Conventional Electrode Materials for Microbial Fuel Cells

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Abstract The use of microbial fuel cells (MFCs) has gained a lot of attention as a means to combat both energy shortages and water pollution. Despite their best efforts, MFCs are unable to produce substantial amounts of energy or effectively remove pollutants due to a number of difficulties, one of which being the electrode. One of the most significant components of an MFC is the electrode. Different types of electrode materials have recently been developed to boost pollutant removal rates and energy production efficiency. Carbon-based materials have been used as the most often used electrode material in MFCs. A wide range of potentials is now accessible for use in the manufacturing of electrode materials, which can significantly reduce current issues such as the demand for high-quality materials and their cost. In the present chapter, the conventional electrode material is briefly discussed with their influence and role in MFC operation and performance. A brief discussion of the current issues and future views of electrode materials is also included.

Keywords Microbial fuel cells · Electrode material · Biomass · Energy generation

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1 Introduction

An eco-friendly and green environment is one of the necessities for human beings to live a healthy life, but due to discharge of industrial effluents containing irorganic and organic pollutants into water bodies, results in water contamination which has adverse effects on human beings and other aquatic life [1–3]. These crises are well countered by the microbial fuel cell approach due to its unique properties of achieving energy and wastewater treatments [4]. The microbial fuel cells (MFCs) approach is an innovative step in research to convert toxic chemicals into non-toxic chemicals and convert chemical outputs to electrical outputs in the form of energies by using various catalysts (e.g., bacteria) present in wastewater [5, 6]. There have been significant advancements in wastewater remediations and power outputs. MFCs have yet to be commercialized due to their low energy generation and removal efficiency. Low energy consumption or removal efficiency can be caused by a variety of factors, including the utilization of low-graded materials as working electrodes or material cost issues. Because it offers the essential surface area for bacterial proliferation, the working electrode seems to be the most critical section of MFCs. These bacteria produce electrons and protons and transferred it to the anode. Fabrication of anode materials for MFCs functioning, on the other hand, remains difficult. Recently, there has been a surge of interest in electrode configurations, materials, and design that results in steadily increased performance of MFCs [7]. Electrode grading materials should have a few general features to face high-performance criteria, including high conductivity, comparable biocompatibility, stable thermal temperature, chemical and electrical stability, mechanical strength, and an expanded surface region. MFCs use a variety of electrode graded materials, however, these graded materials have several limitations that are unsuitable for industrial usage [2, 8]. According to a prior study, electrode modification has emerged as a novel point in the field of MFCs for achieving an expansion of surface regions, bacterial adherence, and have the ability of electron transference

In MFCs, the electrode is known as the cathode and anode in which anode plays a vital role to transfer bacteria toward cathode to generate electricity. The materials used in the fabrication of anodes have some limitations and till now, not applied at large scale. In literature, El Mekawy [9] et al. mention that anode is the crucial part of MFCs fabrication approaches. As in our knowledge that many researchers started their study on graphene derivatives as modifiers or enhancers to provide a good performance of MFCs on electrode surfaces either as anode or cathode. From one of the previous reports [9], the authors come to the conclusion that graphene derivatives based or carbon-based materials electrodes as cathode or anode are shown as superior and emerging materials for electrodes in MFCs. These materials provide a new dimensions to the researchers working in same area due to cost-effective and efficient materials [10]. Nowadays, the most usable graphene derivative, graphene oxide, is easily fabricated through industrial and domestic waste materials. Moreover, the issue of corrosion or the influence of toxic bacteria on MFCs is resolved by using polymer layers or metal oxide layers with graphene derivatives. The modifications of polymers and metallic composites not only resolved the corrosion issues, but also increase the working performance and efficiency of the electrode in MFCs [11, 12]. It increased the conductivity, biocompatibility, and stability between bacteria and electrodes either as anode or cathode. That's why it is an up-to-date approach to modify electrodes with graphene or carbon-based derivatives to achieve better performance. In this chapter, we reviewed the different types of electrode materials with their unique properties of surface modifications, sizes, designs, electricity generation, and inoculation sources. To discuss the significance of biomass wastes as an emerging materials, many ideas and sources based on electrode fabrications have been summarized in this chapter. Furthermore, the effects of electrodes on wastewater remediation and energy processing are discussed, together with new difficulties and prospects.

2 Essential Properties of Electrode Materials

It is foremost and essential step in MFCs to investigate the unique properties of electrode materials in terms of achieving steady electron mobility, electrochemical efficiency, and bacterial adhesions between system and electrode materials [13]. Some of the unique properties which helps us in this matter is mentioned in this chapter to understand the reproducibility of working of MFCs.

2.1 Conductivity of Material

It is an important aspect of electrode because the electrons due to bacterial adhesions travel from negative terminal to positive terminal via the channel of outer circuit. As in literature, the electrode material is in charge of allowing electrons to flow and enhance their speed [14, 15]. The more highly conductive materials are more helpful in resisting the bulk solutions resistance and increasing the electron transfer rate [16]. To improve electron transfer, lower the interfacial impedance between substrate and electrode as mentioned in the literature [17, 18]. Before constructing the electrodes for MFCs, the electrical conductivity of materials is typically investigated.

2.2 Physiological Properties

The surface regions of the electrode severely affects energy generation in MFCs [19–21]. Because resistivity of electrodes depends on ohmic losses in a MFCs, increasing its surface area is the given suggestions in reports to minimize resistance power. More active sites are gained with an expanded surface regions for bacterial colonization and improves the efficiency of the electrode kinetics. Microorganisms, for example, *Geobacter species, E. coli, Pseudomonas species*, and others were immobilized efficiently on the active regions of electrodes, allowing for suitable electron transfer [20]. Because biological responses occur on the active regions of the electrodes, the surface regions has a significant impact on MFC performance [22].

2.3 Material Biocompatibility

The anode electrode's biocompatibility is critical in MFC operations since it comes into direct contact with microscopic organisms and their respiration cycles. Many materials utilized as electrodes in MFCs, such as silver, gold, and copper, are not considered biocompatible due to their corrosive nature [23–25]. The poisonous nature of such compounds can prevent bacterial development during MFC operation, resulting in lower energy generation.

2.4 Stability and Durability

In case of any research-based system, the stability and durability are one of the most significant points for your research. Various environmental factors affect the stability and durability of electrode. The decomposition, corrosion, and swelling are caused due to interaction of electrode with environment that affects its stability and duration of working performance [23, 26, 27]. Thus, the use of more preferable material as an electrode makes your system more durable and stable for good performance.

2.5 Cost and Access of Material

The cost and access of material is a key factor to approach your work without stress and also opens the feasible ways for other researchers. And moreover, the cost of electrode also has chance to provide MFCs system with easy and cheap approach as compared to expensive and heavy approaches. In present time, carbon derived graphene based composites have been widely used due to easily available and low cost. The expensive metal composites such as gold, silver, platinum are also replaced with inexpensive bimetal composites such as ZnO, Fe_2O_3, etc. [28, 29].

3 Electrode Materials

Removal efficiency of pollutants and energy production have been optimized to investigate the effectiveness of electrode materials. The electrode materials, as mentioned above, has some of the basic properties such as high stability and conductivity, more compatible than other materials. For this purpose, we investigated some electrode materials in two categories as electrode material as anode and electrode material as cathode.

3.1 Electrode Materials as Anode

From previous studies, it becomes clear that there are various types of materials used to fabricate anode of MFCs in terms of large surface area to increase the extracellular efficiency of electron transfer via biofilm. Moreover, the anode materials have more significancy because it is useful for metabolic rates in oxidizing organic wastes by anaerobic microorganisms [30–32]. It is notable that the kinds and concentration of bacteria have great effect on power density of MFCs, but now, it is also proven that the anode materials have also significant feature for MFCs to work better. Thus, fabrication of the anode materials through various chemical modifications, must be taken an account in the future to enhance the capacity of anode. Some of the generally used sources are composite materials, allotropes of carbon, conducting polymers, or metal or metal oxides, which seem to have significant value to be worth materials for anode fabrication.

3.2 Carbon-Graded Materials

Nowadays, carbon-derived materials are gaining more attention due to their unique properties such as low cost, chemical and mechanical stability, high electron transfer kinetics, biocompatibility, and highly conductive in nature. By studying the recent literature, it is well known that different types of carbon-graded materials like graphite, carbon nanotubes, fullerenes, carbon nanorods, carbon cloth paper, carbon fiber, reticulated vitreous carbon, glassy carbon, and carbon quantum dots have been investigated. The latest carbon-based materials which are now an emerging class of carbon allotropes are graphene and its derivatives.

Carbon paper, brushes, rods, felt, fabric, meshes, and other carbon-graded materials are normally utilized materials in MFCs. A carbon mesh is somewhat more affordable than other carbon structures, as indicated by Wang et al. [33] and it likewise has a higher current thickness. On the other hand, modification of carbon meshes with alkali or gas give good results. Therefore, no untreated material presently conveys a more powerful thickness. Borsje et al. [34] investigated the functioning of single carbon granules as capacitive bioanodes. Charge stockpiling execution and current creation via solitary carbon granule was utilized to decide the outcomes. The bioanode stored the charge in the form of two-fold sandwich. To assess the undiscovered capability of granular bioanodes, scientists utilized granular and initiated graphite carbon granules. In contrast with Ag/AgCl anodes, single enacted carbon-graded granules create 0.6 mA at 300 mV. Capacitive granules produce 1.3 times extra electricity as compared to graphite granules at the lower surface regions [35–37]. Li et al. [38] investigated granule-activated carbon, which delivered twice more energy than the customary carbon materials. According to the findings, granule-actuated carbon could be a viable alternative for anode preparation. Carbon cloth/sheets are flexible and allow bacteria to grow on their surface. It is, however, much more expensive at larger scales [39]. Actuated carbon cloth has an expanded surface region and suitable adsorption capacity for the expulsion of sulphide in electrochemical oxidation at the anode. Wang et al. [40] arranged carbon cloth that provides an increment of the current effectiveness of 2777.7 mW/m^2. Doped with nitrogen gas, the carbon cloth produced high power production, and it could be valuable for future researches. Likewise, graphite is one of the regular forms utilized for an electrode in MFCs. Graphite is known as a crystalline allotrope of carbon with Sp^2 hybridization. MFCs use graphite as an anode because of its good conductivity and long-term stability. For the production of electrodes, different forms of graphite are effectively used [41–43]. Ter-Heijne et al. [44] observed the raw form of carbon for the electrode in MFC rather than flat forms, which showed higher current density. But they have a low surface region and high cost which makes this material inadequate for commercial use in the production of energy. The graphite brush as the best model for electrodes with the best performance to be used as anodes in MRCs for improved energy generation and toxic pollution removal was reported by Lowy et al. [45]. Yazdi et al. [46] later reported that the rate of bacterial colonization on the electrode's surface is proportional to the anode's surface area. In another study, Zhang et al. [47] found a category of graphite brushes within the range of sizes. Little brushes can deliver more energy output than bigger ones. 1771 mW/m^2 small value of power density is also reported in the Cassava mill by graphitic brushes in wastewater remediation [48, 49]. Bacteria feed on organic material and flourish in environments with lots of carbon because of its increased particular surface area [50]. Yasri et al. [51] created an efficient anode material by doping graphite with calcium sulphide to promote bacterial interaction with the active regions of electrodes. In the modern period, graphene, a newly developing carbon allotrope (found in a 2D hexagonal lattice), has earned a lot of interest. With its emerging features of outstanding conductivity and mechanical and thermal strength, graphene is an ideal material for electrode construction. When compared to graphite materials, graphene possesses a nonlinear and better diamagnetism. Graphene and its derivatives, on the other hand, are still being studied as anodes in MFCs [52]. Graphene has been synthesized using a variety of processes. Commercially available graphene is expensive, whereas graphene made from waste materials is less expensive [53–56] Due to its more energy generation relative to other typical carbons, graphene as an anodic material enables high scale functioning for MFCs. Graphene-based electrodes have better electrode efficiency as anodes than conventional carbon-based electrodes [57]. During MFC operations, graphene has non-toxic impacts on bacterial growth. As a result, by modifying or combining it with conductive polymers and metals, drawbacks of other materials, like copper, can be reduced [58, 59]. Modified carbon allotropes have the potential to revolutionize wastewater treatment and energy.

