We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,200
Open access books available

169,000
International authors and editors

185M
Downloads

154
Countries delivered to

Our authors are among the
TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Microbial Fuel Cell Formulation from Nano-Composites

Fozia Anjum, Nadia Akram, Samreen Gul Khan, Naheed Akhter, Muhammad Shahid and Fatma Hussain

Abstract

Petroleum and oil industry is a rich source of nonrenewable energy that ultimately results in threatening of ecosystem due to emission of greenhouse gases into the environment. In the current panorama of the energy demand, industries focus on alternate and renewable energy resources to meet energy gaps. Thus, an expedient fuel cell based on microbes can be valued as an economical and eco-friendly substitute of energy generator. These microbial fuel cells have commercialized platinum electrodes to generate cost-effective energy after oxidation of organic wastes catalyzed by biocatalyst. Nowadays, conventional carbon electrode as an anode is taking popularity in microbial fuel cell but displays poor performance. So, to improve the chemistry of electrodes, nano-composites fabricated from polar polymeric material as well as cost-effective oxides of metals are the raw material. In this chapter, green synthesis of nano-composites from conducting polymers and oxides of transition metals has been discussed. Anode modification by composite to treat wastewater as well as its role to generate electricity has been discussed briefly.

Keywords: microbes, fuel cell, organic wastes, biocatalyst, transition metal oxides

1. Introduction

At present, the world is facing the crisis of energy as a result of overpopulation in the world. With the passage of time, enormous numbers of industries are increasing that result in the dire need of energy. In the past, scientists introduced number of alternative energy dynamics such as energy generation or conversion by using gravitational force, water, water waves, heat, wind, and solar rays, but these resources could not fulfill the energy requirements [1]. So it is the time to stimulate the research objectives to generate or explore the green, eco-friendly, and renewable energy alternatives that not only meet the energy demands but also encourage the environmental factors such as organic waste utilization that ultimately reduce the burden on the land. These environmental concerns have invigorated the scientists to look into sustainable, ecofriendly, and renewable energy or power-generating categories such as microbial fuel cells [2–4].

2. Microbial fuel cells

Microbial fuel cells are tools that play with microbial activities as biocatalyst for the inter-conversion of electrical and chemical energy involving electron transfer between two electrodes in the presence of proton exchange membrane under optimized conditions comparable with natural environment [2–4]. Microbial fuel cells are catalyzed by microbes for conversion of energy into power generation more efficiently. These microbes such as bacteria, fungi, and algae can utilize any organic matter as substrate and oxidize them to generate energy without involving any intermediate step for domestic, industrial power generation and wastewater treatment [5]. By utilizing microbial redox reaction of substrate in conjunction with chemical and electrical energy, microbial fuel cells, a promising innovation, can be revolutionized to recycle heat energy of natural as well as man-made resources into electrical energy without emission of any greenhouse gases [6, 7].

2.1 Microorganisms used for MFCs

A number of microbes such as members of Proteobacteria, Cytophagales, Firmicutes, Acidobacteria, strains of yeast strains such as *Saccharomyces cerevisiae* [8], *Candida melibiosica* [9, 10], *Hansenula* anomala [11], *Pseudopalaina polymorpha* [12]), and Blastobotrys adeninivorans [13] have potential to transfer electrons produced from metabolism to generate electricity [14]. These microbes can be isolated, purified, and identified from naval sedimentation, loam, running water sediments, wastewater, and activated sludge [15–17]. These microbes, particularly some strains of bacteria, show efficient behavior toward electron transfer through cytochromic pathways and proteins [18]. Some microbes transfer electrons without making any contact physically with the surface of electrode, whereas other microbes require synthetic or naturally produced mediators for electron transfer [19]. Microbes can work solely or in consortia colonies. In consortia, microbes show synergistic effects for bio-decomposition of complex organic matter [20]. **Table 1** displays the data of microorganisms that were exploited by a number of scientists for energy generation in microbial fuel.

2.2 Microbes-electrode material interaction

Microbes form active sites on the surface of anode and are responsible for the oxidation of organic matter provided in the fuel cell. Oxidation reaction of organic matter results in the generation of electrons as well as protons as a result of microbial attachment and colonization [43, 44] In microbial fuel cell, material of anode plays a key role to accelerate not only the flow of electron following conduction but also biofilm formation. In microbial fuel cell, anodes in the form of plates, rods, or brushes are made conventionally from different materials such as graphite, paper, cloth, or felts of carbon [45]. Generally, carbon is a suitable material for electrode formation as it is resistant to oxidation.

2.3 Shortcoming for microbial fuel cell

In spite of all these merits of microbial fuel cells, some drawbacks make it unfit for power generation at industrial scale. Microbial fuel cells face the challenges of low-voltage production due to weak biofilm formation, low-efficiency electrodes, and proton exchange membrane. As microbial oxidation of substrate generates electrons

Microbes	Organic matter as substrate	References
Streptococcus lactis	$C_6H_{12}O_6$	[21]
Erwinia dissolvens	$C_6H_{12}O_6$	[21]
Lactobacillus plantarum	$C_6H_{12}O_6$	[21]
Aeromonas hydrophila	CH_3COOH	[22]
Proteus mirabilis	$C_6H_{12}O_6$	[23]
Geobacter metallireducens	CH_3COOH	[24]
Pseudomonas aeruginosa	$C_6H_{12}O_6$	[19]
Klebsiella pneumoniae	$C_6H_{12}O_6$	[25]
Blastobotrys adeninivorans	$C_6H_{12}O_6$	[26]
Candida melibiosica	$C_6H_{12}O_6$	[27]
Saccharomyces cerevisiae	$C_6H_{12}O_6$	[28]
Desulfovibrio desulfuricans	$C_{12}H_{22}O_{11}$	[29]
P. anomala	$C_6H_{12}O_6$	[30]
Clostridium beijerinckii	$C_6H_{10}O_5$, $C_6H_{12}O_6$	[31]
Candida sp.	$C_6H_{12}O_6$	[32]
S. cerevisiae	$C_3H_6O_3$	[33]
Shewanella oneidensis	$C_3H_6O_3$	[34]
C. melibiosica	$C_6H_{12}O_6$	[35]
Methylomusa anaerophila	CH_3OH	[36]
Escherichia coli	$C_6H_{12}O_6$, $C_{12}H_{22}O_{11}$	[37]
Gluconobacter oxydans	$C_6H_{12}O_6$, C_2H_5OH	[38, 39]
Shewanella putrefaciens	$C_3H_6O_3$	[40]
S. cerevisiae	$C_6H_{12}O_6$	[41]
Geobacter sulfurreducens	CH_3COOH	[42]

Table 1.
Microbes used in microbial fuel cell.

that are not fully attracted toward the cathode surface and ultimately resulted in the less output energy and short-term stability limit its utility. This attraction of electrons toward the electrode can be enhanced by increasing the exposed surface area of electrode by using nanoparticles or any nano-composite material to increase bio-catalytic activity of microbes [45]. A number of scientists reported the microbial fuel cell in which anode was impregnated with chemical catalyst [46–48]. This anode impregnation increased the active sites of anode to value power density, but bacterial cells entrapped into these pores to clog them thus, ultimately the cell death resulted in decline in the electrochemical reaction on the cell surface.

