencedirect.com/science/article/pii/B9780128168226000070%v3%3Dihub.

[39] Wang SY, Sun XF, Gao WJ, Wang YF, Jiang BB, Afzal MZ, et al. Mitigation of membrane biofouling by D-amylo acids: Effect of bacterial cell-wall property and D-amylo acid type. Colloids Surfaces B Biointerfaces. 2018;164:20–6. doi: 10.1016/j.colsurfb.2017.12.055.

[40] Ma W, Panecka M, Tufenjki N, Rahaman MS. Bacteriophage-based strategies for biofouling control in ultrafiltration: In situ biofouling mitigation, biocidal additives and biofilm cleanser. J Colloid Interface Sci. 2018;523:254–65. doi: 10.1016/j.jcis.2018.03.105.

[41] Mahmoudi N. Design of peptoid-based coating to reduce biofouling in gas exchange devices. Theses Diss; 2018. https://scholarworks.ualr.edu/etd/2904.

[42] Filman SGA, Hassan SHA, Rahaman MM, Oh SE. The effect of Nafion membrane fouling on the power generation of a microbial fuel cell. Int J Hydrogen Energy. 2018;March:2–11. doi: 10.1016/j.ijhydene.2018.02.097.

[43] Li X, Lv P, Yao Y, Feng Q, Mensah A, Li D, et al. A novel single-enzyme biofuel cell based on highly flexible conductive bacterial cellulose electrode utilizing pollutants as fuel. Chem Eng J. 2020;379:122316. doi: 10.1016/j.cej.2019.122316.

[44] Santoro C, Babanova S, Artyushkova K, Cornejo JA, Isla L, Bretschger O, et al. Influence of anode surface chemistry on microbial fuel cell operation. Bioelectrochemistry. 2015;106:141–9. doi: 10.1016/j.bioelechem.2015.05.002.

[45] Alhariri M, Majrashi MA, Bahkali AH, Almajed FS, Aghzani AO, Khiyami MA, et al. Efficacy of neutral and negatively charged liposome-loaded gentamicin on planktonic bacteria and biofilm communities. Int J Nanomedicine. 2017;12:6949–61.
[46] Drygaś, B., Burka, P., Rashid, K., Drygaś, P. Optimal growth rate conditions of microorganisms. World Sci News. 2016;57:397–403.

[47] Ma, G., Xu, X., Tesfai, M., Wang, H., Xu, P. Developing anti-biofouling and energy-efficient cation-exchange membranes using conductive polymers and nanomaterials. J Membr. Sci. 2020;603(March):118034. doi: 10.1016/j.memsci.2020.118034.

[48] Rijnarts, T., Moreno, J., Saakes, M., de Vos WM, Nijmeijer K. Role of anion exchange membrane fouling in reverse electrodialysis using natural feed waters. Colloids Surfaces A Physicochem Eng Asp. 2019;560(October 2018):198–204. doi: 10.1016/j.colsurfa.2018.10.020.

[49] Park, S.G., Rajesh, P.P., Hwang, M.H., Chu, K.H., Cho, S., Chae, K.J. Long-term effects of anti-biofouling proton exchange membrane using silver nanoparticles and polydopamine on the performance of microbial electrolysis cells. Int J Hydrogen Energy. 2020;46:11345–56. doi: 10.1016/j.ijhydene.2020.04.059.

[50] Lee, H., Ahmad, R., Kim, J. Alginate to simulate biofouling in submerged fluidized ceramic membrane reactor: effect of solution pH and ionic strength. Bioresour Technol. 2020;302:122813. doi: 10.1016/j.biortech.2020.122813.

[51] Li, X., Abu-Reesh, I.M., He, Z. Development of Bioelectrochemical Systems to Promote Sustainable Agriculture. Agriculture 2015;5(3):367–88.

[52] Kokabian, B., Gude, V.G. Chapter 6 – 2-Microbial desalination systems for energy and resource recovery. Microbial electrochemical technology. Elsevier B.V.; 2019. p. 999–1020. doi: 10.1016/B978-0-444-64052-9.00041-8. https://www.sciencedirect.com/science/article/pii/B9780444640529000418?via%3Dihub.