3.3 Natural Biomass Source as Anode

The properties of the electrode materials vary significantly in terms of physical, chemical, and biological nature. The electrodes require electrical, and specifically microbial, compatibility with specific bacteria strains to affect the movement of electrons, just as surface opposition of electrodes [60]. Nonetheless, electrode materials, fabrication, and processing have been recently becoming a popular and up-and-coming research area. MFCs use waste materials for construction. Changing waste materials into worthy and valuable materials is time-consuming and somehow effective in contrast with commercial materials in a few features [61]. Cheng et al. [62] researched a waste-inferred decreased graphene (rGO) composite for anodes to accomplish more powerful outcomes as far as energy age and wastewater treatment by means of MFCs. Utilizing dried eucalyptus leaves as waste material, the rGO was prepared successfully. Later, rGO/gold nanoparticle nanocomposites were fabricated by layering for the manufacturing of biocompatible anodes. The electrode prepared in this study has a higher surface roughness, which facilitates bacterial colonization. Gold nanoparticles are considered as a highly electroactive agent which tranfer the electrons and produces electricity at negative terminal. Singh et al. [63] prepared an effective electrode for MFCs using carbon nanoparticles derived from candle soot. The candle sediment was disseminated on the outer layer of a hardened steel circle, which permitted the carbon nanoparticles to be utilized as cathodes straightforwardly. The consequences of the electrical, physical, and compound portrayal of an anode's mechanical, chemical and electrical strength are just as progressively permeable qualities. The production of carbon nanoparticle electrodes from candle soot is reusable, budget-friendly, robust, and dependable. Bose et al. [64] have also used biomass to manufacture a bioenergy active carbon cathode via MFCs. This was one of a kind method of generating electricity and treating water that had no negative environmental consequences. Platinum is commonly utilized as an impetus for oxygen decrease at the terminal of the cathode. In terms of reliability, functionality, and prices, the authors examined the effectiveness of actuated carbon derived from sugar cane waste. At different temperatures for 60 min, this useless material followed the carbonization process. Electrodes derived from various biomass sources are considered as an alternative for the treatment of pollutants from wastewater with electricity generation simultaneously. As we know that in MFCs, there have been only a small number of publications on the source of biomass anodes. That's why the concept of reusability of biomass is a viable substitute for enhancing MFC's working efficiency with no high costs. Graphene and its derivatives can easily be produced by numerous methods like chemical vapor deposition, arc detection, epitaxial growth, scotch tape, electrochemical synthesis, reduction of GO/rGO, exfoliation, confined self-assembly, and Hummer's method. Its favorable points over other methods made it the most important and promising method. This is an eco-friendly method, for example, without producing harmful gases during processing, with a structured product, and with a larger output supplied. Hung et al. recently used [65] a coffee-based renewable waste anode in MFCs to expand the power thickness. The authors have transformed waste material into precious carbonized materials and have used it to lessen squander from the environment as an anodic material in MFC. The energy density achieved was 3800 mW/m^2, much higher than traditional techniques. In our vicinity, various types of waste materials cause serious dangers. Therefore, the use of biomass waste materials as valuable materials is a positive approach. In Hummer's process, however, various useless materials are carbonized to obtain fine carbonated powder materials affected by argon gas at 1050 °C. The graphic powder is treated to obtain graphene oxide with the oxidizing agent $KMnO_4/H_2O_2$. Fabricated graphene oxide can also be used to manufacture the graphene oxide material in anode-shaped electrodes with polymer binders like nafion, polyethyleneimine, and polylactic acid [66]. The graphene oxide synthesized can be utilized as positive or negative terminal material, however, its use as the anode is preferable, as previously stated. This type of modification may enhance the materials efficiency and reduces the expenses. The use of composites synthesized for low-cost use with metal oxides such as CuO/GO, ZnO/GO, etc., is an optimal way to deal with various difficulties. Table 1 summarizes the electrodes produced in recent years using natural biomass resources.

3.4 Metal/metal Oxide-Sourced Materials

Different materials were utilized to fabricate metal/metal oxides based anode–cathode, but consumption restricts the utilization of metal-sourced terminals, especially for MFC anodes. Metals are commonly penetrable than carbon-graded materials because of their capacity to work with proficient electron stream [76]. While each metal has exceptional properties, not all metals are reasonable for cathode creation because of the noncorrosive necessities of the interaction. Also, certain metals repress bacterial bonds. For instance, in contrast with other carbon-graded materials, for example, graphite and graphene, non-destructive tempered steel materials don't have a powerful thickness. Overall, the smooth surfaces of metals are not helpful for bacterial grip. Predefined non-destructive materials, like tempered steel, can't accomplish higher energy thickness than materials dependent on carbon. At the

Table 1 List of electrodes synthesized using natural waste resource for MFCs

Electrode materials	Inoculum sources	Surface area of electrodes (cm^2)	Power density (mW/m^2)	Size of electrodes (cm^2)	References
Loofah sponge/PANI	Mix sludge	10.99	2590	0.5 × 3.0	Tang et al. [67]
Barbed chestnut shell	Mix sludge	91	759	2.7 × 2.7	Chen et al. [68]
Coconut shell/ sewage sludge	Mix sludge	10.99	1069	0.5 × 3.0	Yuan et al. [69]
Onion peels	Mix sludge	7	742	1.0 × 2.0 × 0.5	Li et al. [70]
Silk cocoon	Mix sludge	7	5	–	Li et al. [71]
Coffee wastes	Domestic waste	1	3927	–	Hung et al. [65]
Loofah sponge	Anaerobic sludge	10.99	701	0.5 × 3.0	Tang et al. [72]
Compressed milling residue	Anaerobic mix sludge	10.99	532	0.5 × 3.0	Huggins et al. [73]
Bamboo charcoal	Anaerobic mix sludge	59.21	1652	2.4 × 1.57	Zhang et al. [74]
Kenaf	Domestic sewage	2.5	–	0.23 × 1.52	Chen et al. [75]
Chestnut shells	Anaerobic mix sludge	125.65	850	0.3 × 66.4	Cheng et al. [62]

anode chamber, stainless steel had a power density of 23 mW/m^2 [77]. An anode-based stainless-steel grid increased the relative current density of a single electrode of graphite [78, 79]. Silver, platinum, gold, and titanium are ideal anode metals. While noble metal-based anode electrodes contribute to the reduction of interior obstruction in MFCs, their significant expense and poor bacterial grip block their far and widespread use in MFC operation [24, 80]. Platinum and titanium are commonly suitable as catalysts to enhance electrode performance [81]. Moreover, commercialization of some of pure metal-based anodes in MFCs have some limitation due to their high expense. The reactivity of metallic nanoparticles and transition metals is comparable to precious metals, altogether decreasing obstruction and working on microscopic organisms' connection to surfaces. Additionally, nanometallic particles offer an excellent opportunity to diminish the impact of harmfulness on bacterial cells [82]. These issues are mitigated by coating metal/metal oxide nanoparticles (Ag, ZnO, etc.) with comparable materials such as carbon-graded or polymers.

3.5 Polymer Composite Material

Various conductive polymers, namely polypyyrole, polyindoles, polythiophene, polycarbazoles, polyaniline, polyadenines, etc., were used in terms of highly conductive materials at anode surfaces on the basis of their efficient conductive properties [83–85]. The combination of carbon-based materials and conductive polymers produce very efficient and good results. As shown in previous reports, the polyaniline-modified carbon cloth produced more power production than unmodified carbon cloth [86]. In another report, one of the most important conductive polymers, polypyyrole with the layer of carbon paper, showed a 452 mW/m^2 power output [87]. To our knowledge, Polypyyrole can enter bacterial cell membranes and transport electrons via metabolic pathway easily [88]. Thus, polymer composites combined with different materials, similar to carbon-graded materials and metals, significantly further develop anode productivity. For example, Dumitru et al. [89] investigated two polymers such as polypyyrole and polyaniline with CNTs as a nanocomposite anode. Due to their synergistic effect, CNTs and conducting polymer nanocomposites perform justifiably well enough in electrochemical applications [90]. The use of conductive polymers (especially polyaniline and polycarbazole) with metal oxide composites could significantly improve MFC performance [91–93] But despite more researches, there is little exertion that has been made to plan polymeric composite-based MFC electrodes. Figure 1 depicts common electrodes such as conductive polymer, metal, and carbon electrodes.

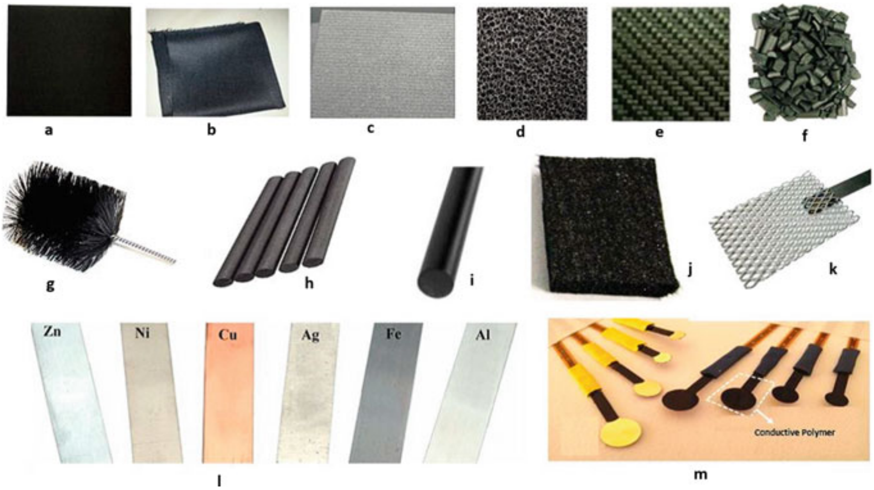

Fig. 1 List of commonly used electrodes: **a** carbon paper, **b** carbon cloth, **c** carbon fiber, **d** reticulated vitrified carbon, **e** carbon mesh, **f** graphitic granular, **g** carbon brushes, **h** graphite rod, **i** polycrystalline graphite, **j** carbon felt, **k** platinum mesh, **l** different metal electrode strips, and **m** conductive polymer-based strips. Adapted from reference [25] with MDPI permission

4 Electrode Materials as Cathode

Despite the anode (negative terminal), the cathode (positive terminal) material has also a significant place in the functioning of MFCs. Nowadays, the most widespread material for the cathode is carbon-based, but their features like size, model, and efficiency for cathode materials are challenging as compared to anode material [94–97]. The mostly reported anode materials are also used as cathode material. Due to deprived catalyst activity, reactions to reduce substrate commonly occur in the cathode section, reducing MFC performance [98–101]. The cathode terminals can be derived as with catalyst or without catalyst. The main distinction between these setups is the spark. Platinum and titanium are the most commonly used catalysts. A terminal named air cathode is directly influenced by oxygen [102]. The setup has drawn attention for its lack of aeration, functional simplicity, and appropriate electrode design. An air cathode can significantly expand the energy effectiveness through MFCs [103, 104]. Aqueous air cathodes use conductive materials like platinum meshes and carbon felt, cloth, and fiber to form electrodes. The catalyst is sandwiched with aqueous regions in low oxygen contact [105]. As an air cathode, carbon-derived forms are the most ideal conductive material. Catalysts (platinum, copper, etc.) are fixed to electrodes using binders [106, 107]. Poly(tetrafluoroethylene) and perfluorosulfonic acid are popular binders (nafion). Zhang et al. [108] compared the performance of articulated carbon and its derivatives as cathode utilizing poly(tetrafluoroethylene) for binding. In the presence of Pt as a catalyst, articulated carbon outperforms carbon cloth (1220 mW/m^2) in terms of power density. So articulated carbon seems to be a good cathode material substitute for the fabrication of a positive terminal. Zhao et al. [109] employed catalyst Pt combined carbon derived as a motivating factor. According to the latest findings, this catalyst has a power efficiency of 1.2 W/m^3. Cu is a preferable catalyst to Pt at lower temperatures due to its sustainable power. Under normal conditions, Pt is considered better and more generally known catalyst than other metals [110]. As a result, the materials utilized in the fabrication of positive and negative terminals (cathode/anode) can be performed as oxygen reduction catalysts. Due to their low overpotential, gold and platinum are considered potential catalysts, but their expensive cost makes them unsuitable [76, 111, 112]. Transition metals are cosidered as a alternative materials to fabricate potential electrode due to high stability, affordable and avoid any disruption in the microbial fuel system. Composite materials, known as molybdenum and carbide, perform well, but stainless steel and nickel alloys outperform them all [113]. Nanocomposites, on the other hand, are less expensive and provide a significant chance to boost MFC efficiency (for example, Ni and palladium nanoparticles/nanomaterials) [114]. In comparison to conventional materials, nanomaterials have an expanded surface region, superior electrochemical functioning, and stronger thermal and mechanical durability [115]. To improve the oxygen reduction reaction, a recent trend involves modifying the electrode using additional materials. According to the literature, fresh materials must be studied in order to improve the feasibility of electrodes, particularly anodes. Utilization of high-graded materials for anodes, for example, graphene and its derivatives with metal oxides, could usher in a major shift in the MFC area. The preferable composites are GO/Ag, GO/Fe_2O_3, GO/ZnO, GO/chitosan, and GO/TiO_2, all of which have a significant influence on power outputs. In addition, Table 2 lists the many types of classic carbon-graded materials, composite-based, metal/metal oxides, and Carbon-based + Polymer composite that can be utilized as electrodes (anodes and cathodes).