3. Nano-structured microbial fuel cells

Nano-composite materials are used for coating surface of electrodes to enhance their efficiency. These composite materials are multiphase and each phase having

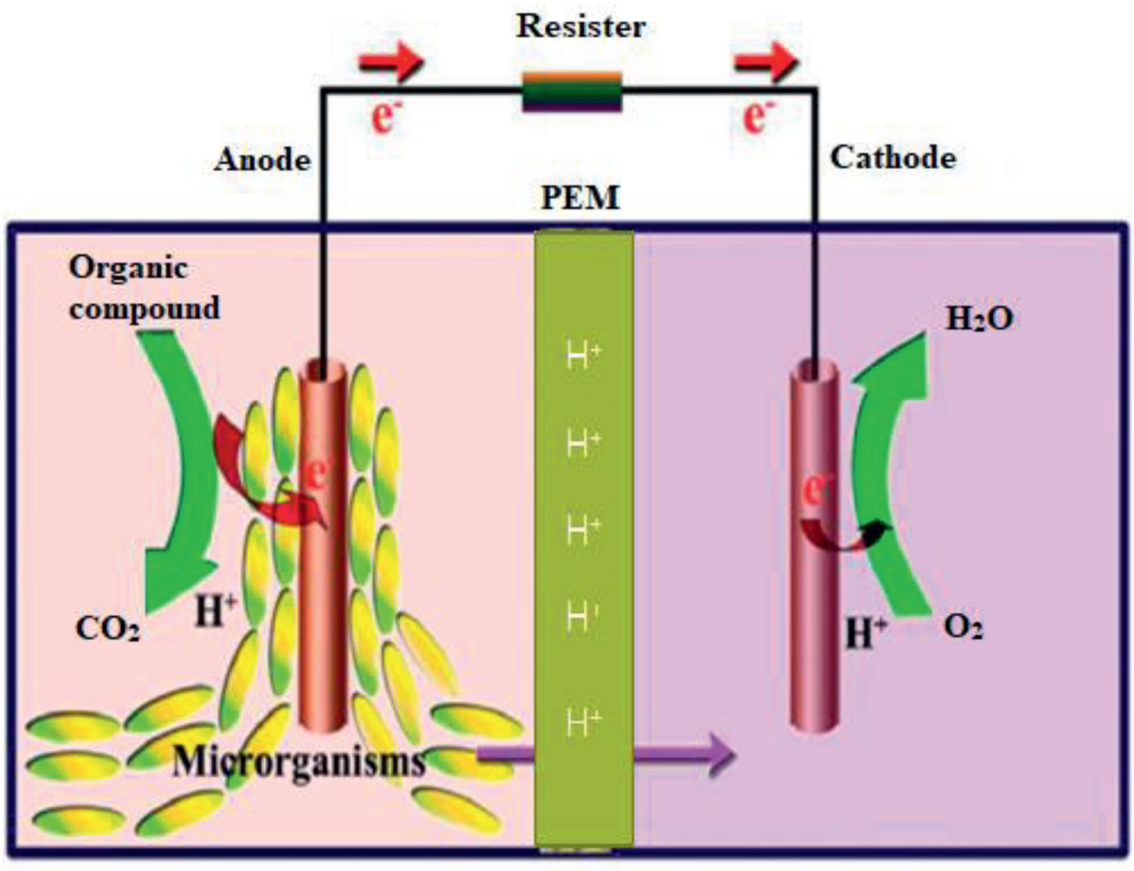

Figure 1.
Microbial Fuel cell [51].

multiple dimensions of nano-meters. These nano-materials are of different types such as carbon nano-tubes coated with poly pyrrole, carbon nano-tube composites coated with poly aniline, and nano-fibers of activated carbon [48–50]. During the process of energy generation by microbial fuel cells, oxidation of substrate takes place at the anode with the emission of electrons leaving behind the protons. These electrons are attracted toward the nano-material-coated electrodes ultimately for energy generation, whereas protons react with oxygen to produce water after passing through proton exchange membrane, and carbon dioxide is the side product in this process (**Figure 1**). Reactivity of oxygen can be catalyzed by using nano-carbons or metals [52].

Nanotechnology has played an impact on the performance of microbial fuel cells and its constituents. Best of the knowledge about microbial fuel cell presentation, its constituents, and applications are presented in **Table 2** as reported in a literature survey comprehensively by Mashkour et al. [53]. They reported not only microbes-nano-composite interaction but also potential exploitation of nano-materials for electron transfer to generate electricity as well as green water reclamation.

3.1 Microbes, cell compartments, and mechanism

In microbial fuel cell, microbes such as bacteria, fungi, or algae that reside on anode/bio-anode are called exoelectrogens, which donate electrons, and microbes that reside on cathode/bio cathodes are called electrotrophs, which attract electrons coming from the anode (**Figure 2a**) [67, 68]. At anode surface, microbes form biofilm

DOI: http://dx.doi.org/10.5772/intechopen.108744

Nanostructured microbial fuel cell constituents			Applied fields of nanostructured microbial fuel cell				
Microbial culture–nanocomposite interaction	**Anode/ PEM/ Cathode**	**Power generation**	**Microbs catalyzed Redox reaction**	**Microbial Hydrogen Emission**	**Clean water reclamation**	**Nano bio detector**	**References**
Yes	Yes/Yes/Yes	Yes	Yes	Yes	Yes	Yes	[53]
No	No/No/Yes	Yes	No	No	No	No	[54]
Yes	No/No/No	No	No	No	No	No	[55]
	Yes/No/Yes	Yes	No	No	No	No	[56]
	No/No/No	Yes	Yes	No	No	No	[57]
No	Yes/No/Yes	No	Yes	No	No	No	[58]
No	Yes/No//No	Yes	No	No	No	No	[59]
Yes	Yes/Yes/Yes	Yes	No	No	No	No	[60]
No	No/Yes/No	Yes	No	No	Yes	No	[61]
Yes	Yes/No/Yes	No	No	No	No	No	[62]
Yes	No/No/No	No	No	No	No	No	[63]
No	Yes/No/No	Yes	No	No	No	No	[64]
No	No/No/Yes	Yes	No	No	No	No	[65]
No	Yes/No/Yes	Yes	No	No	No	No	[66]

Table 2.
Nano structured microbial fuel cell and its exploitation.