[53] Orellana, MV, Leck, C. Chapter 9 – Marine microgels. In: Hansell DA, Carlson CA, editors. Biogeochemistry of marine dissolved organic matter. (2nd ed.); Boston: Academic Press; 2015. p. 451–80. https://www.sciencedirect.com/science/article/pii/B9780124059405000091?via%3Dihub.

[54] Al-Mamun, A., Baawain, M.S., Dhar, B.R., Kim, I.S. Improved recovery of bioenergy and osmotic water in an osmotic microbial fuel cell using micro-diffuser assisted marine aerobic biofilm on cathode. Biochem Eng J. 2017;128:235–42. doi: 10.1016/j.bej.2017.09.020.

[55] Alimamili H, Jafary T, Al-Mamun A, Baawain MS, Vakili-Nezhad GR. New insights into the application of microbial desalination cells for desalination and bioelectricity generation. Biofuel Res J. 2019;6(4):1090–9.

[56] Fang, J., Wu, Y., Zhang, Y., Lyu, M., Zhao, J. Novel anion exchange membranes based on pyridinium groups and fluoroacrylate for alkaline anion exchange membrane fuel cells. Int J Hydrogen Energy. 2015;40(36):12392–9. doi: 10.1016/j.ijhydene.2015.07.074.

[57] Wang, C., Mo, B., He, Z., Shao, Q., Pan, D., Wujick, E. et al. Crosslinked norbornene copolymer anion exchange membrane for fuel cells. J Membr. Sci. 2018;556(March):118–25. doi: 10.1016/j.memsci.2018.03.080.

[58] Niu, M., Zhang, C., He, G., Zhang, F., Wu, X. Pendent piperidinium-functionalized blend anion exchange membrane for fuel cell application. Int J Hydrogen Energy. 2019;44(29):15482–93. doi: 10.1016/j.ijhydene.2019.04.172.

[59] Elangovan, M., Dharmalingam, S. Effect of polydopamine on quaternized poly(ether ether ketone) for antibiofouling anion exchange membrane in microbial fuel cell. Polym Adv Technol. 2018;29(1):275–84.

[60] Ping Q, Cohen B, Dosoretz C, He Z. Long-term investigation of fouling of cation and anion exchange membranes in microbial desalination cells. Desalination. 2013;325:48–55. doi: 10.1016/j.desal.2013.06.025.

[61] Orellana, MV, Leck, C., Bailly du Bois P, Laguionie P, Boust D, Korsakissok I, Didier D, Fievèt B. Estimation of marine source-term following Fukushima Dai-ichi accident. J Environ Radioact. 2012;114:2–9. https://pubmed.ncbi.nlm.nih.gov/22172688/.

[62] Zhang, M., Cheng, C., Xie, R. Control and cleaning of membrane biofouling by biogenic silver nanoparticles. IOP Conf Ser Earth Environ Sci. 2019;356(1):2–11.

[63] Ghasemi, M., Wan Daud WR, Ismail M, Rahimnejad M, Ismail AF, Leong JX, et al. Effect of pre-treatment and bio-fouling of proton exchange membrane on microbial fuel cell performance. Int J Hydrogen Energy. 2013;38(13):5480–4. doi: 10.1016/j.ijhydene.2012.09.148.

[64] Kardi SN, Ibrahim N, Rashid NAA, Darzi GN. Investigating effect of proton-exchange membrane on new air-cathode single-chamber microbial fuel cell configuration for bio-energy recovery from Azorubine dye degradation. Environ Sci Pollut Res. 2019;26(21):21201–15.

[65] Naik S, Jujivavarappu SE. Simultaneous bioelectricity generation from cost-effective MFC and water treatment using various wastewater samples. Environ Sci Pollut Res. 2019;27(October):27383–93.