5 Influence of Electrodes (Cathode/Anode/) in MFCs

In the presence of a biocatalyst, the electrode (anode/cathode) is a critical component due to its unique feature of assisting in the remediation of hazardous agents and generation of energy during MFC operations. During the respiration process of bacteria, the bacteria are cooperated with the electrode region to create protons and electrons. As seen in Fig. 2, the electrode provides enough surface region for bacteria to proliferate and oxidize. The performance of the anode as compared to the cathode provides MFCs with high electric production, wastewater bioremediation, and compactable economic features.

6 Influence of Electrode (Anode/Cathode) on Removal of Pollutants

MFCs are thought to be a particularly efficient prospective use for wastewater bioremediation. Many traditional wastewater treatment technologies have been described, but they all have significant limitations such as high prices, being difficult to run, the possibility of self-toxicity, and being unstable in terms of ecosystem safety [51]. Fossil fuel industrial wastewater, scum wastewater, aquaculture wastewater, cassava mill wastewater, food processing waste, dairy wastewater, crop residues, and surgical cotton waste, are all examples of wastewater that could benefit from the MFC approach [151]. Organic agents are oxidized to generate electrons and protons in the chamber of the anode via exoelectrogens, thereby destroying the hazardous organic pollutants in water [152, 153]. Protons were transmitted directly to the cathode or via membrane sources, while electrons were transported via the outer circuit. The electrodes' functioning efficiency is crucial to this procedure. The electrodes offer bacteria a surface area for respiration and growth, making it easier for electrons and protons to be transferred to the negative chamber through bacteria and ultimately to the positive chamber.

Zhang et al. [154] investigated the suppression of two elements with the implementation of electricity utilizing vanadium-sourced water with waste as an electron acceptor in dual terminal microbial fuel cells. V(V) and Cr (VI) are primary metals found in vanadium-sourced effluent, both of which are highly hazardous and abundant. Qiu et al. [155] reported vanadium based biocathode and got 60% fatality rate

Table 2 Some reported materials used as electrodes in microbial fuel cells

Type of materials	Anode	Cathode	Catalyst	Power density	Inoculum source/bacteria	References
Carbon-based	Carbon mesh	Carbon mesh	Pt	893 mW/m^2	Pre-acclimated bacteria from an active MFC	Wang et al. [116]
Carbon-based	Activated carbon cloth	Graphite foil	Pt	0.51 mW/cm^2	D desulfuricans strain	Sokol and Bradford [37]
Carbon-based	Non-wet proofed carbon cloth	Wet proofed carbon cloth	Pt	766 mW/m^2	Domestic wastewater	Cheng et al. [117]
Carbon-based	Plain carbon paper	Carbon paper	Pt	33 mW/m^2	Sediment sludge	Logan et al. [118]
Carbon-based	Granular graphite	Granular graphite	Pt	8 W/m^3	Mixture of sediment, aerobic and anaerobic sludge	Clauwaert et al. [119]
Carbon-based	Granular graphite	Graphite felts	Pt	83 ± 11 W/m^3	Mixture of sediment, aerobic and anaerobic sludge	Clauwaert et al. [120]
Carbon-based	Graphite plate	Graphite fiber brushes	Pt	68.4 W/m^3	Aerobic sludge	You et al. [121]
Carbon-based	Carbon cloth	Carbon cloth	Without catalyst	679.7 mW/m^2	*S.putrefaciens CN32*	Qiao et al. [122]
Carbon-based	Carbon cloth	Carbon cloth	Without catalyst	1292 ± 69 mW/m^2	Wastewater	ter Heijne et al. [44]
Carbon-based	Graphene oxide	Carbon paper	Ti	102 mW/m^2	*S. oneidensis MR-1*	Zhao et al. [105]

(continued)

Table 2 (continued)

Type of materials	Anode	Cathode	Catalyst	Power density	Inoculum source/bacteria	References
Carbon-based	3D-Graphene	Carbon cloth	Pt	1516 ± 87 mW/m^2	*E. coli*	Osgood et al. [100]
Carbon-based	Graphene	Carbon cloth	Pt	2850 mW/m^2	*E. coli*	Najafabadi et al. [123]
Carbon-based	rGO sheets/carbon cloth	carbon cloth	Pt	2.5 W/m^3	Anaerobic sludge	Xiao et al. [124]
Carbon-based	Carbon cloth/CNTs	Carbon cloth/CNTs	Pt	65mW/m^2	Domestic wastewater acetate	Tsai et al. [125]
Carbon-based	Graphene oxide with CNT	Carbon cloth	Pt	434 mWm^{-2}	*E. coli*	kumar et al. [126]
Carbon-based	Non-wet-proof carbon paper	Non-wet-proof carbon paper	Pt	188 mWm^{-2}	Mixed community	Hassan et al. [127]
Carbon-based	Carbon felt	Carbon fiber felt	Pt	784 mW/m^2	Anaerobic sludge	Yang et al. [128]
Carbon-based	Glassy carbon	Carbon cloth	Pt	1905 mW/m^2	Anaerobic sludge	Yuan et al. [129]
Carbon-based	Carbon brush	Carbon cloth with gas diffusion layers	Ti	4.25 mW/m^2	Sludge	Choi and Cui [130]
Carbon-based	Graphite brush	Carbon cloth	Pt	1280 mW/m^2	Native wastewater	Santoro et al. [131]
Carbon-based	Carbon paper	Carbon paper	Pt	600mW/m^2	Primary clarifier overflow	Wei et al. [8]
Carbon-based	Graphene coating on Carbon cloth	Carbon cloth	Pt	52.5 mW/m^2	*P. aeruginosa*	Liu et al. [132]
Carbon-based	Graphene oxide modification with carbon paper	Carbon paper	–	368 mW/m^2	Anaerobic Sludge	Guo et al. [133]
Carbon-based	Graphene nanosheet coating on carbon paper	Carbon cloth	Pt	610 mW/m^2	*S. oneidensis MR-1*	Ma et al. [107]

(continued)

Table 2 (continued)

Type of materials	Anode	Cathode	Catalyst	Power density	Inoculum source/bacteria	References
Composite-based	Polypyyrole/ graphene oxide	Carbon felt	Pt	1326 mWm^{-2}	S. oneidensis	Lv et al. [134]
Composite- based	TiO_2 and rGO composite	Carbon fiber/brush	Ti	3169 mW/m^2	*S. putrefaciens CN32*	Zou et al. [135]
Composite-based	Graphene/Au composite	Carbon paper	Pt	508 mW/m^2	*S. oneidensis MR-1*	Zhao et al. [136]
Composite-based	Graphite plates	Platinum meshes	–	1410 mW/m^2	*Shewanellaonei densi*	Dewan et al. [137]
Composite-based	Zero-dimension nitrogen doped carbon dots modification with carbon paper	Carbon paper	Pt	0.32 mW/m^2	*Pseudomonas*	Guan et a. [138]
Composite-based	Graphene/PPy	Carbon cloth	Without catalyst	145 mW/m^2	*S. oneidensis MR-1*	Yong et al. [139]
Composite-based	N-doped graphene nanosheets (NGNS) on carbon cloth	carbon cloth	Pt	1008 mW/m^2	*E. coli*	Kirubaharan et al. [140]
Composite-based	rGO/SnO_2/Carbon cloth	Pt rod	Pt	1624 mW/m^2	E. coli	Mehdinia et al. [141]
Metal and metal oxides	Stainless steel mesh coated with carbon cloth	Carbon black	Pt	1610 ± 56 mW/m^2	Domestic wastewater	Zhang et al. [142]
Metal and metal oxide	Ti/TiO_2	Pt meshes	Pt	2317 W/m^3	Swamp sediments	Benetton et al. [143]
Metal	Stainless steel	Stainless steel	Pt	23 mW/m^2	Marine sediments	Dumas et al. [144]
Metal and metal oxide	Titanium	–	Pt	–	*G. sulfurreducens*	Dominguez-Benetton et al. [145]

(continued)

Table 2 (continued)

Type of materials	Anode	Cathode	Catalyst	Power density	Inoculum source/bacteria	References
Metal and metal oxide	Titanium rod	graphite felt	Pt	–	Pre-acclimated bacteria	Michaelidou et al. [146]
Carbon-based polymer composite	RGO/carbon cloth-PANI	Carbon felt	Pt	1390 mWm^{-2}	Anaerobic Sludge	Hou et al. [147]
Carbon-based + polymer composite	rGO/PPy	Carbon paper	Pt	1068 mW/m^2	*E. coli*	Gnana Kumar et al. [88]
Carbon-based + polymer composite	Polypyyrole coating on carbon cloth	Granular activated carbon	Pt	5 W/m^3	Domestic wastewater	Jiang and Li [148]
Carbon-based + polymer composite	Nickel foam/CNTs/PANI	carbon cloth	Without catalyst	113 W/m^3	*Shewanella Sp*	Nourbakhsh et al. [149]
Carbon-based + polymer composite	Graphene powder/polytetrafluoroethylene on Carbon cloth	Carbon cloth	Pt	0.329 mW/m^2	Anaerobic pretreated sludge	Pareek et al. [150]
Carbon-based + polymer composite	Polyaniline (PANI) networks onto graphene nanoribbons (GNRs)-coated on carbon Paper (CP/GNRs/PANI)	Carbon paper	Ti	856 mW/m^2	*S. oneidensis MR-1*	Chen et al. [104]

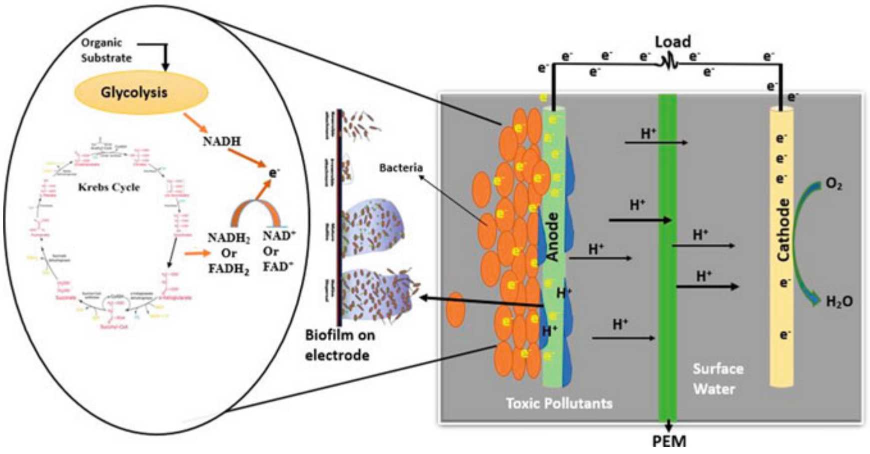

Fig. 2 Functioning of the electrode in MFCs. Adapted from reference [25] with MDPI permission

through MFC in presence of *Dysgonomonas and Klebsiella.* The power density of MFCs after seven days of operation with a 200 mg/L starting concentration of anaerobic sludge was 529 12 mW/m^2. Jiang et al. [156] looked at wastewater from the oil sands process to see if MFCs could create electricity while also treating oil sand tailings. The MFCs cleaned various heavy metals from wastewater derived from the oil sands process with constant energy production and with good outputs of efficiencies percentages. The removal efficiency was somehow low due to the usage of carbon derivatives as cathode and anode. For a variety of reasons, the carbon fiber felt outperformed the carbon cloth, but graded anode and surface region available to bacteria were essential. Habibul et al. [157] utilized a graphite manufactured anode to research electro kinetic biosorption of heavy metals from disturbed soils, in order to improve the anode's quality. However, research into the breakdown of particularly harmful metals such as cadmium, lead, and mercury is scarce. Bacteria require high-quality anode materials to digest harmful elements from the water supply. Similarly, the researchers utilized various MFC used anodic chamber agents to decolorize the organic dyes that were damaging the ecosystem. Fang et al. [158] investigated the potential of MFCs which are made of activated carbon and a cathode built of stainless-steel mesh to process azo dye. The decolorization rate was high due to articulated carbon serving as an anode. To decolorize methyl orange from anaerobic sludge, Kawale et al. [159] utilized a graphitic rod as an anode to decolorize methyl orange from anaerobic sludge. Both decolorization and energy output were significantly influenced by the electrode. However, several researchers used MFCs with various anode materials to remove organic contaminants. Kabutey et al. [160] utilized a macrophyte cathode silt microbial power module to research the evacuation of natural impurities and energy age from metropolitan waterway dregs. Carbon fiber was utilized as both cathode and anode terminals in this investigation, with an expulsion proficiency of 28.2%. Microorganisms like *Euryarchaeota and Proteobacteria* were unable to separate phosphorus due to its acidic nature and inefficient ability of cathode used in this work. Marks et al. [161] investigated the functioning of MFCs in anoxic surroundings and found that they could remove 22% of nitrate from anaerobic sludge. The cathode and anode electrodes in this experiment were graphite plates. According to an exhaustive literature study, the authors determined that different types of anode materials are utilized under different situations since MFC functioning is influenced by a variety of parameters. One of the most significant functions of an anode is to give bacteria sufficient surface area for respiration while also assisting them in carrying electrons from colonization of bacterium to the cathode via an outer circuit. As a result, it has been shown that employing a high-graded anode will yield superior outcomes with less environmental constraints. Many difficulties that cause disruption during processing, such as long-term stability, might be addressed using this high-quality material. To reduce metal corrosion, we may fabricate anode more efficiently with the help of conductive material and high surface regions materials like composite materials, graphene, and its derivatives, containing metal/metal oxides. As a result, in order to get better outcomes for remediation purposes, the anode should be unique and efficient.