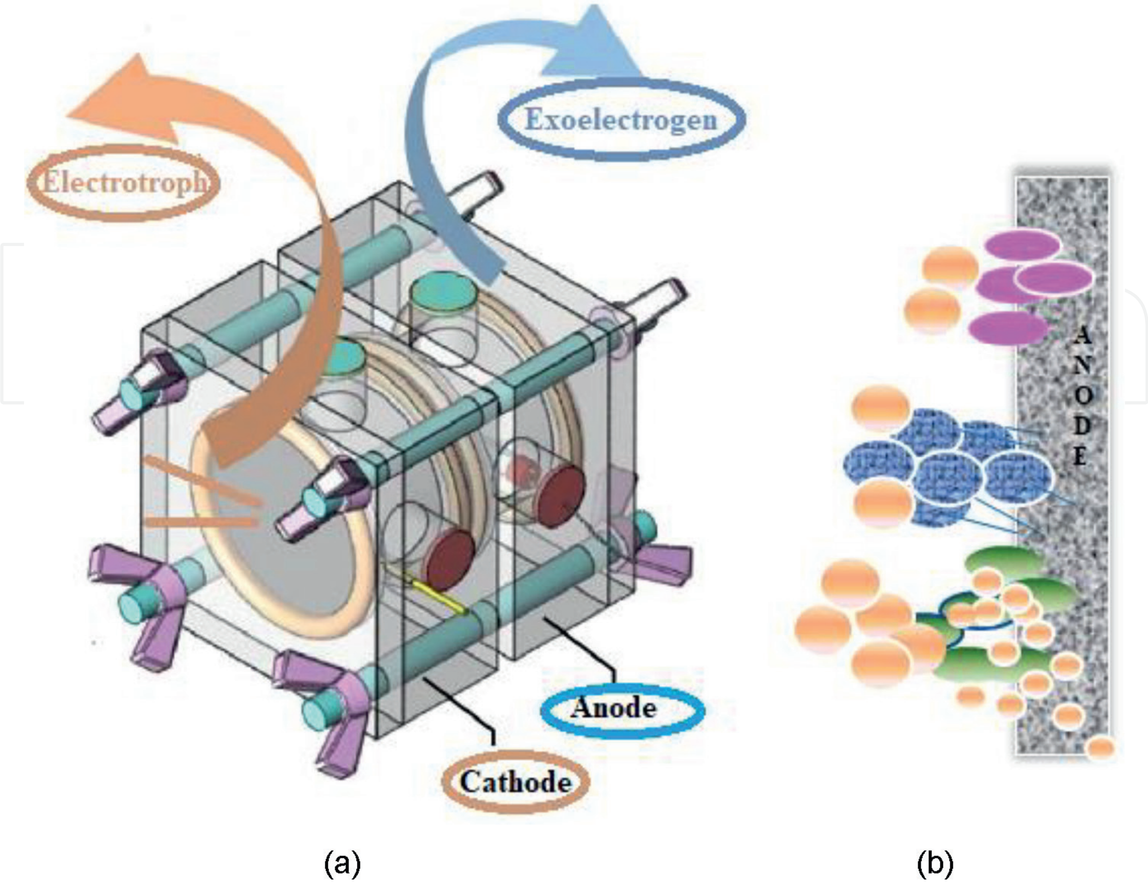

Figure 2.
Anode and cathode inhabiting microbes in microbial fuel cell (a), electron transmission from exoelectrogens electrode surface: direct contact (voilet), nanowire (textured blue), and mediators (green and orange) (b).

and decompose organic matter to generate electrons and protons. These electrons through nano-composite intermediates, bio-mediators, or direct contact are accepted by cathode having carbon dioxide as electron acceptor, thus, responsible for power generation (**Figure 2b**) [15]. At cathode surface, electrotrophic microbes reside, which require energy for their activities from electrons reached through electron transport mechanism generated as a result of organic matter decomposition. These microbes play a key part in the instrumentation to electro-synthesize the product.

3.2 Bacterial fuel cells

Bacterial fuel cells are novel innovation applicable in multidisciplinary fields of physical and biological and applied sciences. Bacterial fuel cell enclosed the components such as bacteria, proton exchange membrane, anode, and cathode [69]. These fuel cells are prepared by using electrode modified by nano-composite material made from metal oxides loaded with bacterial biomass. These cells exhibit better performance for electricity generation, treatment of polluted water, and as a biosensor for the detection of pullutants [1, 70].

3.3 Fungal fuel cell

In microbial fuel cell compartment, fugal mycelia can be interacted with nanomaterial-modified electrodes and taken as anodic or cathodic biocatalyst to transfer electrons sometime using mediators such as methylene blue (MB) and neutral red (NR). These fungal fuel cells can be manipulated to treat polluted water in addition to generating electricity. This fungal-mediated anode works in an anaerobic environment in a sterilized system requiring no input energy or any chemical [71]. Potential exploitation of fungal fuel cell is an economical, eco-friendly, and green alternative technology that plays with living microbes to oxidize organic matter leaving behind minimum side products, thus resulting in the electricity generation. As microbial fuel cell factories, fungal microbes can work at optimal temperature using wide range of organic matter as substrates with minimum requirement of energy [72, 73]. These fungal fuel cells can be a future candidate for the treatment of wastewater, bioremediation of organic wastes, thus valued the organic wastes for energy generation, biofuel and chemical production on commercial scale. In fungal fuel cell, redox reaction takes place via series of electrochemical and fungal metabolic pathways. At the anode, microbial oxidation of substrate takes place that results in the generation of electrons and protons. Electrons are attracted toward the cathode where these electrons are captured to be reduced [74].