[66] Oliot, M., Etcheverry L., Mosdale A., Basseguy R., Délia ML., Bergel A. Separator electrode assembly (SEA) with 3-dimensional bioanode and removable air-cathode boosts microbial fuel cell performance. J Power Sources. 2017;356:389–99.

[67] Xu Q, Wang L, Li C, Wang X, Li C, Geng Y. Study on improvement of the proton conductivity and anti-fouling of proton exchange membrane by doping SGO@SiO2 in microbial fuel cell applications. Int J Hydrogen Energy. 2019;44(29):15322–32. doi: 10.1016/j.ijhydene.2019.03.238.

[68] Alresheedi MT, Barbeau B, Basu OD. Comparisons of NOM fouling and cleaning of ceramic and polymeric membranes during water treatment. Sep Purif Technol. 2018;209:452–60. doi: 10.1016/j.seppur.2018.07.070.

[69] Winfield J, Gadja I, Greenman J, Ieropoulos I. A review into the use of ceramics in microbial fuel cells. Bioresour Technol. 2016;215:296–303. doi: 10.1016/j.biortech.2016.03.135.

[70] Hubadilllah SK, Othman MHD, Matsuura T, Ismail AF, Rahman MA, Harun Z, et al. Fabrications and applications of low cost ceramic membrane from kaolin: a comprehensive review. Ceram Int. 2018;44(5):4538–60.

[71] Almojjly A, Johnson D, Hilal N. Investigations of the effect of pure size of ceramic membranes on the pilot- scale removal of oil from oil-water emulsion. J Water Process Eng. 2019;31(May):100868. doi: 10.1016/j.wjpe.2019.100868.

[72] Lech M, Trusek A. Biofouling phenomena on the ceramic microfiltration membranes – an experimental research. Desalint Water Treat. 2018;128(June):236–42.

[73] Gadja I, Obata O, Jose Salar-Garcia M, Greenman J, Ieropoulos IA. Long-term bio-power of ceramic microbial fuel cells in individual and stacked configurations. Bioelectrochemistry. 2020;133:133107459. doi: 10.1016/j.bioelechem.2020.107459.
[74] Miskan M, Ismail M, Ghasemi M, Md Jahim J, Nordin D, Abu Bakar MH. Characterization of membrane biofouling and its effect on the performance of microbial fuel cell. Int J Hydrogen Energy. 2016;41(1):543–52. doi: 10.1016/j.ijhydene.2015.09.037.

[75] Jiang S, Li Y, Ladewig BP. A review of reverse osmosis membrane fouling and control strategies. Sci Total Environ. 2017;595(August):567–83. doi: 10.1016/j.scitotenv.2017.03.235.

[76] Code L. Practical application of bacterial quorum quenching and development of quorum quenching medium for biofouling control in membrane bioreactor for wastewater treatment. School of Chemical Biological Engineering, Graduate School, Seoul National University; 2018. https://s-space.snu.ac.kr/bitstream/10371/119808/1/000000136730.pdf.

[77] Flemming HC. Biofouling in water treatment. Biofouling Biocorrosion Ind Water Syst. 1991;47–80. https://link.springer.com chapter/10.1007%2F978-3-642-76543-8_4##citeas.

[78] Laqbaqbi M, Sanmartino JA, Khayet M, García-Alcázar E, Trovón-Pereno J, Chauouch M. Fouling in membrane distillation, osmotic distillation and osmotic membrane distillation. Appl Sci. 2017;7(4):334.

[79] Park J, Gill GA, Strivens JE, Kuo LJ, Jeters RT, Avila A, et al. Effect of biofouling on the performance of amidoamine-based polymeric uranium adsorbents. Ind Eng Chem Res. 2016;55(15):4328–38.

[80] Kim HS, Lee JY, Ham SY, Lee JH, Park JH, Park HD. Effect of biofilm inhibitor on biofouling resistance in RO processes. Fuel. 2019;253(May):823–32. doi: 10.1016/j.fuel.2019.05.062.