7 Influence of Electrode (Anode/Cathode) on Energy Production

MFCs as an innovative approach opened new avenues in the domain of ecosystem pollution and its safe elimination. MFCs generate energy from various organic waste materials using microorganisms as exoelectrogens [162, 163]. In Single chamber MFCs, 3D terminal materials and the improved anodes are utilized for the generation of energy. [128]. Many materials and operating parameters were regularly modified at the start, making it difficult to pinpoint the aspects that helped improve the present generation over traditional approaches. In view of the progression of this framework, more consideration is currently needed to produce a more prominent electrical yield [164, 165]. The electrode is straightforwardly connected to the creation of power. The production of energy rises as the electrode's strength and conductivity improve. Wang et al. [96] additionally demonstrated proficiency of carbon felt as an anode within sight of platinum in form of impetus, but force creation was exceptionally low. Zhang et al. [154] utilized the incorporated adsorption method to separate chromium from anaerobic assimilation ooze and had the option to accomplish a current force of 343 mV. Utilizing engineered arrangements, Liu et al. [166] explored MFC execution utilizing carbon fabric as both terminals within sight of Fe/Ni/actuated carbon as an impetus and delivered remarkable energy yield. To improve the material, Santoro et al. [131] utilized graphite brushes within sight of Pt impetus SMFCs to accomplish a high energy yield. In the wake of utilizing local wastewater as an inoculum source, a force thickness of 1280 mW/m^2 was reached. The performance of the electrodes determines the amount of energy produced. Carbon felt, for example, has a lower surface area and conductive efficiency than graphite-based materials. As a result, graphite-based materials produce multiple times the results of carbon-derived items. Nguyen et al. [167] reported a novel method to develop a high quality anode's material. Zhang et al. [168] recently published a paper describing the outstanding electrochemical presentation of MFCs with an allotropic form of carbon named graphene oxide for electrode enhancing performance. When contrasted with other carbon-based materials, graphene oxide further developed electron transport and created more energy. Therefore, graphene is preferable and encouraging material for the fabrication of electrode (anode/cathode) in MFCs.

Natural assets, on the other hand, are used in current research for anode fabrication since they are practical and elite materials when contrasted with manufactured materials. Yang et al. [169] found that banana strips and underwater wetland dregs, which were utilized as an inoculum hotspot for MFC activity, straightforwardly created energy. Accordingly, utilizing regular materials as terminals (anodes/cathode) is a viable answer for tending to introduce difficulties and orchestrating excellent anode materials, like GO and derivatives modified with metal oxides. The attributes of the anode can be improved by joining GO composites with metal oxides. Anodes made of ZnO/GO, Fe_2O_3/GO, and CuO/GO are generally utilized in MFCs to acquire high power execution. From the last few decades, low-cost anode and cathode materials have been developed for the removal of toxic pollutants with energy generation in MFCs system (Table 3).

8 Challenges and Future Recommendations

Regardless of the multitude of advancements in MFCs, mainstream researchers actually face numerous difficulties and issues as far as power age and aqueous treatment. It must be evidently quick advancement in designing MFCs as productive and preferable. Besides, reactors of various plans have already been presented, such as one and two-fold chambers, film less, H-shape, and rounded MFCs [191, 192]. Basically, the primary objective of all improvements is to accomplish commonsense execution of MFCs for remediation purposes at a business level. The principal segment in MFCs is the anode, that additionally dependable somewhat for their financial and functional capability. There are a few challenges related to electrode (anode/cathode) that have reduced the use of MFCs on a modern level:

1. The electrode components are crucial for the monetary province of MFCs. Thusly, removing costs for materials is a significant issue for executions in MFC applications. To resolve this matter, we ought to consider the waste material sources and converted them into carbonized structures that can be furthermore used as terminal material in a couple of constructions, similar to posts, brushes, bars, and plates. Nevertheless, one more technique is the improvement of composites with metals and utilizing polymers to fabricate them more compelling at an insignificant cost [193].

Table 3 Influence of the electrode (anode/cathode) on removal efficiency and energy production through MFCs

Category of pollutant	suspected analytes	Anode	Cathode	Source	Removal efficiency %	Reference
	Cu^{2+}	Carbon brush	Reduced Graphene oxide	*Geobacter and Pseudomonas*	98	Abourached et al. [170]
	Cu^{2+}	Graphite felt	Graphite plate	Anaerobic sludge	70	Wang et al. [171]
	$CuSO_4$/CuO	Graphite plate	Graphite felt	Anaerobic sludge	>99	Tao et al. [172]
	Co	Graphite felt	Graphite felt	Lithium cobalt oxide Solution	62.5 ± 1.8	Yun-Hai et al. [173]
	Cr (VI)	Graphite felt	Graphite rod	*Shewanella oneidensis MR-1*	67	Singhvi [174]
Metal-based water pollutant	Cr (VI)	Graphite felts	Graphite felts	*Actinobacteria, B-Proteobacteria*	5 mg/L with 93 25 mg/L with 61	Tao et al. [175]
	Cr (VI)	Carbon fiber felt	Carbon fiber felt	Anaerobic sludge	75.4 ± 1.9	Zhang et al. [154]
	Cr (VI)	Activated charcoal	Activated charcoal	Algae biomass	98	Ryu et al. [176]
	Cr (VI)	Carbon felt	Carbon felt	*Shewanelladecolorationis S12, K. pneumonia*	99.9	Wu et al. [177]
	V(V)	Carbon fiber felt	Carbon fiber felt	*Dysgonomonas and Klebsiella*	60.7	Qiu et al. [155]
	V(V)	Carbon fiber felt	Carbon fiber felt	Anaerobic sludge	67.9 ± 3.1	Zhang et al. [154]
	Au^{3+}	Carbon brush	Carbon cloth	Tetrachloroaurate wastewater	99.89 ± 0.00	[178]
	Ag^{+} ions	Carbon brush	Carbon cloth	Sludge mixture	99.91	Zhang et al. [154]
	Ag^{+}	Carbon cloth	Graphite	NH_3 chelated silver waste water	99.9	Choi and Hu [179]

(continued)

Table 3 (continued)

Category of pollutant	suspected analytes	Anode	Cathode	Source	Removal efficiency %	Reference
	Platinum (Pt)	Graphite plate	Graphite plate	Anaerobic sludge bed	90	Li et al. [180]
	Zn	Carbon cloth (no wet proofing)	carbon cloth (30% wet proofing)	Sewage sludge	90	Huang et al. [181]
	Oil sands tailings	Carbon cloth	Carbon cloth with Pt coating	Oil sands tailings affected water	97.8 Se, 96.8 Ba, 77.1 Mo, 32.5 Pb	Jiang et al. [156]
	Active brilliant red X-3B	Porous carbon paper	Porous carbon paper	Aerobic sludges	90	Chen et al. [182]
	Methyl orange	Unpolished graphite	Rutile—coated graphite	Anaerobic sludge	73.4	[159]
	Acid navy blue R	Graphite rods	Graphite rods	Anaerobic sludge	–	Solanki et al. [183]
Dyes-based water pollutant	Congo RED	Graphite felt	Carbon paper	Anaerobic sludge	70	Li et al. [184]
	Acid Orange 7	Graphite rod	Graphite rod	Microbial consortium	78	Liu et al. [185]
	Azo dye	Carbon felt	Carbon felt	Mixed-culture sludge	94	Khan et al. [186]
	Model textile dyes	Activated carbon	Hydrophobic carbon cloth	*Proteus hauseri*	75	Ding et al. [187]
	Thionine-based textile dyes	Porous carbon cloth	Porous carbon cloth	*Proteus hauseri*	50	Li et al. [71]
	Amaranth	Granular graphite	Spectrographic pure graphite	–	82.59	Mu et al. [188]
	Congo red	Plain carbon papers (non-wet proofed)	Carbon paper (wetproofed)	Culture of aerobic and sludge	85	Sun et al. [189]
	Acid orange 7	Carbon cloth	Carbon cloth	*Shewanellaoneidensis*	>98	Sun et al. [190]

(continued)

Table 3 (continued)

Category of pollutant	suspected analytes	Anode	Cathode	Source	Removal efficiency %	Reference
	Azo dye	Activate carbon	Stainless steel mesh	Concentrated anaerobic sludge	96.5	Jiang et al. [156]

2. During the creation of an electrode, the cover is indispensable for assembling material in its ideal shape. To confirm the assurance of an astoundingly essential factor for researchers to develop materials to make it firmer and steadier. It is alluring to find more sensible and spending plan agreeable folios for the terminal (anode/cathodes).
3. The size and setup are imperative viewpoints in the creation of electrodes. The surface area of electrode play significant role in bacterial growth and electron transferred from negative to positive terminal in MFCs [194].
4. Adjustment of the electrode has made critical redesigns regards to power age and the bioremediation of wastewater. So that, material parts and fitting standards stay dim. Researchers ought to discover more authentic parts for preferable adjustments.
5. One flaw is the long-term steadiness of electrodes at the bulk level. At present, for the genaration of energy, nobody has yet explored the strength of electrode for long term use [195, 196]. Steadiness is a significant issue that resists MFCs functioning at a mechanical scale. Accordingly, scientists should carry on tracking a compelling manufacturing procedure for electrodes while remembering the strength factor for electrode materials. An exceptionally steady fastener like nafion or polysulfides can be utilized to tie the graphene derivatives to keep up with long-term steadiness.

9 Conclusion

The impacts of electrode (cathode/anode) in MFCs were summarized in this chapter. Carbon-graded materials, conductive polymers, composite-based materials, and metal/metal oxide-based materials have all been proposed as electrode materials in MFCs. The adhesion of bacteria and the growth of biofilm are major areas of progress in the development of electrodes. To achieve higher biofilm densities, significant effort has been put into expanding the surface area of electrode materials. As indicated in this chapter, there are a variety of different materials proposed for use as anodes or cathodes. Notwithstanding, there is as yet a critical hole in the advancement of conceivable cathode materials. A terminal (anode/cathode) in MFCs can be made of incredibly spongy and conductive materials like metallic composites and 3D graphene. During long haul MFCs activity, cathode materials should be amazingly steady in wastewater. These qualities make a terminal more significant on a modern scale when it stays stable for quite a while. A terminal material should thusly have a huge pore size to forestall issues in the bioremediation of wastewater applications from being discouraged. The utilization of MFCs is mainly depend on the material expense and surface modification of electrode. Cheap and accessible materials and effective methods should, therefore, be introduced in the MFCs applications industry for metallic or polymer nanocomposite or carbon-based electrons. In future, the testing of upscaling of resource anodes should be a key effort. It is vital to develop an electrode/diaphragm collection for excellent membrane assembly for practical use. But the anode efficiency available is still not enough to be used on a business level. Further studies should focus on the use and optimization of waste material to fabricate electrodes.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Umar K, Yaqoob AA, Ibrahim MNM, Parveen T, Safian MT (2020) Environmental applications of smart polymer composites. Smart Polym Nanocompos Biomed Environ Appl 15:295–320
2. Ahmad A, Setapar SH, Yaqoob AA, Ibrahim MNM (2021) Synthesis and characterization of GO-Ag nanocomposite for removal of malachite dye from aqueous solution, Mater Today: Proc 12
3. Ibrahim N, Zainal SFFS, Aziz HA (2018) Application of UV-based advanced oxidation processes in water and wastewater treatment, 384–414. https://doi.org/10.4018/978-1-5225-5766-1.ch014
4. Logan BE, Rabaey K (2012) Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. Science 337:686–690. https://doi.org/10.1126/science.1217412
5. Yaqoob AA, Khatoon A, Setapar SHM, Umar K, Parveen T, Ibrahim MNM, Ahmad A, Rafatullah M (2020) Outlook on the role of microbial fuel cells in remediation of environmental pollutants with electricity generation. Catalysts 10:819
6. Asim AY, Ibrahim MNM, Khalid U, Tabassum P, Akil A, Lokhat D, Siti HA (2021) A glimpse into the microbial fuel cells for wastewater treatment with energy generation. Desal Water Treat 214:379–389
7. Yaqoob AA, Ibrahim MNM, Guerrero-Barajas C (2021) Modern trend of anodes in microbial fuel cells (MFCs): an overview. Environ Technol Innov 21:101579
8. Wei J, Liang P, Huang X (2011) Recent progress in electrodes for microbial fuel cells. Bioresour Technol 102:9335–9344. https://doi.org/10.1016/j.biortech.2011.07.019
9. ElMekawy A, Hegab HM, Losic D, Saint CP, Pant D (2017) Applications of graphene in microbial fuel cells: the gap between promise and reality. Renew Sustain Energy Rev 72:1389–1403. https://doi.org/10.1016/j.rser.2016.10.044
10. Yaqoob AA, Ibrahim MNM, Rodríguez-Couto S (2020) Development and modification of materials to build cost-effective anodes for microbial fuel cells (MFCs): an overview. BiochemEng J 3:107779
11. Cai T, Meng L, Chen G, Xi Y, Jiang N, Song J, Zheng S, Liu Y, Zhen G, Huang M (2020) Application of advanced anodes in microbial fuel cells for power generation: a review. Chemosphere 248. https://doi.org/10.1016/j.chemosphere.2020.125985
12. Logan BE, Wallack MJ, Kim KY, He W, Feng Y, Saikaly PE (2015) Assessment of microbial fuel cell configurations and power densities. Environ Sci Technol Lett 2:206–214. https://doi.org/10.1021/acs.estlett.5b00180
13. Yaqoob AA, Ibrahim MNM, Umar K, Bhawani SA, Khan A, Asiri AM, Khan MR, Azam M, AlAmmari AM (2021) Cellulose derived graphene/polyaniline nanocomposite anode for

energy generation and bioremediation of toxic metals via benthic microbial fuel cells. Polymer 13:135