3.4 Microbial fuel cell components

Microbial fuel cell is composed of two distinct anodic and cathodic chambers separated by separator such as proton exchange membrane. Electrochemical system of fuel cell is mediated by microbes due to their potential to catalyze electron transfer from anode to cathode called exoelectrogens. These exoelectrogens play a significant role in the oxidation of organic matter and subsequent release of electrons, which then migrate from anode to cathode through external circuit for power generation, whereas protons are delivered through proton exchange membrane to cathode and react with oxygen to form water (**Figure 3**). Microbial fuel cell alignment, optimal

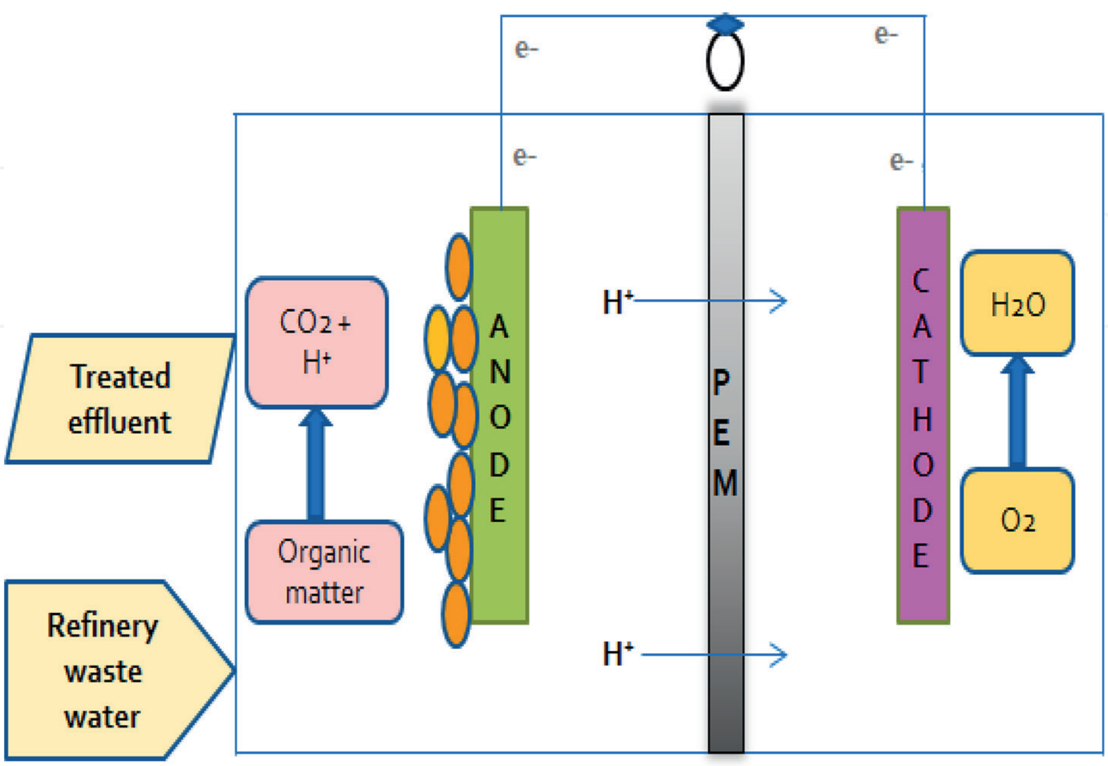

Figure 3.
Fungal fuel cell.

Microbial fuel cell constituents	Potential attributes of constituents
Microorganisms: Bacteria, fungi	microbial growth rate, microbial attachment, extracellular electron transfer, the activity of biofilm in a redox reaction, biofilm resistance
Anode: Poly aniline/ TIO_2 Polypyrrole/ carbon nano tube, Ni/ Carbon nano fibers, Polyaniline/ 3D graphene	Conductivity, Increased exposed surface area, porous network, enhanced charge transfer, More compatible to microbes,
Cathode	Conductive, More exposed surface area, porous network to enhance charge transfer, reducing environment at cathode, reduce oxygen,
Proton exchange membrane	conductive, exchange of ions, oxygen transfer, water formation, separation, to make charge balance

Table 3.
Potential effects of nanotechnology on enhancing the attributes of different constituents of MFC.

substrate, fungal culture load, texture of anode and cathode, and other environmental factors are the key factors that affect the working of fuel cell. These components involving nanotechnology are enhancing the different attributes of microbial fuel cells (**Table 3**).

3.4.1 Microbial fuel cell anode modified with nano-composite

Microbial growth and other activities such as electron movement are greatly influenced by the anodic performance, and anodic performance is directly dependent on the anodic texture. Anode under optimal conditions of microbial environment has good potential for electrical conduction [42, 75]. Anode in the form of carbon material such as paper or fabric has been in practice might be due to their biocompatibility as well as economical but reduction in exposed surface area for microbial attachment [9, 10, 53], thus, limiting their use for microbial colonies formation and energy generation [11, 76].

Exposed surface area of anode can be increased by using economical and cheap nano-composite material that not only increases the microbial growth but also improves the microbial attachment to the surface of anode. This enhancement in microbial attachment or rich colonization of microbes or exoelectrogens accelerates the rate of oxidation of organic matter that ultimately results in the release of electrons and protons, thus, increasing the rate of electron transfer in microbial fuel cell [75, 76]. **Table 4** gives an overview of the extraordinary performance of anode modified with various nano-composite materials filmed with different microbial culture and subsequent progression in the power generation of microbial fuel cell under investigation. For anode alteration, multiphase nano-tubes made from carbon sheets expose maximum active sites for microbial attachment followed by the maximum oxidation of organic matter to release electrons and protons. Electrons are attracted toward the cathode made from carbon sheet coated with platinum as reported by Nambiar et al. [77]. Power generated in this work optimally up to 256%. Out-performance of microbial fuel cells constructed by modified anode is reported by a number of scientists (**Table 4**). They reported best synergistic catalytic effects of microbial cells and nano-composite in microbial fuel cell formulation. In this cell, anode was made from nano-composite of oxide of titanium and poly aniline using culture of *Escherichia Coli*. In this microbial fuel

Exoelectrogen	Modified anode	Cathode	Power density (Milli Watt/ m2	Reference
Escherichia Coli	Sheet of TiO2 modified with Polyanilin	Graphitic paper	Out perform	[1]
Escherichia Coli	Carbon nano tubes filmed with polypyrrole	—	228	[48]
Enterobacter cloacae	Carbon paper modified with nano tubes of carbon	Sheet of carbon	256% improvement	[77]
Escherichia Coli	Three dimensional graphene hybridized with polyaniline	—	Out perform	[49]
Escherichia Coli	Micro-nano fibers of carbon with dispersed web of nickel nano particles	—		[50]
Geobacter sulfurreducens	Sheet of carbon modified with carbon nano tubes	Graphitic plate	200% improvement	[78]
Shewanella loihica	Sheet of TiO2 modified with Polyanilin	Carbon cloth coated with platinum	63% improvement	[79]
Shewanella putrefaciens	Felts of carbon modified with graphene oxide	Sheet of platinum	240	[80]
Escherichia coli	Poly ethylene dioxy thiophene/ graphene/nickel-nanoparticles	Graphitic sheet	3200	[81]
Saccharomyces cerevisiae	Felts of carbon modified with nanoparticles of gold	Graphitic sheet	2271	[82]
Shewanella xiamenensis	Sheet of TiO2 modified with Polyanilin	Graphitic sheet	179	[83]
S. loihica	Carbon felts modified with iron oxide	Paper of carbon with coating of platinum	797	[70]

