Review Article

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Mitigating membrane biofouling in biofuel cell system – A review

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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

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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

Table 1: Common reported BFC systems and their general functions till 2019

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 solar 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]

Figure 1: (a) Development and dispersion of biofilm life cycle stages before becoming biofouling and (b) electron micrographs of biofilm life cycle stages [31].

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 D-amino acids [39] and improving biofilm cleaning by manually scraping the surface of the membrane in ultra-filtration [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 Mg^{2+} , Ca^{2+} , and 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/cm^2 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/m^2 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/m^2 . However, after 80 days of operation, the power density dropped about 16.2% to 830 mW/m^2 and further reduced about 32.5% to 560 mW/m^2 after

Figure 2: Schematic of an MDC [51].

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/m^2 , which is 79% lesser than the power generated by pretreatment Nafion (100 mW/m^2) [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 $0.45 \mu\text{m}$) 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 $14.7 \pm 0.4 \mu\text{m}$ in 2 months after start-up. In the fourth month, the result showed the biofouling layer increased by 11-fold ($165.1 \pm 22.4 \mu\text{m}$) and 17-fold after 6 months ($250.1 \pm 10.7 \mu\text{m}$) [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

Figure 3: Advances in biofouling control [81].

Figure 4: PVDF membrane modified via electron transfer ARGET ATRP method [85].

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 (TiO_2) [92]. TiO_2 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

Figure 5: ZnO effect on biofilm adhered onto the fishing net [102].

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]. Meanwhile, 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 6: BFC membrane surface modified with (a) AgNP and polydopamine and (b) AgNP and PEM.

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 $503.8 \pm 95.6 \mu\text{A}$ [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.

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