14. Yaqoob AA, Ibrahim MNM, Umar K (2021) Electrode material as anode for improving the electrochemical performance of microbial fuel cells. In: Energy storage battery systems-fundamentals and applications. IntechOpen
15. Yaqoob AA, Serrà A, Ibrahim MNM, Yaakop AS (2021) Self-assembled oil palm biomass-derived modified graphene oxide anode: an efficient medium for energy transportation and bioremediating Cd (II) via microbial fuel cells. Arabian J Chem 14:103121
16. Kirubaharan CJ, Kumar GG, Sha C, Zhou D, Yang H, Nahm KS, Raj BS, Zhang Y, Yong YC (2019) Facile fabrication of Au@polyaniline core-shell nanocomposite as efficient anodic catalyst for microbial fuel cells. Electrochim Acta 328:135136. https://doi.org/10.1016/j.electacta.2019.135136
17. Mustakeem (2015) Electrode materials for microbial fuel cells: nanomaterial approach. Mater Renew Sustain Energy 4:1–11. https://doi.org/10.1007/s40243-015-0063-8
18. Yaqoob AA, Ibrahim MNM, Rodríguez-Couto S, Ahmad A (2021) Preparation, characterization, and application of modified carbonized lignin as an anode for sustainable microbial fuel cell. Pro Safe Environ Protect. 155:49–60
19. Schröder U, Patil SA, Di Lorenzo M, Gonzalez Olias L, Cameron PJ (2019) Effect of electrode properties on the performance of a photosynthetic microbial fuel cell for atrazine detection. Front Energy Res 7:105. Www.Frontiersin.Org. https://doi.org/10.3389/fenrg.2019.00105
20. Yaqoob AA, Ibrahim MNM, Umar K. Yaakop AS, Ahmad A (2021) Modified graphene oxide anode: a bioinspired waste material for bioremediation of Pb^{2+} with energy generation through microbial fuel cells. Chem Eng J 417:128052
21. Yaqoob AA, Ibrahim MNM, Umar K (2021) Biomass-derived composite anode electrode: synthesis, characterizations, and application in microbial fuel cells (MFCs). J Environ Chem Eng 9:106111
22. Kamedulski P, Ilnicka A, Lukaszewicz JP, Skorupska M (2019) Highly effective three-dimensional functionalization of graphite to graphene by wet chemical exfoliation methods. Adsorption 25:631–638. https://doi.org/10.1007/s10450-019-00067-9
23. Hindatu Y, Annuar MSM, Gumel AM (2017) Mini-review: Anode modification for improved performance of microbial fuel cell. Renew Sustain Energy Rev 73:236–248. https://doi.org/10.1016/j.rser.2017.01.138
24. Yaqoob AA, Umar K, Ibrahim MNM (2020) Silver nanoparticles: various methods of synthesis, size affecting factors and their potential applications—A review. Appl Nanosci 10:1369–1378. https://doi.org/10.1007/s13204-020-01318-w
25. Yaqoob AA, Nasir M, Ibrahim M, Rafatullah M, Shen Chua Y, Ahmad A, Umar K (n.d.) Materials recent advances in anodes for microbial fuel cells: an overview. https://doi.org/10.3390/ma13092078
26. Senthilkumar N, Pannipara M, Al-Sehemi AG, Gnana kumar G (2019) PEDOT/$NiFe_2O_4$ nanocomposites on biochar as a free-standing anode for high-performance and durable microbial fuel cells. New J Chem 43:7743–7750. https://doi.org/10.1039/C9NJ00638A
27. Sauerteig D, Hanselmann N, Arzberger A, Reinshagen H, Ivanov S, Bund A (2018) Electrochemical-mechanical coupled modeling and parameterization of swelling and ionic transport in lithium-ion batteries. J Power Sour 378:235–247. https://doi.org/10.1016/j.jpowsour.2017.12.044
28. Kang YL, Pichiah S, Ibrahim S (2017) Facile reconstruction of microbial fuel cell (MFC) anode with enhanced exoelectrogens selection for intensified electricity generation. Int J Hydrog Energy 42:1661–1671. https://doi.org/10.1016/j.ijhydene.2016.09.059
29. Islam AKMS, Hussain RT, Khairuddean M, MohdSuah FB, Ahmed NM (2021) Innovative approaches to synthesize novel graphene materials. Curr Nanosci 17. https://doi.org/10.2174/1573413717666210208183349
30. Li B, Zhou J, Zhou X, Wang X, Li B, Santoro C, Grattieri M, Babanova S, Artyushkova K, Atanassov P, Schuler AJ (2014) Surface modification of microbial fuel cells anodes: approaches to practical design. Electrochim Acta 134:116–126. https://doi.org/10.1016/j.electacta.2014.04.136

31. Fadzli FS, Rashid M, Yaqoob AA, Ibrahim MNM (2021) Electricity generation and heavy metal remediation by utilizing yam (Dioscorea alata) waste in benthic microbial fuel cells (BMFCs). Biochem Eng J 172:108067
32. Srivastava P, Yadav AK, Mishra BK (2015) The effects of microbial fuel cell integration into constructed wetland on the performance of constructed wetland. Bioresour Technol 195:223–230. https://doi.org/10.1016/j.biortech.2015.05.072
33. Wang K, Liu Y, Chen S (2011) Improved microbial electrocatalysis with neutral red immobilized electrode. J Power Sour 196:164–168. https://doi.org/10.1016/j.jpowsour.2010.06.056
34. Borsje C, Liu D, Sleutels THJA, Buisman CJN, ter Heijne A (2016) Performance of single carbon granules as perspective for larger scale capacitive bioanodes. J Power Sour 325:690–696. https://doi.org/10.1016/j.jpowsour.2016.06.092
35. Yaqoob AA, Ibrahim MNM, Yaakop AS, Ahmad A (2021) Application of microbial fuel cells energized by oil palm trunk sap (OPTS) to remove the toxic metal from synthetic wastewater with generation of electricity. App Nanosci 11:1949–1961
36. Sonawane JM, Yadav A, Ghosh PC, Adeloju SB (2017) Recent advances in the development and utilization of modern anode materials for high performance microbial fuel cells. Biosens Bioelectron 90:558–576. https://doi.org/10.1016/j.bios.2016.10.014
37. Sokol NW, Bradford MA (2019) Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nat Geosci 12:46–53. https://doi.org/10.1038/S41561-018-0258-6
38. Li F, Sharma Y, Lei Y, Li B, Zhou Q, Li F, Zhou Q, Sharma Y, Li B, Lei Y (2010) Microbial fuel cells: the effects of configurations, electrolyte solutions, and electrode materials on power generation. Appl Biochem Biotechnol 160:168–181. https://doi.org/10.1007/s12010-008-8516-5
39. Zhao F, Rahunen N, Varcoe JR, Chandra A, Avignone-Rossa C, Thumser AE, Slade RCT (2008) Activated carbon cloth as anode for sulfate removal in a microbial fuel cell. Environ Sci Technol 42:4971–4976. https://doi.org/10.1021/es8003766
40. Wang X-D, Xu Y-F, Rao H-S, Xu W-J, Chen H-Y, Zhang W-X, Kuang D-B, Su C-Y (2016) Novel porous molybdenum tungsten phosphide hybrid nanosheets on carbon cloth for efficient hydrogen evolution. Energy Environ Sci 9:1468–1475. https://doi.org/10.1039/C5EE03801D
41. Yaqoob AA, Ibrahim MNM, Ahmad A, Khatoon A, Setapar SH (2021) Polyaniline-based materials for supercapacitors. Handbook of supercapacitor materials: synthesis, characterization, and applications 1:113–130
42. Bhamare YM, Koinkar P, Furube A, More MA (2019) Femtosecond transient absorption spectroscopy of laser-ablated graphite and reduced graphene oxide for optical switching behavior. Opt Mater X 2:100026. https://doi.org/10.1016/j.omx.2019.100026
43. Ren Z, Meng N, Shehzad K, Xu Y, Qu S, Yu B, Luo J (2015) Mechanical properties of nickel-graphene composites synthesized by electrochemical deposition. Nanotechnology 26(6):65706
44. ter Heijne A, Hamelers HVM, Saakes M, Buisman CJN (2008) Performance of non-porous graphite and titanium-based anodes in microbial fuel cells. Electrochim Acta 53:5697–5703. https://doi.org/10.1016/j.electacta.2008.03.032
45. Lowy DA, Tender LM, Zeikus JG, Park DH, Lovley DR (2006) Harvesting energy from the marine sediment-water interface II. Kinetic activity of anode materials. BiosensBioelectron 21: 2058–2063. https://doi.org/10.1016/j.bios.2006.01.033
46. Yazdi AA, D'Angelo L, Omer N, Windiasti G, Lu X, Xu J (2016) Carbon nanotube modification of microbial fuel cell electrodes. Biosens Bioelectron 85:536–552. https://doi.org/10.1016/j.bios.2016.05.033
47. Zhang C, Liang P, Yang X, Jiang Y, Bian Y, Chen C, Zhang X, Huang X (2016) Binder-free graphene and manganese oxide coated carbon felt anode for high-performance microbial fuel cell. Biosens Bioelectron 81:32–38. https://doi.org/10.1016/j.bios.2016.02.051
48. Sun H, Xu S, Zhuang G, Zhuang X (2016) Performance and recent improvement in microbial fuel cells for simultaneous carbon and nitrogen removal: a review. J Environ Sci (China) 39:242–248. https://doi.org/10.1016/j.jes.2015.12.006