Table 4.
Performance of electrode modified with nano-composite/exoelectrogen in microbial fuel system.

cell, current and voltage measurements were made by using digital multimeter, and external resistance was set at 1.95 kΩ. During microbial fuel cell working, electrons and protons are released as a result of anaerobic oxidation of substrate. Through external circuit, these electrons move from anode to cathode where reaction takes place in the presence of oxygen and protons [84–86]. Another economical and cost-effective microbial fuel cell with 0.18 voltages was reported by Zoua et al. [48], who formulated fuel cell using anode made from composite of carbon nanotubes filmed around with polypyrrole using culture *Escherichia coli*. It was found that fuel cell voltage was dependent on composite material loaded. Similarly, Yong et al. [49] assembled the microbial fuel cell using three-dimensional graphene hybridized with poly aniline that was filmed with culture of microbes on three dimensions to facilitate electron transfer through super-conductive passage. Another research finding reported the microbial fuel cell involving porous network of micro- and nano-fibers of carbon with dispersed nickel by using biofilm of *E. coli* [50]. This prepared cell exhibited wonderful catalytic reduction of oxygen and facilitated excellent electron conduction to anode. Nambiar et al. [77] constructed microbial fuel cell using sheet of carbon as cathode, whereas anode was made from carbon paper modified with multidimensional carbon nanotubes loaded with *Enterobacter cloacae* culture. They found 256% improvement in cell working.

3.4.2 Microbial fuel cell cathode modified with nanocomposite

To improve the performance of electrotrophs, in microbial fuel cell cathode or electrotroph can be modified by using nano-composite to increase the exposed surface are for the adsorption of gas molecules. This modification of cathode by photocatalytic nano-composite may lead to enhanced chemical reactions on the surface of cathode. **Table 5** displays the research findings of microbial fuel cell with different electrotrophs in which cathode was modified with nano-materials to produce acetate. Bian et al. [89] have increased the exposed surface area of cathode using nanorods of carbon along with porous nickel fibers loaded with *Sporomusa ovate*. These microbes captured CO_2 from the surface of cathode due to porous nickel fibers. On cathode surface, carbon nanotubes have increased the adsorption capacity for CO_2 that resulted in the significant increase in current density of cathode up to 332 mA/m^2 due to enhanced charge transfer. Similarly, under the same conditions, Aryal et al. [88] used sheet of grapheme oxide for microbial culturing of electrotrophs, and increased acetate production was detected 7–8 times comparable with electrode made from carbon paper. Consistently, Han et al. [90] reported the optimal acetate production and increased cathodic current density in comparison with cloth of carbon by using three-dimensional cathode biofilm of *Clostridium ljungdahlii* modified with incorporation of carbon nanotubes and graphene. Recently, modified cathode advanced the CO_2 fixation by Methano bacterium to enhance the acetate production [59]. For generation of acetate from HCO_3, cathode was modified with nanoparticles of oxides of molybdenum and tungsten, whereas *Serratia marcescens* was used as an electrotroph for microbial electro-synthesis system assisted by light. Generally, nanomaterials having excellent biocompatibility with microbes can play a crucial role for increasing the exposed surface area of cathode to absorb more CO_2 in microbial electro-synthesis system using electrotrophs for chemical production. This chemical production in fuel cell is catalyzed by Pt as catalyst that is more expensive and toxic toward the microbes, so economic nano-materials with more exposed surface area can be an excellent substitute of Pt catalyst to accelerate the cathode reaction such as reaction of oxygen reduction [93, 94]. The performance of cathode modified with nano-materials in microbial fuel cell has been investigated by a number of scientists as reported in **Table 5**.

3.5 Microbial fuel cell electrode modified with metallic nanoparticles

Nanoparticles made from transition and noble metals such as copper, zinc, nickel, cobalt, silver gold, platinum, and palladium have been exploited for electrode formation in energy generation owing to their excellent electrochemical, opto-magnetic, and mechanical properties [87, 91]. These nanoparticles have distinctive characters of displaying enlarged exposed surface area and dynamic shape. Metallic nanoparticles in the form of electrodes are being used in analytical equipment, optoelectronics, catalysis, biosensor fabrication, devices to monitor diseases such as cancerous cells,

Electrotrophs	Modified cathode	Anode	Power density (Milli Watt/ m2 (Modified/ control)	Reference
Sporomusa ovate with alcohol tolererance	Carbon cloth modified with oxides of graphene, tetraethylenepentamine	Graphite rods	2358/420	[87]
S. ovata	paper of reduced graphene oxide	Graphite rod	Up to 700%	[88]
S. ovata	Hollow rods of nickel modified with carbon nano tubes	Fabric of carbon	232/214	[89]
Clostridium ljungdahlii	Carbon cloth modified with carbon nanotubes and graphene	Graphite rod	595/135	[90]
S. ovata	Porous Copper modified with graphene oxide	Graphite rod	Up to 300%	[91]
Autotrophs	Carbon felts modified with oxides of manganese	Felts of carbon	Up to 200%	[92]
Serratia marcescens	Carbon felts modified with nano composite of oxides of tungsten and molybdenum	Carbon rod	2500/1500	[57]
Methanobacterium	Graphene oxide-PEDOT modified carbon fabric	Fabric of carbon	2540/840	[59]
Mixed culture	Carbon nano tubes modified with cobalt dopped with nitrogen	Felts of carbon	2479/714	[45]

Table 5.
Performance of electrode modified with nano-composite/electrotroph in microbial fuel system.

drug discovery, toxic metal detector for environmental monitoring as well as therapeutics [45, 92, 95, 96].