[81] Aslam M, Ahmad R, Kim J. Recent developments in biofouling control, particularly with crack in membrane bioreactors for domestic wastewater treatment. Sep Purif Technol. 2018;206:297–315. doi: 10.1016/j.seppur.2018.06.004.

[82] Yang W, Rossi R, Tian Y, Kim KY, Logan BE. Mitigating external and internal cathode fouling using a polymer bonded separator in microbial fuel cells. Bioresour Technol. 2018;249(October 2017):1080–4. doi: 10.1016/j.biortech.2017.10.109.

[83] Ping M, Zhang X, Liu M, Wu Z, Wang Z. Surface modification of polyvinylidene fluoride membrane by atom-transfer radical-polymerization of quaternary ammonium compound for mitigating biofouling. J Memb Sci. 2019;570–571(2018):286–93. doi: 10.1016/j.memsci.2018.10.070.

[84] Zhai Y, Zhang X, Wu Z, Wang Z. Modification of polyvinylidene fluoride membrane by quaternary ammonium compounds loaded on silica nanoparticles for mitigating biofouling. J Memb Sci. 2019;November:117679. doi: 10.1016/j.memsci.2019.117679.

[85] Ren L, Ping M, Zhang X. Membrane biofouling control by surface modification of quaternary ammonium compound using atom-transfer radical-polymerization method with silica nanoparticles as interlayer. Membranes (Basel). 2020;10(12):1–16.

[86] Zhang X, Wang Z, Chen M, Ma J, Chen S, Wu Z. Membrane biofouling control using polyvinylidene fluoride membrane blended with quaternary ammonium compound assembled on carbon material. J Memb Sci. 2017;539(May):229–37. doi: 10.1016/j.memsci.2017.06.008.

[87] Ayaru S, Pandiyam R, Ahn Y. Fabrication and characterization of anti-fouling and non-toxic polyvinylidene fluoride -Sulphonated carbon nanotube ultrafiltration membranes for membrane bioreactor applications. Chem Eng Res Des. 2018;142:176–88. doi: 10.1016/j.cherd.2018.12.008.

[88] McClay T, Zabin C, Davidson I, Young R, Elam D. Vessel biofouling prevention and management options report. 2015;42:1–42. https://apps.dtic.mil/sti/pdfs/ADA626612.pdf.

[89] Perreault F, Jaramillo H, Xie M, Ude M, Nghiem LD, Elimelech M. Biofouling mitigation in forward osmosis using graphene oxide functionalized thin-film composite membranes. Environ Sci Technol. 2016;50(11):5840–8.

[90] Guo X, Yang H, Liu Q, Liu J, Chen R, Zhang H, et al. A chitosan-graphene oxide/ZIF foam with anti-biofouling ability for uranium recovery from seawater. Chem Eng J. 2020;382(September 2019):122850. doi: 10.1016/j.cej.2019.122850.

[91] Sun Q, Yan F, Yao L, Su B. Anti-biofouling isoporous silicamicelle membrane enabling drug detection in human whole blood. Anal Chem. 2016;88(17):8364–8.

[92] Graziani L, Quagliarini E, D’Orazio M. TiO2–treated different fired brick surfaces for biofouling prevention: experimental and modelling results. Ceram Int. 2016;42(3):4002–10.

[93] Bora NS, Mazumder B, Chattopadhayay P. Prospects of topical protection from ultraviolet radiation exposure: a critical review on the juxtaposition of the benefits and risks involved with the use of chemoprotective agents. J Dermatol Treat. 2018;29(3):256–68. doi: 10.1080/09546634.2017.1364691.

[94] Sathe P, Laxman K, Myint MTZ, Dobretsov S, Richter J, Dutta J. Biobased nanocoatings for biofouling prevention by photocatalytic redox reactions. Sci Rep. 2017;7(1):1–12.

[95] Dolina J, Gončuková Z, Bobák M, Dvořák L. Modification of a hollow-fibre polyethersulfone membrane using silver nanoparticles formed: In situ for biofouling prevention. RSC Adv. 2018;8(26):14552–60.