49. Sonu K (2017) Generation of bio-electricity from sewage sludge using single chamber microbial fuel cell. J Environ Sci Public Heal 01:68–74. https://doi.org/10.26502/jesph.9612007
50. Guo X, Zhan Y, Chen C, Cai B, Wang Y, Guo S (2016) Influence of packing material characteristics on the performance of microbial fuel cells using petroleum refinery wastewater as fuel. Renew Energy 87:437–444. https://doi.org/10.1016/j.renene.2015.10.041
51. Yasri NG, Nakhla G (2016) Electrochemical behavior of anode-respiring bacteria on doped carbon electrodes. ACS Appl Mater Interfaces 8:35150–35162. https://doi.org/10.1021/acsami.6b09907
52. Bhanvase BA, Shende TP, Sonawane SH (2016) Environmental technology reviews a review on graphene-TiO_2 and doped graphene-TiO_2 nanocomposite photocatalyst for water and wastewater treatment) a review on graphene-TiO_2 and doped graphene-TiO_2 nanocomposite photocatalyst for water and wastewater treatment. Environ Technol Rev 6:1–14. https://doi.org/10.1080/21622515.2016.1264489
53. Agnoli S, Favaro M (2016) Doping graphene with boron: a review of synthesis methods, physicochemical characterization, and emerging applications. J Mater Chem A 4:5002–5025. https://doi.org/10.1039/C5TA10599D
54. Tan RKL, Reeves SP, Hashemi N, Thomas DG, Kavak E, Montazami R, Hashemi NN (2017) Graphene as a flexible electrode: review of fabrication approaches. J Mater Chem A 5:17777–17803. https://doi.org/10.1039/C7TA05759H
55. Deng Y, Fang C, Chen G (2016) The developments of SnO_2/graphene nanocomposites as anode materials for high performance lithium ion batteries: a review. J Power Sour 304:81–101. https://doi.org/10.1016/j.jpowsour.2015.11.017
56. Gao Y (2012) Graphene and polymer composites for supercapacitor applications: a review. https://doi.org/10.1186/s11671-017-2150-5
57. Zhou G, Li L, Ma C, Wang S, Shi Y, Koratkar N, Ren W, Li F, Cheng HM (2015) A graphene foam electrode with high sulfur loading for flexible and high energy Li-S batteries. Nano Energy 11:356–365. https://doi.org/10.1016/j.nanoen.2014.11.025
58. Li F, Chen L, Knowles GP, Macfarlane DR, Zhang J (n.d.) Electrocatalysis hierarchical mesoporous SnO_2 nanosheets on carbon cloth: a robust and flexible electrocatalyst for CO_2 reduction with high efficiency and selectivity. https://doi.org/10.1002/ange.201608279
59. Hussain RT, Islam AKMS, Khairuddean M, Suah FBM (2021) A polypyrrole/GO/ZnO nanocomposite modified pencil graphite electrode for the determination of andrographolide in aqueous samples. Alex Eng J. https://doi.org/10.1016/j.aej.2021.09.040
60. Slate AJ, Whitehead KA, Brownson DAC, Banks CE (2019) Microbial fuel cells: an overview of current technology. Renew Sustain Energy Rev 101:60–81. https://doi.org/10.1016/j.rser.2018.09.044
61. Kanwal A, Yaqoob AA, Siddique A, Bhawani SA, Ibrahim MNM, Umar K (2021) Hybrid nanocomposites based on graphene and its derivatives: from preparation to applications. In: Graphene and nanoparticles hybrid nanocomposites: from preparation to applications, p 261
62. Cheng Y, Mallavarapu M, Naidu R, Chen Z (2018) In situ fabrication of green reduced graphene-based biocompatible anode for efficient energy recycle. Chemosphere 193:618–624. https://doi.org/10.1016/j.chemosphere.2017.11.057
63. Singh S, Bairagi P, Verma N (2018) Candle soot-derived carbon nanoparticles: an inexpensive and efficient electrode for microbial fuel cells. Electrochim Acta 264:119–127. https://doi.org/10.1016/j.electacta.2018.01.110
64. Bose D, Sridharan S, Dhawan H, Vijay P, Gopinath M (2019) Biomass derived activated carbon cathode performance for sustainable power generation from microbial fuel cells. Fuel 236:325–337. https://doi.org/10.1016/j.fuel.2018.09.002
65. Hung Y-H, Liu T-Y, Chen H-Y (2019) Renewable coffee waste-derived porous carbons as anode materials for high-performance sustainable microbial fuel cells. ACS Sustain Chem Eng 7:16991–16999. https://doi.org/10.1021/acssuschemeng.9b02405
66. Chang WT, Chao YH, Li CW, Lin KL, Wang JJ, Kumar SR, Lue SJ (2019) Graphene oxide synthesis using microwave-assisted versus modified Hummer's methods: efficient fillers for

improved ionic conductivity and suppressed methanol permeability in alkaline methanol fuel cell electrolytes. J Power Sour 414:86–95. https://doi.org/10.1016/j.jpowsour.2018.12.020

67. Tang J, Yuan Y, Liu T, Zhou S (2015) High-capacity carbon-coated titanium dioxide core-shell nanoparticles modified three dimensional anodes for improved energy output in microbial fuel cells. J Power Sour 274:170–176. https://doi.org/10.1016/j.jpowsour.2014.10.035
68. Chen S, Tang J, Jing X, Liu Y, Yuan Y, Zhou S (2016) A hierarchically structured urchin-like anode derived from chestnut shells for microbial energy harvesting. Electrochim Acta 212:883–889. https://doi.org/10.1016/j.electacta.2016.07.077
69. Yuan Y, Liu T, Fu P, Tang J, Zhou S (2015) Conversion of sewage sludge into high-performance bifunctional electrode materials for microbial energy harvesting. J Mater Chem A 3:8475–8482. https://doi.org/10.1039/C5TA00458F
70. Li D, Deng L, Yuan H, Dong G, Chen J, Zhang X, Chen Y, Yuan Y (2018) N, P-doped mesoporous carbon from onion as trifunctional metal-free electrode modifier for enhanced power performance and capacitive manner of microbial fuel cells. Electrochim Acta 262:297–305. https://doi.org/10.1016/j.electacta.2017.12.164
71. Li F, Chen L, Knowles GP, MacFarlane DR, Zhang J (2017) Hierarchical mesoporous SnO_2 nanosheets on carbon cloth: a robust and flexible electrocatalyst for CO_2 reduction with high efficiency and selectivity. Angew Chem Int Ed 56:505–509. https://doi.org/10.1002/anie.201608279
72. Tang J, Chen S, Yuan Y, Cai X, Zhou S (n.d.) In situ formation of graphene layers on graphite surfaces for efficient anodes of microbial fuel cells. https://doi.org/10.1016/j.bios.2015.04.074
73. Huggins T, Wang H, Kearns J, Jenkins P, Ren ZJ (2014) Biochar as a sustainable electrode material for electricity production in microbial fuel cells. Bioresour Technol 157:114–119. https://doi.org/10.1016/j.biortech.2014.01.058
74. Zhang J, Li J, Ye D, Zhu X, Liao Q, Zhang B (2014) Tubular bamboo charcoal for anode in microbial fuel cells. J Power Sour 272:277–282. https://doi.org/10.1016/j.jpowsour.2014.08.115
75. Chen S, He G, Hu X, Xie M, Wang S, Zeng D, Hou H, Schröder U (2012) A three-dimensionally ordered macroporous carbon derived from a natural resource as anode for microbial bioelectrochemical systems. Chemsuschem 5:1059–1063. https://doi.org/10.1002/cssc.201100783
76. Yaqoob AA, Parveen T, Umar K, Nasir M, Ibrahim M (n.d.) Role of nanomaterials in the treatment of wastewater: a review. https://doi.org/10.3390/w12020495
77. Nitisoravut R, Thanh CND, Regmi R (2017) Microbial fuel cells: advances in electrode modifications for improvement of system performance microbial fuel cells: advances in electrode modifications for improvement of system performance. Int J Green Energy. https://doi.org/10.1080/15435075.2017.1326049
78. Erable B, Byrne N, Etcheverry L, Achouak W, Bergel A (2017) Single medium microbial fuel cell: stainless steel and graphite electrode materials select bacterial communities resulting in opposite electrocatalytic activities. Int J Hydrog Energy 42:26059–26067. https://doi.org/10.1016/j.ijhydene.2017.08.178
79. Santoro C, Arbizzani C, Erable B, Ieropoulos I (2017) Microbial fuel cells: from fundamentals to applications. A review. J Power Sour 356:225–244. https://doi.org/10.1016/j.jpowsour.2017.03.109
80. Torabiyan A, Nabi Bidhendi GR, Mehrdadi N, Javadi K (2014) Application of nano-electrode platinum (Pt) and nano-wire titanium (Ti) for increasing electrical energy generation in microbial fuel cells of synthetic wastewater with carbon source (Acetate). Int J Environ Res 8:453–460
81. Stariha S, Artyushkova K, Serov A, Atanassov P (2015) Non-PGM membrane electrode assemblies: optimization for performance. Int J Hydrog Energy 40:14676–14682. https://doi.org/10.1016/j.ijhydene.2015.05.185
82. Füeg M, Borjas Z, Estevez-Canales M, Esteve-Núñez A, Pobelov IV, Broekmann P, Kuzume A (2019) Interfacial electron transfer between Geobacter sulfurreducens and gold electrodes via carboxylate-alkanethiol linkers: effects of the linker length. Bioelectrochemistry 126:130–136. https://doi.org/10.1016/j.bioelechem.2018.11.013

83. Kaur G, Adhikari R, Cass P, Bown M, Gunatillake P (2015) Electrically conductive polymers and composites for biomedical applications. https://doi.org/10.1039/c5ra01851j
84. Shi Y, Ma C, Peng L, Yu G, Shi Y, Ma C, Peng L, Yu G (2015) Conductive "Smart" hybrid hydrogels with PNIPAM and nanostructured conductive polymers. https://doi.org/10.1002/adfm.201404247
85. Yaqoob AA, Umar K, Adnan R, Ibrahim MNM, Rashid M (2021) Graphene oxide–ZnO nanocomposite: an efficient visible light photocatalyst for degradation of rhodamine B. App Nanosci 11:1291–1302
86. Shahadat M, Bushra R, Khan MR, Rafatullah M, Teng TT (2014) A comparative study for the characterization of polyaniline based nanocomposites and membrane properties. RSC Adv 4:20686–20692. https://doi.org/10.1039/C4RA01040J
87. Phoon BL, Lai CW, Juan JC, Show P-L, Chen W-H (2019) A review of synthesis and morphology of $SrTiO_3$ for energy and other applications. Int J Energy Res 43:5151–5174. https://doi.org/10.1002/er.4505
88. Gnana kumar G, Kirubaharan CJ, Udhayakumar S, Ramachandran K, Karthikeyan C, Renganathan R, Nahm KS (2014) Synthesis, structural, and morphological characterizations of reduced graphene oxide-supported polypyrrole anode catalysts for improved microbial fuel cell performances. ACS Sustain Chem Eng 2:2283–2290. https://doi.org/10.1021/sc500244f
89. Dumitru A, Vulpe S, Radu A, Antohe S (2018) Influence of nitrogen environment on the performance of conducting polymers/CNTs nanocomposites modified anodes for microbial fuel cells (MFCs). Rom J Phys 63:10–15
90. Ates M, Eker AA, Eker B (2017) Carbon nanotube-based nanocomposites and their applications. J Adhes Sci Technol 31:1977–1997. https://doi.org/10.1080/01694243.2017.1295625
91. Larouche F, Tedjar F, Amouzegar K, Houlachi G, Bouchard P, Demopoulos GP, Zaghib K (2020) Progress and status of hydrometallurgical and direct recycling of Li-Ion batteries and beyond. Materials (Basel) 13. https://doi.org/10.3390/ma13030801
92. Li Z, Gong L (n.d.) Materials review research progress on applications of polyaniline (PANI) for electrochemical energy storage and conversion. https://doi.org/10.3390/ma13030548
93. Chen Y-M, Wang C-T, Yang Y-C, Chen W-J (2013) Application of aluminum-alloy mesh composite carbon cloth for the design of anode/cathode electrodes in Escherichia coli microbial fuel cell. Int J Hydrog Energy 38:11131–11137. https://doi.org/10.1016/j.ijhydene.2013.01.010
94. Yaqoob AA, Ibrahim MNM, Ahmad A, Reddy AVB (2020) Toxicology and environmental application of carbon nanocomposite. In: Environmental remediation through carbon based nanocomposites. Green Energy and Technology; Springer, Singapore
95. Chen S, Patil SA, Brown RK, Schröder U (2019) Strategies for optimizing the power output of microbial fuel cells: transitioning from fundamental studies to practical implementation. Appl Energy 233–234:15–28. https://doi.org/10.1016/j.apenergy.2018.10.015
96. Shi J-L, Qi R, Zhang X-D, Wang P-F, Fu W-G, Yin Y-X, Xu J, Wan L-J, Guo Y-G (2017) High-thermal- and air-stability cathode material with concentration-gradient buffer for Li-Ion batteries. ACS Appl Mater Interfaces 9:42829–42835. https://doi.org/10.1021/acsami.7b14684
97. Deng Q, Li X, Zuo J, Ling A, Logan B (2010) Power generation using an activated carbon fiber cathode in an upflow microbial fuel cell. J Power Sour 195:1130–1135. https://doi.org/10.1016/j.jpowsour.2009.08.092
98. Yaqoob AA, Noor M, Serrà A, Ibrahim MNM (2020) Advances and challenges in developing efficient graphene oxide-based ZnO photocatalysts for dye photo-oxidation. Nanomaterial 10:932
99. Ghasemi M, Ismail M, Kamarudin SK, Saeedfar K, Daud WRW, Hassan SHA, Heng LY, Alam J, Oh SE (2013) Carbon nanotube as an alternative cathode support and catalyst for microbial fuel cells. Appl Energy 102:1050–1056. https://doi.org/10.1016/j.apenergy.2012.06.003