3.5.1 Microbial fuel cell electrode modified with gold nanoparticles

Metallic gold is an inert substance, which is the best representative of the catalyst as well as an electrode in the form of nanoparticles [35, 97] that have potential utilities in lab equipment, optoelectronics, and biomedicines. Gold nanoparticles having different dimensions are produced by using microbes as reducing agent. In microbial fuel cell, electrode surface can be modified with more stable and biocompatible nanoparticles of gold in the form of colloids called electron detector [81, 82, 98–101]. Literature supported the exploitation of modified electrode with gold nanoparticles for immobilization of redox enzymes and proteins, carbon paper modified with Au nanoparticles generated high-intensity current as well as healthy microbial biofilm formation as reported by Sun et al. [96]. Electrode modified with Au nanoparticles can be prepared by different methods such as sputtering and layer-by-layer methods. Sputtering method involves the deposition of Au vapors on the surface of electrode to make a uniform film, whereas layer-by-layer method involves the assembly of different layers of gold on the surface of electrode under the influence of electrostatic force to make multilayered thin film with uniform thickness. Guo et al. [101] assembled the Au nanoparticles and polyethylene imine under the electrostatic force of attraction to form multilayers of gold on the surface of electrode made of carbon paper. Gold nanoparticles-modified carbon paper electrode exhibited enhanced capabilities of electron transfer and power generation. Kalathil et al. [102] prepared gold nanoparticles in situ that facilitated not only the electricity generation but also hydrogen emission under controlled conditions of discrete capacitors loading in a microbial fuel cell. Similarly, Kasem et al. [102] reported the significant increase in adhesion of microbes on the surface of anode modified by using nanoparticles of gold or cobalt that ultimately boost the performance of fuel cell as a result of electron transfer. Han et al. [97] generated electricity by degrading methylene blue by using microbial fuel cell having gold nanoparticles on the cathode surface. They concluded that microbial fuel cell did well for power generation just because of modified cathode with gold nanoparticles. Cheng et al. [103] modified the anode surface by following the method of layer-by-layer binding of nano-composites of reduced graphene oxide and gold in microbial fuel cell for power generation up to 33.7 Wm^{-3} as well as wastewater management. Intensity of current approached 69.4 Am^{-3}, which might be due to more exposed active points of gold nanoparticles to attract electron on the surface of electrode. Similarly, a number of potential scientists reported the power generation by microbial fuel cells using electrode modified with nanoparticles of gold (**Table 6**).

3.6 Applications of nano-composite-based microbial fuel cell

3.6.1 Electricity generation

Microbial fuel cell is an excellent alternative for electricity generation due to flow of electron and proton between nano-material-modified exoelectrogen and electrotrophs. This cell is more eco-friendly and economic to use as microbes require energy for their growth activities, so organic wastes are the good source of substrate, which is decomposed by microbes as a result of oxidation that results in the generation of electron as well as proton. From anode in the medium source, electron transfer to cathode through external source of electromotive force [84, 111, 112].

3.6.2 Wastewater treatment

Microbial fuel cells are used to bio-remediate the industrial and domestic wastewater leaving behind less waste comparable with other treatment technologies. During this bio-remediation, a number of elements of potential importance in different fields, chemicals, and dyes stuffs are removed from this wastewater using exoelectrogen [113], whereas nitrogen and phosphorous-containing compounds can be eliminated from wastewater by using electrotrophs.

3.6.3 Nano biodetector

Microbial fuel cell can be used as self-motivated and highly sensitive biosensor to evaluate the qualities of wastewater by sensing the value of dissolved oxygen, toxic compounds, volatile organic compounds, biological oxygen demand, and microbial load [3, 114–116]. Some of their features such as low detection limit, poor durability, and less reproducibility make it unfit for applicability on commercial scale [115, 116]. However, modification of anode and cathode by using nano-composite material can

Exoelectrogen	Modified anode with gold nano particles	Technique	Power density (Milli Watt/m^2)	Reference
bacteria	gold nanoparticles (Au NPs) modified carbon paper	Layer-by-layer assembly	346 mWm^{-2}	[101]
Shewanella oneidensis	gold nanoparticles (Au NPs) modified carbon paper	Sputtering	47% higher than C electrode	[96]
Yeast *Saccharomyces cerevisia*	surfactant-mediated gold nanoparticles on carbon felt anode	In situ deposition	2771 ± 569 $mW{\cdot}m^{-2}$	[82]
Geobacter sulfurreducens	Gold mediated graphite anode	Stripping pattern	688 ± 159	[104]
E. coli	carbon nanotube-gold-titania nanocomposite	Nano suspension coating	2.4 mW m^{-2}	[95]
Bacteria	gold nanoparticles (Au NPs) modified carbon paper	In situ deposition	—	[102]
G. sulfurreducens	Gold modified polystyrene	Sputtering	—	[105]
S. platensis	Gold modified carbon felt	Sputtering	1.64 mW/m,	[106]
S. platensis	Gold modified carbon paper	Sputtering	10 mW/m^2	[107]
S. oneidensis	gold line microarray electrode PMMA	Sputtering	1400 mA m^{-2}	[108]
S. oneidensis	carbon nanotubes blended with BioAu	sputtering	178.34 ± 4.79 mW/m^2	[40]
bacteria	titanium and gold deposited plain silicium (one side)	sputtering	2.5 mW/m^2	[109]
bacteria	titanium and gold deposited plain silicium	sputtering	86.0 mW/m^2	[109]
bacteria	Gold modified carbon paper (one side)	sputtering	346.9 mW/m^2	[109]
Saccharomyces cerevisiae	Gold modified carbon fiber	sputtering	12.9 mW/m^2	[110]

Table 6.
Exploitation of electrode modified with gold nanoparticles in microbial fuel cell.

enhance the working of fuel cell as a nano-biosensor. For the detection of contaminants in the wastewater, anode can be modified as exoelectrogen to sense the waste bin in the water. In the same way, cathode can be modified as an electrotroph to detect pollutant, and system detection power can be enhanced by increasing the voltage current.

4. Upcoming prospects for research

Microbial fuel cells modified by nano-materials are used for the detection and bio-remediation of wastewater as well as biosensor for contaminants. A number of enormous materials are available for improving the reproducibility and vast applicability of fuel cells. However, more utilization of fuel cells modified with nano-materials may lead to emission of some toxic nano-metals into air, water, or soil, thus being environmental concerns. In future prospects, fuel cells modified with nano-materials should be formulated in such ways that minimize the risk factor to living organisms especially humans and ecosystem.