[96] Biswas P, Bandyopadhyay R. Biofouling prevention using silver nanoparticle impregnated polyethersulfone (PES) membrane: E. coli cell-killing in a continuous cross-flow membrane module. J Colloid Interface Sci. 2017;491:33–26. doi: 10.1016/j.jcis.2016.11.060.

[97] Ham SY, Kim HS, Jang Y, Ryoo HS, Lee JH, Park JH, et al. Synergistic control of membrane biofouling using linoleic acid and sodium hypochlorite. Chemosphere. 2021;268:128802. doi: 10.1016/j.chemosphere.2020.128802.

[98] Ivanova N, Gogleva V, Dobreva M, Pehlivanov I, Stefanov S, Andonova V. Silver nanoparticles as multi-functional drug delivery systems. Nanomedicines. 2019:71–92.

[99] Rodríguez-Serrano C, Guzmán-Moreno J, Ángeles-Chávez C, Rodríguez-González V, Ortega-Sigala JJ, Ramirez-Santoyo RM, et al. Biosynthesis of silver nanoparticles by Fusarium scirpi and its potential as antimicrobial agent against uropathogenic Escherichia coli biofilms. PLoS One. 2020;15(3):1–20.

[100] Gomaa EZ. Silver nanoparticles as an antimicrobial agent: a case study on Staphylococcus aureus and Escherichia coli as models for gram-positive and gram-negative bacteria. J Gen Appl Microbiol. 2017;63(1):36–43.
Pasternak G, Greenman J, Ieropoulos I. Regeneration of the power performance of cathodes affected by biofouling. Appl Energy. 2016;173:431–7. doi: 10.1016/j.apenergy.2016.04.009.

Bakonyi P, Košk L, Kumar G, Tóth G, Rózensberszki T, Nguyen DD, et al. Architectural engineering of bioelectrochemical systems from the perspective of polymeric membrane separators: a comprehensive update on recent progress and future prospects. J Memb Sci. 2018;564:508–22. doi: 10.1016/j.memsci.2018.07.051.

Li M, Zhou M, Tian X, Tan C, McDaniel CT, Hassett DJ, et al. Microbial fuel cell (MFC) power performance improvement through enhanced microbial electrogenericity. Biotechnol Adv. 2018;36:1316–27. doi: 10.1016/j.biotechnad.2018.04.010.

Guang L, Koomson DA, Jingyu H, Ewusi-Mensah D, Miwornunyaie N. Performance of exoelectrogenic bacteria used in microbial desalination cell technology. Int J Environ Res Public Health. 2020;17(3):10–2.

Katuri KP, Ali M, Saikaly PE. The role of microbial electrolysis cell in urban wastewater treatment: integration options, challenges, and prospects. Curr Opin Biotechnol. 2019;57(June):101–10. doi: 10.1016/j.copbio.2019.03.007.

Tan Y, Adhikari RY, Malvankar NS, Pi S, Ward JE, Woodard TL, et al. Synthetic Biological Protein Nanowires with High Conductivity. Small. 2016;12(33):4481–5.

Mohanakrishna G, Vanbroekhoven K, Pant D. Imperative role of applied potential and inorganic carbon source on acetate production through microbial electrosynthesis. J CO2 Util. 2016;15:57–64. doi: 10.1016/j.jcou.2016.03.003.

Liu L, Mohammadifar M, Choi S. Supercapacitive micro-biophotovoltaics. J Phys Conf Ser. 2019;1407(1):012027.

Saratale GD, Saratale RG, Shahid MK, Zhen G, Kumar G, Shin HS, et al. A comprehensive overview on electro-active biofilms, role of exo-electrogens and their microbial niches in microbial fuel cells (MFCs). Chemosphere. 2017;178(July):534–47. doi: 10.1016/j.chemosphere.2017.03.066.

Song Y. C-MEMS based micro enzymatic biofuel cells. Florida International University; 2015. https://digitalcommons.fiu.edu/cgi/viewcontent.cgi?article=3265&context=etd.