100. Osgood H, Devaguptapu SV, Xu H, Cho J, Wu G (2016) Transition metal (Fe Co, Ni, and Mn) oxides for oxygen reduction and evolution bifunctional catalysts in alkaline media. Nano Today 11:601–625. https://doi.org/10.1016/j.nantod.2016.09.001
101. Huang L, Li X, Ren Y, Wang X (n.d.) A monolithic three-dimensional macroporous graphene anode with low cost for high performance of microbial fuel cell
102. Akbari E, Buntat Z (2017) Benefits of using carbon nanotubes in fuel cells: a review. Int J Energy Res 41:92–102. https://doi.org/10.1002/er.3600
103. Zhao C, Gai P, Liu C, Wang X, Xu H, Zhang J, Zhu J-J (2013) Polyaniline networks grown on graphene nanoribbons-coated carbon paper with a synergistic effect for high-performance microbial fuel cells. J Mater Chem A 1:12587–12594. https://doi.org/10.1039/C3TA12947K
104. Chen J, Deng F, Hu Y, Sun J, Yang Y (2015) Antibacterial activity of graphene-modified anode on Shewanella oneidensis MR-1 biofilm in microbial fuel cell. J Power Sour 290:80–86
105. Zhao C, Wang Y, Shi F, Zhang J, Zhu JJ (2013) High biocurrent generation in shewanella-inoculated microbial fuel cells using ionic liquid functionalized graphene nanosheets as an anode. Chem Commun 49:6668–6670. https://doi.org/10.1039/c3cc42068j
106. Iigatani R, Ito T, Watanabe F, Nagamine M, Suzuki Y, Inoue K (2019) Electricity generation from sweet potato-shochu waste using microbial fuel cells. J Biosci Bioeng 128:56–63. https://doi.org/10.1016/j.jbiosc.2018.12.015
107. Ma M, You S, Gong X, Dai Y, Zou J, Fu H (2015) Silver/iron oxide/graphitic carbon composites as bacteriostatic catalysts for enhancing oxygen reduction in microbial fuel cells. J Power Sour 283:74–83. https://doi.org/10.1016/j.jpowsour.2015.02.100
108. Zhang F, Cheng S, Pant D, Van Bogaert G, Logan BE (2009) Power generation using an activated carbon and metal mesh cathode in a microbial fuel cell. Electrochem Commun 11:2177–2179. https://doi.org/10.1016/j.elecom.2009.09.024
109. Zhao L, Deng J, Hou H, Li J, Yang Y (n.d.) Investigation of PAH and oil degradation along with electricity generation in soil using an enhanced plant-microbial fuel cell. J Clean Prod 221
110. Wang Y, Chen Y, Wen Q (2018) Microbial fuel cells: enhancement with a polyaniline/carbon felt capacitive bioanode and reduction of Cr(VI) using the intermittent operation. Environ Chem Lett 16:319–326. https://doi.org/10.1007/s10311-017-0678-3
111. Antolini E (2018) Photo-assisted methanol oxidation on Pt-TiO_2 catalysts for direct methanol fuel cells: a short review. Appl Catal B Environ 237:491–503. https://doi.org/10.1016/j.apcatb.2018.06.029
112. Mitov M, Chorbadzhiyska E, Rashkov R, Hubenova Y (2012) Novel nanostructured electrocatalysts for hydrogen evolution reaction in neutral and weak acidic solutions. Int J Hydrog Energy 37:16522–16526. https://doi.org/10.1016/j.ijhydene.2012.02.102
113. Behera M, Jana PS, Ghangrekar MM (2010) Performance evaluation of low cost microbial fuel cell fabricated using earthen pot with biotic and abiotic cathode. Bioresour Technol 101:1183–1189. https://doi.org/10.1016/j.biortech.2009.07.089
114. Daud NN, Ahmad A, Yaqoob AA, Ibrahim MNM (2021) Application of rotten rice as a substrate for bacterial species to generate energy and the removal of toxic metals from wastewater through microbial fuel cells. Environ Sci Pollut Res 28:62816–62827
115. Hou B, Lu J, Wang H, Li Y, Liu P, Liu Y, Chen J (2019) Performance of microbial fuel cells based on the operational parameters of biocathode during simultaneous Congo red decolorization and electricity generation. Bioelectrochemistry 128:291–297. https://doi.org/10.1016/j.bioelechem.2019.04.019
116. Wang X, Cheng S, Feng Y, Merrill MD, Saito T, Logan BE (2009) Use of carbon mesh anodes and the effect of different pretreatment methods on power production in microbial fuel cells. Environ Sci Technol 43:6870–6874. https://doi.org/10.1021/es900997w
117. Cheng S, Liu H, Logan BE (2006) Increased performance of single-chamber microbial fuel cells using an improved cathode structure. ElectrochemCommun 8:489–494. https://doi.org/10.1016/j.elecom.2006.01.010
118. Logan BE, Murano C, Scott K, Gray ND, Head IM (2005) Electricity generation from cysteine in a microbial fuel cell. Water Res 39:942–952. https://doi.org/10.1016/j.watres.2004.11.019

119. Clauwaert P, Rabaey K, Aelterman P, De Schamphelaire L, Pham TH, Boeckx P, Boon N, Verstraete W (2007) Biological denitrification in microbial fuel cells. Environ Sci Technol 41:3354–3360. https://doi.org/10.1021/es062580r
120. Clauwaert P, Van der Ha D, Boon N, Verbeken K, Verhaege M, Rabaey K, Verstraete W (2007) Open air biocathode enables effective electricity generation with microbial fuel cells. Environ Sci Technol 41:7564–7569. https://doi.org/10.1021/es0709831
121. You S-J, Ren N-Q, Zhao Q-L, Wang J-Y, Yang F-L (2009) Power generation and electrochemical analysis of biocathode microbial fuel cell using graphite fibre brush as cathode material. https://doi.org/10.1002/fuce.200900023
122. Qiao Y, Wen G-Y, Wu X-S, Zou L (2015) l-Cysteine tailored porous graphene aerogel for enhanced power generation in microbial fuel cells. RSC Adv 5:58921–58927. https://doi.org/10.1039/C5RA09170E
123. Najafabadi AT, Ng N, Gyenge E (2016) Electrochemically exfoliated graphene anodes with enhanced biocurrent production in single-chamber air-breathing microbial fuel cells. Biosens Bioelectron 81:103–110. https://doi.org/10.1016/j.bios.2016.02.054
124. Xiao L, Damien J, Luo J, Jang HD, Huang J, He Z (2012) Crumpled graphene particles for microbial fuel cell electrodes. J Power Sour 208:187–192. https://doi.org/10.1016/j.jpowsour.2012.02.036
125. Tsai H-Y, Wu C-C, Lee C-Y, Shih EP (2009) Microbial fuel cell performance of multiwall carbon nanotubes on carbon cloth as electrodes. J Power Sour 194:199–205. https://doi.org/10.1016/j.jpowsour.2009.05.018
126. Kumar GG, Hashmi S, Karthikeyan C, GhavamiNejad A, Vatankhah-Varnoosfaderani M, Stadler FJ (2014) Graphene oxide/carbon nanotube composite hydrogels—Versatile materials for microbial fuel cell applications. Macromol Rapid Commun 35:1861–1865. https://doi.org/10.1002/marc.201400332
127. Hassan SHA, Kim YS, Oh SE (2012) Power generation from cellulose using mixed and pure cultures of cellulose-degrading bacteria in a microbial fuel cell. Enzyme Microb Technol 51:269–273. https://doi.org/10.1016/j.enzmictec.2012.07.008
128. Yang W, Kim K-Y, Saikaly PE, Logan BE (2017) The impact of new cathode materials relative to baseline performance of microbial fuel cells all with the same architecture and solution chemistry. Energy Environ Sci 10:1025–1033. https://doi.org/10.1039/C7EE00910K
129. Yuan Y, Zhou S, Zhao B, Zhuang L, Wang Y (2012) Microbially-reduced graphene scaffolds to facilitate extracellular electron transfer in microbial fuel cells. Bioresour Technol 116:453–458. https://doi.org/10.1016/j.biortech.2012.03.118
130. Choi C, Cui Y (2012) Recovery of silver from wastewater coupled with power generation using a microbial fuel cell. Bioresour Technol 107:522–525. https://doi.org/10.1016/j.biortech.2011.12.058
131. Santoro C, Gokhale R, Mecheri B, Licoccia S, Serov A, Rtyushkova K, Atanassov A (n.d.) Design of Iron(II) phthalocyanine-derived oxygen reduction electrocatalysts for high-power-density microbial fuel cells. www.chemsuschem.org
132. Liu J, Qiao Y, Guo CX, Lim S, Song H, Li CM (2012) Graphene/carbon cloth anode for high-performance mediatorless microbial fuel cells. Bioresour Technol 114:275–280. https://doi.org/10.1016/j.biortech.2012.02.116
133. Guo W, Cui Y, Song H, Sun J (2014) Layer-by-layer construction of graphene-based microbial fuel cell for improved power generation and methyl orange removal. Bioprocess Biosyst Eng 37:1749–1758. https://doi.org/10.1007/s00449-014-1148-y
134. Lv Z, Chen Y, Wei H, Li F, Hu Y, Wei C, Feng C (2013) One-step electrosynthesis of polypyrrole/graphene oxide composites for microbial fuel cell application. Electrochim Acta 111:366–373. https://doi.org/10.1016/j.electacta.2013.08.022
135. Zou L, Qiao Y, Wu XS, Ma CX, Li X, Li CM (2015) Synergistic effect of titanium dioxide nanocrystal/reduced graphene oxide hybrid on enhancement of microbial electrocatalysis. J Power Sour 276:208–214. https://doi.org/10.1016/j.jpowsour.2014.11.127
136. Zhao C, Gai P, Song R, Zhang J, Zhu J-J (2015) Graphene/Au composites as an anode modifier for improving electricity generation in Shewanella-inoculated microbial fuel cells. Anal Methods 7:4640–4644. https://doi.org/10.1039/C5AY00976F

137. Dewan A, Beyenal H, Lewandowski Z (2008) Scaling up microbial fuel cells. Environ Sci Technol 42:7643–7648. https://doi.org/10.1021/es800775d
138. Guan YF, Zhang F, Huang BC, Yu HQ (2019) Enhancing electricity generation of microbial fuel cell for wastewater treatment using nitrogen-doped carbon dots-supported carbon paper anode. J Clean Prod 229:412–419. https://doi.org/10.1016/j.jclepro.2019.05.040
139. Yong Y-C, Dong X-C, Chan-Park MB, Song H, Chen P (2012) Macroporous and monolithic anode based on polyaniline hybridized three-dimensional graphene for high-performance microbial fuel cells. ACS Nano 6:2394–2400. https://doi.org/10.1021/nn204656d
140. Kirubaharan CJ, Santhakumar K, Kumar GG, Senthilkumar N, Jang J-H (2015) Nitrogen doped graphene sheets as metal free anode catalysts for the high performance microbial fuel cells. Int J Hydrog Energy 40:13061–13070
141. Mehdinia A, Ziaei E, Jabbari A (2014) Facile microwave-assisted synthesized reduced graphene oxide/tin oxide nanocomposite and using as anode material of microbial fuel cell to improve power generation. Int J Hydrog Energy 39:10724–10730. https://doi.org/10.1016/j.ijhydene.2014.05.008
142. Zhang B-G, Zhou S-G, Zhao H-Z, Shi C-H, Kong L-C, Sun J-J, Yang Y, Ni J-R (2010) Factors affecting the performance of microbial fuel cells for sulfide and vanadium (V) treatment. Bioprocess Biosyst Eng 33:187–194. https://doi.org/10.1007/s00449-009-0312-2
143. Benetton XD, Navarro-Ávila SG, Carrera-Figueiras C (2010) Electrochemical evaluation of Ti/TiO_2-polyaniline anodes for microbial fuel cells using hypersaline microbial consortia for synthetic-wastewater treatment. J New Mater Electrochem Syst 13:1–6. https://doi.org/10.14447/jnmes.v13i1.184
144. Dumas C, Mollica A, Féron D, Basséguy R, Etcheverry L, Bergel A (2007) Marine microbial fuel cell: use of stainless steel electrodes as anode and cathode materials. Electrochim Acta 53:468–473. https://doi.org/10.1016/j.electacta.2007.06.069
145. Dominguez-Benetton X, Srikanth S, Satyawali Y, Vanbroekhoven K, Pant D (2013) Enzymatic electrosynthesis: an overview on the progress in enzyme-electrodes for the production of electricity, fuels and chemicals. J MicrobBiochem Technol 5. https://doi.org/10.4172/1948-5948.s6-007
146. Michaelidou U, Ter Heijne A, Euverink GJW, Hamelers HVM, Stams AJM, Geelhoed JS (2011) Microbial communities and electrochemical performance of titanium-based anodic electrodes in a microbial fuel cell. Appl Environ Microbiol 77:1069–1075. https://doi.org/10.1128/AEM.02912-09
147. Hou J, Liu Z, Zhang P (2013) A new method for fabrication of graphene/polyaniline nanocomplex modified microbial fuel cell anodes. J Power Sour 224:139–144. https://doi.org/10.1016/j.jpowsour.2012.09.091
148. Jiang D, Li B (2009) Novel electrode materials to enhance the bacterial adhesion and increase the power generation in microbial fuel cells (MFCs). Water Sci Technol 59:557–563. https://doi.org/10.2166/wst.2009.007
149. Nourbakhsh F, Mohsennia M, Pazouki M (2017) Nickel oxide/carbon nanotube/polyaniline nanocomposite as bifunctional anode catalyst for high-performance Shewanella-based dual-chamber microbial fuel cell. Bioprocess Biosyst Eng 40:1669–1677. https://doi.org/10.1007/s00449-017-1822-y
150. Pareek A, Sravan JS, Mohan SV (2019) Fabrication of three-dimensional graphene anode for augmenting performance in microbial fuel cells. Carbon Resour Convers 2:134–140. https://doi.org/10.1016/j.crcon.2019.06.003
151. Nancharaiah YV, Mohan SV, Lens PNL (2015) Metals removal and recovery in bioelectrochemical systems: a review. Bioresour Technol 195:102–114. https://doi.org/10.1016/j.biortech.2015.06.058
152. Abbas SZ, Rafatullah M, Ismail N, Lalung J (2014) Isolation, identification, characterization, and evaluation of cadmium removal capacity of enterobacter species. J Basic Microbiol 54:1279–1287. https://doi.org/10.1002/jobm.201400157
153. Abbas SZ, Rafatullah M, Ismail N, Nastro RA (2017) Enhanced bioremediation of toxic metals and harvesting electricity through sediment microbial fuel cell. Int J Energy Res 41:2345–2355. https://doi.org/10.1002/er.3804