Author details

Fozia Anjum[1]*, Nadia Akram[1], Samreen Gul Khan[1], Naheed Akhter[2], Muhammad Shahid[3] and Fatma Hussain[3]

1 Department of Chemistry, Government College University, Faisalabad, Pakistan

2 Department of Biochemistry, Government College University, Faisalabad, Pakistan

3 Department of Biochemistry, University of Agriculture, Faisalabad, Pakistan

*Address all correspondence to: drfoziaanjum@gcuf.edu.pk

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

[1] Qiao Y, Bao SJ, Li CM, Cui XQ, Lu ZS, Guo J. Nanostructured polyaniline/titanium dioxide composite anode for microbial fuel cells. ACS Nano. 2007;**2**(1):113-119

[2] Izadi P, Rahimnejad M, Ghoreyshi A. Power production and wastewater treatment simultaneously by dual-chamber microbial fuel cell technique. Biotechnology and Applied Biochemistry. 2015;**62**(4):483-488

[3] Ivars-Barcelo F, Zuliani A, Fallah M, Mashkour M, Rahimnejad M, Luque R. Novel applications of microbial fuel cells in sensors and biosensors. Applied Sciences. 2018;**8**(7):1184

[4] Masoudi M, Rahimnejad M, Mashkour M. Fabrication of anode electrode by a novel acrylic based graphite paint on stainless steel mesh and investigating biofilm effect on electrochemical behavior of anode in a single chamber microbial fuel cell. Electrochimica Acta. 2020;**344**:136168

[5] Kiran V, Gaur B. Microbial fuel cell: Technology for harvesting energy from biomass. Reviews in Chemical Engineering. 2013;**29**(4):189-203

[6] Xu L, Zhao Y, Doherty L, Hu Y, Hao X. The integrated processes for wastewater treatment based on the principle of microbial fuel cells: A review. Critical Reviews in Environmental Science and Technology. 2016;**46**(1):60-91

[7] Berchmans S. Microbial fuel cell as alternate power tool: Potential and challenges. In: Microbial Fuel Cell. Springer; 2018. pp. 403-419

[8] Gunawardena A, Fernando S, To F. Performance of a yeast-mediated biological fuel cell. International Journal of Molecular Sciences. 2008;**9**:1893-1907. DOI: 10.3390/ijms9101893

[9] Babanova S, Hubenova Y, Mitov M. Influence of artificial mediators on yeastbased fuel cell performance. Journal of Bioscience and Bioengineering. 2011;**112**:379-387. DOI: 10.1016/j.jbiosc.2011.06.008

[10] Hubenova Y, Mitov M. Extracellular electron transfer in yeast-based biofuel cells: A review. Bioelectrochemistry Spec. Issue “Biological fuel cells”. 2015;**106**:177-185

[11] Prasad D, Arun S, Murugesan M, Padmanaban S, Satyanarayanan RS, Berchmans S. Direct electron transfer with yeast cells and construction of a mediatorless microbial fuel cell. Biosensors and Bioelectronics. et al., 2007;**22**:2604-2610

[12] Shkil H, Schulte A, Guschin DA, Schuhmann W. Electron transfer between genetically modified hansenula polymorpha yeast cells and electrode surfaces via os complex modified redox polymers. ChemPhysChem. 2011;**12**:806-813. DOI: 10.1002/cphc.201000889

[13] Haslett ND, Rawson FJ, Barriëre F, Kunze G, Pasco N, Gooneratne R, et al. Characterisation of yeast microbial fuel cell with the yeast Arxulaadeninivorans as the biocatalyst. Biosensors & Bioelectronics. 2011;**26**:3742-3747

[14] Franks AE, Nevin KP. Microbial fuel cells, a current review. Energies. 2010;**3**:899-919. DOI: 10.3390/en3050899

[15] Pisciotta JM, Zaybak Z, Call DF, Nam JY, Logan BE. Enrichment of microbial electrolysis cell biocathodes

from sediment microbial fuel cell bioanodes. Applied and Environmental Microbiology. 2012;**78**(15):5212-5219

[16] Caccavo F, Lonergan DJ, Lovley DR, Davis M, Stolz JF, McInerney MJ. *Geobacter sulfurreducens* sp. nov., a hydrogen- and acetate-oxidizing dissimilatory metal-reducing microorganism. Applied and Environmental Microbiology. 1994;**60**:3752-3759

[17] Zhuwei D, Haoran L, Tingyue G. A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy. Biotechnology Advances. 2007;**25**(5):464-482

[18] Lovley DR. Long-range electron transport to Fe(III) oxide via pili with metallic-like conductivity. Biochemical Society Transactions. 2012;**40**(6):1186-1190

[19] Rabaey K, Boon N, Höfte M, Verstraete W. Microbial phenazine production enhances electron transfer in biofuel cells. Environmental Science and Technology. 2005;**39**(9):3401-3408

[20] Ishii S, Suzuki S, Tenney A, Norden-Krichmar TM, Nealson KH, Bretschger O. Microbial metabolic networks in a complex electrogenic biofilm recovered from a stimulus-induced metatranscriptomics approach. Scientific Reports. 2015;**5**(1):1-14. DOI: 10.1038/srep14840

[21] Vega CA, Fernández I. Mediating effect of ferric chelate compounds in microbial fuel cells with Lactobacillus plantarum, Streptococcus lactis, and Erwinia dissolvens. Bioelectrochemistry and Bioenergetics. 1987;**17**(2):217-222

[22] Pham CA, Jung SJ, Phung NT, Lee J, Chang IS, Kim BH, et al. A novel electrochemically active and Fe(III)-reducing bacterium phylogenetically related to Aeromonas hydrophila, isolated from a microbial fuel cell. FEMS Microbiology Letters. 2003;**223**(1):129-134

[23] Choi Y, Jung E, Kim S, Jung S. Membrane fluidity sensoring microbial fuel cell. Bioelectrochemistry. 2003;**59**(1-2):121-127

[24] Min B, Cheng S, Logan BE. Electricity generation using membrane and salt bridge microbial fuel cells. Water Research. 2005;**39**(9):1675-1686

[25] Rhoads A, Beyenal H, Lewandowski Z. Microbial fuel cell using anaerobic respiration as an anodic reaction and biomineralized manganese as a cathodic reactant. Environmental Science and Technology. 2005;**39**(12):4666-4671

[26] Haslett ND, Rawson FJ, Barriëre F, Kunze G, Pasco N, Gooneratne R, et al. Characterization of yeast microbial fuel cell with the yeast *Arxula adeninivorans* as the biocatalyst. Biosensors & Bioelectronics. 2011;**26**:3742-3747

[27] Babanova S, Hubenova Y, Mitov M. Influence of artificial mediators on yeast-based fuel cell performance. Journal of Bioscience and Bioengineering. 2011;**112**:379-387

[28] Kasem E, Tsujiguchi T, Nakagawa N. Effect of metal modification to carbon paper anodes on the performance of yeast-based microbial fuel cells part I: In the case without exogenous mediator. Key Engineering Materials. 2013;**534**:76-81

[29] Ieropoulos IA, Greenman J, Melhuish C, Hart J. Comparative study of three types of microbial fuel cell. Enzyme and Microbial Technology. 2005;**37**(2):238-245

[30] Kaneshiro H, Takano K, Takada Y, Wakisaka T, Tachibana T, Azuma M. A milliliter-scale yeast-based fuel cell with high performance. Biochemical Engineering Journal. 2014;**83**:90-96