154. Zhang B, Feng C, Ni J, Zhang J, Huang W (2012) Simultaneous reduction of vanadium (V) and chromium (VI) with enhanced energy recovery based on microbial fuel cell technology. J Power Sour 204:34–39. https://doi.org/10.1016/j.jpowsour.2012.01.013
155. Qiu R, Zhang B, Li J, Lv Q, Wang S, Gu Q (2017) Enhanced vanadium (V) reduction and bioelectricity generation in microbial fuel cells with biocathode. https://doi.org/10.1016/j.jpowsour.2017.05.099
156. Jiang Y, Ulrich AC, Liu Y (2013) Coupling bioelectricity generation and oil sands tailings treatment using microbial fuel cells. Bioresour Technol 139:349–354. https://doi.org/10.1016/j.biortech.2013.04.050
157. Habibul N, Hu Y, Sheng GP (2016) Microbial fuel cell driving electrokinetic remediation of toxic metal contaminated soils. J Hazard Mater 318:9–14. https://doi.org/10.1016/j.jhazmat.2016.06.041
158. Fang Z, Song HL, Cang N, Li XN (2015) Electricity production from Azo dye wastewater using a microbial fuel cell coupled constructed wetland operating under different operating conditions. Biosens Bioelectron 68:135–141. https://doi.org/10.1016/j.bios.2014.12.047
159. Kawale HD, Ranveer AC, Chavan AR (2017) Electricity generation from wastewater using a microbial fuel cell by using mixed bacterial culture. J Biochem Technol 7:1123–1127
160. Kabutey FT, Ding J, Zhao Q, Antwi P, Quashie FK, Tankapa V, Zhang W (2019) Pollutant removal and bioelectricity generation from urban river sediment using a macrophyte cathode sediment microbial fuel cell (mSMFC). Bioelectrochemistry 128:241–251. https://doi.org/10.1016/j.bioelechem.2019.01.007
161. Marks S, Makinia J, Fernandez-Morales FJ (2019) Performance of microbial fuel cells operated under anoxic conditions. Appl Energy 250:1–6. https://doi.org/10.1016/j.apenergy.2019.05.043
162. Abbas SZ, Rafatullah M, Ismail N, Syakir MI (2017) A review on sediment microbial fuel cells as a new source of sustainable energy and heavy metal remediation: mechanisms and future prospective. Int J Energy Res 41:1242–1264. https://doi.org/10.1002/er.3706
163. Chuo SC, Mohamed SF, Setapar SHM, Ahmad A, Jawaid M, Wani WA, Yaqoob AA, Ibrahim MNM (2020) Insights into the current trends in the utilization of bacteria for microbially induced calcium carbonate precipitation. Material 13:4993
164. Abbas SZ, Rafatullah M, Ismail N, Syakir M (2018) The behaviour of membrane less sediment microbial fuel cell in the terms of bioremediation and power generation
165. Yang W, Ogan BL (n.d.) Immobilization of a metal-nitrogen-carbon catalyston activated carbon with enhanced cathode performance in microbial fuel cells. https://doi.org/10.1002/cssc.201600573
166. Liu Y, Fan YS, Liu ZM (2019) Pyrolysis of iron phthalocyanine on activated carbon as highly efficient non-noble metal oxygen reduction catalyst in microbial fuel cells. Chem Eng J 361:416–427. https://doi.org/10.1016/j.cej.2018.12.105
167. Nguyen D-T, Taguchi K (2019) A disposable water-activated paper-based MFC using dry E. coli biofilm. BiochemEng J 143:161–168
168. Zhang Y, Mo G, Li X, Zhang W, Zhang J, Ye J, Huang X, Yu C (2011) A graphene modified anode to improve the performance of microbial fuel cells. J Power Sour 196:5402–5407. https://doi.org/10.1016/j.jpowsour.2011.02.067
169. Yang Y, Lin E, Sun S, Chen H, Chow A (2019) Direct electricity production from subaqueous wetland sediments and banana peels using membrane-less microbial fuel cells. Ind Crops Prod 128:70–79
170. Abourached C, Catal T, Liu H (2014) Efficacy of single-chamber microbial fuel cells for removal of cadmium and zinc with simultaneous electricity production. Water Res 51:228–233. https://doi.org/10.1016/j.watres.2013.10.062
171. Wang Z, Zhang B, Jiang Y, Li Y, He C (2018) Spontaneous thallium (I) oxidation with electricity generation in single-chamber microbial fuel cells. Appl Energy 209:33–42. https://doi.org/10.1016/j.apenergy.2017.10.075
172. Tao HC, Li W, Liang M, Xu N, Ni JR, Wu WM (2011) A membrane-free baffled microbial fuel cell for cathodic reduction of Cu(II) with electricity generation. Bioresour Technol 102:4774–4778. https://doi.org/10.1016/j.biortech.2011.01.057

173. Yun-Hai W, Bai-Shi W, Bin P, Qing-Yun C, Wei Y (2013) Electricity production from a bio-electrochemical cell for silver recovery in alkaline media. Appl Energy 112:1337–1341. https://doi.org/10.1016/j.apenergy.2013.01.012
174. Singhvi P (2013) Simultaneous chromium removal and power generation using algal biomass in a dual chambered salt bridge microbial fuel cell. J BioremedBiodegrad 04. https://doi.org/10.4172/2155-6199.1000190
175. Tao HC, Liang M, Li W, Zhang LJ, Ni JR, Wu WM (2011) Removal of copper from aqueous solution by electrodeposition in cathode chamber of microbial fuel cell. J Hazard Mater 189:186–192. https://doi.org/10.1016/j.jhazmat.2011.02.018
176. Ryu EY, Kim M, Lee S-J (2011) Characterization of microbial fuel cells enriched using Cr(VI)-containing sludge. J Microbiol Biotechnol 21:187–191. https://doi.org/10.4014/jmb.1008.08019
177. Wu Y, Wang L, Jin M, Kong F, Qi H, Nan J (2019) Reduced graphene oxide and biofilms as cathode catalysts to enhance energy and metal recovery in microbial fuel cell. Bioresour Technol 283:129–137. https://doi.org/10.1016/j.biortech.2019.03.080
178. Xafenias N, Zhang Y, Banks CJ (2013) Enhanced performance of hexavalent chromium reducing cathodes in the presence of Shewanella oneidensis MR-1 and Lactate. Environ Sci Technol 47:4512–4520. https://doi.org/10.1021/es304606u
179. Choi C, Hu N (2013) The modeling of gold recovery from tetrachloroaurate wastewater using a microbial fuel cell. https://doi.org/10.1016/j.biortech.2013.01.143
180. Li F, Jin C, Choi C, Lim B (2019) Simultaneous removal and/or recovery of Cr(VI) and Cr(III) using a double MFC technique. Environ EngManag J 18:235–242. https://doi.org/10.30638/eemj.2019.023
181. Huang L, Li T, Liu C, Quan X, Chen L, Wang A, Chen G (2013) Synergetic interactions improve cobalt leaching from lithium cobalt oxide in microbial fuel cells. Bioresour Technol 128:539–546. https://doi.org/10.1016/j.biortech.2012.11.011
182. Chen B-Y, Wang Y-M, Ng I-S (2011) Understanding interactive characteristics of bioelectricity generation and reductive decolorization using Proteus hauseri. Bioresour Technol 102:1159–1165. https://doi.org/10.1016/j.biortech.2010.09.040
183. Solanki K, Subramanian S, Basu S (2013) Microbial fuel cells for azo dye treatment with electricity generation: a review. Bioresour Technol 131:564–571. https://doi.org/10.1016/j.biortech.2012.12.063
184. Li Z, Zhang X, Lin J, Han S, Lei L (2010) Azo dye treatment with simultaneous electricity production in an anaerobic-aerobic sequential reactor and microbial fuel cell coupled system. Bioresour Technol 101:4440–4445. https://doi.org/10.1016/j.biortech.2010.01.114
185. Liu Y, Song P, Gai R, Yan C, Jiao Y, Yin D, Cai L, Zhang L (2019) Recovering platinum from wastewater by charring biofilm of microbial fuel cells (MFCs). J Saudi Chem Soc 23:338–345. https://doi.org/10.1016/j.jscs.2018.08.003
186. Khan MZ, Singh S, Sultana S, Sreekrishnan TR, Ahammad SZ (2015) Studies on the biodegradation of two different azo dyes in bioelectrochemical systems. New J Chem 39:5597–5604. https://doi.org/10.1039/C5NJ00541H
187. Ding H, Li Y, Lu A, Jin S, Quan C, Wang C, Wang X, Zeng C, Yan Y (2010) Photocatalytically improved azo dye reduction in a microbial fuel cell with rutile-cathode. Bioresour Technol 101:3500–3505. https://doi.org/10.1016/j.biortech.2009.11.107
188. Mu Y, Rabaey K, Rozendal RA, Yuan Z, Keller J (2009) Decolorization of Azo dyes in bioelectrochemical systems. Environ Sci Technol 43:5137–5143. https://doi.org/10.1021/es900057f
189. Sun J, Bi Z, Hou B, Cao YQ, Hu YY (2011) Further treatment of decolorization liquid of azo dye coupled with increased power production using microbial fuel cell equipped with an aerobic biocathode. Water Res 45:283–291. https://doi.org/10.1016/j.watres.2010.07.059
190. Sun J, Li Y, Hu Y, Hou B, Xu Q, Zhang Y, Li S (n.d.) Enlargement of anode for enhanced simultaneous azo dye decolorization and power output in air-cathode microbial fuel cell. https://doi.org/10.1007/s10529-012-1002-8

191. Yu F, Wang C, Ma J (2016) Applications of graphene-modified electrodes in microbial fuel cells. Materials (Basel) 9. https://doi.org/10.3390/ma9100807
192. Oon YL, Ong SA, Ho LN, Wong YS, Dahalan FA, Oon YS, Lehl HK, Thung WE, Nordin N (2018) Up-flow constructed wetland-microbial fuel cell for azo dye, saline, nitrate remediation and bioelectricity generation: from waste to energy approach. Bioresour Technol 266:97–108. https://doi.org/10.1016/j.biortech.2018.06.035
193. Abbas SZ, Rafatullah M, Ismail N, Shakoori FR (2018) Electrochemistry and microbiology of microbial fuel cells treating marine sediments polluted with heavy metals. https://doi.org/10.1039/c8ra01711e
194. Kumar R, Singh L, Zularisam AW, Hai FI (2018) Microbial fuel cell is emerging as a versatile technology: a review on its possible applications, challenges and strategies to improve the performances. Int J Energy Res 42:369–394. https://doi.org/10.1002/er.3780
195. Zhou M, Chi M, Luo J, He H, Jin T (2011) An overview of electrode materials in microbial fuel cells. J Power Sour 196:4427–4435. https://doi.org/10.1016/j.jpowsour.2011.01.012
196. Do MH, Ngo HH, Guo WS, Liu Y, Chang SW, Nguyen DD, Nghiem LD, Ni BJ (2018) Challenges in the application of microbial fuel cells to wastewater treatment and energy production: a mini review. Sci Total Environ 639:910–920. https://doi.org/10.1016/j.scitotenv.2018.05.136