[31] Liu Q, Liu B, Li W, Zhao X, Zuo W, Xing D. Impact of ferrous iron on microbial community of the biofilm in microbial fuel cells. Frontiers in Microbiology. 2017;**8**:1-9. DOI: 10.3389/fmicb.2017.00920

[32] Lee Y-Y, Kim TG, Cho K-S. Isolation and characterization of a novel electricity-producing yeast, Candida sp. IR11. Bioresource Technology. 2015;**192**:556-563

[33] Gal I, Schlesinger O, Amir L, Alfonta L. Yeast surface display of dehydrogenases in microbial fuel-cells. Bioelectrochemistry. 2016;**112**:53-60

[34] Lamberg P, Bren KL. Extracellular electron transfer on sticky paper electrodes: Carbon paste paper anode for microbial fuel cells. ACS Energy Letters. 2016;**1**(5):895-898

[35] Sekrecka-Belniak A, Toczyłowska-Maminska R. Fungi-based microbial fuel cells. Energies. 2018;**11**(10):2827

[36] Amano N, Yamamuro A, Miyahara M, Kouzuma A, Abe T, Watanabe K. Methylomusa anaerophila gen. Nov., sp. nov., an anaerobic methanol-utilizing bacterium isolated from a microbial fuel cell. International Journal of Systematic and Evolutionary Microbiology. 2018;**68**(4):1118-1122

[37] Feng C, Tsai CC, Ma CY, Yu CP, Hou CH. Integrating cost-effective microbial fuel cells and energy-efficient capacitive deionization for advanced domestic wastewater treatment. Chemical Engineering Journal. 2017;**330**:1-10

[38] Lee SA, Choi Y, Jung S, Kim S. Effect of initial carbon sources on the electrochemical detection of glucose by *Gluconobacter oxydans*. Bioelectrochemistry. 2002;**57**(2):173-178

[39] Plekhanova Y, Tarasov S, Kolesov V, Kuznetsova I, Signore M, Quaranta F, et al. Effects of polymer matrices and carbon nanotubes on the generation of electric energy in a microbial fuel cell. Membranes. 2018;**8**(4):99

[40] Wu X, Qiao Y, Shi Z, Li CM. Enhancement of interfacial bioelectrocatalysis in Shewanella microbial fuel cells by a hierarchical porous carbon–silica composite derived from distiller's grains. Sustainable Energy & Fuels. 2018;**2**(3):655-662

[41] Badea SL, Enache S, Tamaian R, Niculescu VC, Varlam M, Pirvu CV. Enhanced open-circuit voltage and power for two types of microbial fuel cells in batch experiments using *Saccharomyces cerevisiae* as biocatalyst. Journal of Applied Electrochemistry. 2019;**49**(1):17-26

[42] Krige A, Sjöblom M, Ramser K, Christakopoulos P, Rova U. On-Line Raman Spectroscopic Study of Cytochromes Redox State of Biofilms in Microbial Fuel Cells. Molecules. 2019;**24**(3):646

[43] Palanisamy G, Jung HY, Sadhasivam T, Kurkuri MD, Kim SC, Roh S-H. A comprehensive review on microbial fuel cell technologies: Processes, utilization, and advanced developments in electrodes and membranes. Journal of Cleaner Production. 2019;**221**:598-621

[44] Lv C, Liang B, Zhong M, Li K, Qi Y. Activated carbon- supported multi-doped graphene as high-efficient catalyst to modify air cathode in microbial fuel cells. Electrochimica Acta. 2019;**304**:360-369

[45] Ghasemi M, Daud WRW, Hassan SH, Oh SE, Ismail M, Rahimnejad M, et al. Nano-structured carbon as electrode material in microbial fuel cells: A comprehensive review. Journal of Alloys and Compounds. 2013;**580**:245-255

[46] Rosenbaum MA, Franks AE. Microbial catalysis in bioelectrochemical technologies: Status quo, challenges and perspectives. Applied Microbiology and Biotechnology. 2014;**98**:509-518

[47] Park DH, Zeikus JG. Improved fuel cell and electrode designs for producing electricity from microbial degradation. Biotechnology and Bioengineering. 2002;**81**:348-355

[48] Zoua Y, Xianga C, Yanga L, Suna LX, Xua F, Caoc Z. A mediatorless microbial fuel cell using polypyrrole coated carbon nanotubes composite as anode material. International Journal of Hydrogen Energy. 2008;**33**:4856-4862

[49] Yong YC, Dong XC, Chan-Park MB, Song H, Chen P. Macroporous and monolithic anode based on polyaniline hybridized three-dimensional graphene for high-performance microbial fuel cells. ACS Nano. 2012;**6**(3):2394-2400

[50] Singh S, Verma N. Fabrication of Ni nanoparticles dispersed carbon micro nanofibers as the electrodes of a microbial fuel cell for bio-energy production. International Journal of Hydrogen Energy. 2014;**11**:073

[51] Zhao C-e, Gai P, Song R, Chen Y, Zhang J, Zhu J-J. Nanostructured material-based biofuel cells: Recent advances and future prospects. Chemical Society Reviews. 2017;**46**:1545-1564. DOI: 10.1039/c6cs00044d

[52] Santoro C, Arbizzani C, Erable B, Ieropoulos I. Microbial fuel cells: From fundamentals to applications. A review. Journal of Power Sources. 2017;**356**:225-244

[53] Mashkour M, Rahimnejad M, Raouf F, Navidjouy N. A review on the application of nanomaterials in improving microbial fuel cells. Biofuel Research Journal. 2021;**30**:1400-1416

[54] Peer J, Baek G, Shi L, Rossi R, Logan BE. The effect of high applied voltages on bioanodes of microbial electrolysi cells in the presence of chlorides. Chemical Engineering Journal. 2021;**405**(1):126742

[55] Wang R, Li H, Sun J, Zhang L, Jiao J, Wang Q, et al. Nanomaterials facilitating microbial extracellular electron transfer at interfaces. Advanced Materials. 2021;**33**(6):2004051

[56] Narayanasamy S, Jayaprakash J. Application of carbon- polymer based composite electrodes for microbial fuel cells. Reviews in Environmental Science and Biotechnology. 2020;**19**:595-620

[57] Cai Z, Huang L, Quan X, Zhao Z, Shi Y, Puma GL. Acetate production from inorganic carbon (HCO^-) in photo-assisted biocathode microbial electrosynthesis systems using WO3/MoO3/g-C3N4 heterojunctions and *Serratia marcescens* species. Applied Catalysis. 2020b;**B. 267**:118611

[58] Kaur R, Marwaha A, Chhabra VA, Kim KH, Tripathi S. Recent developments on functional nanomaterial-based electrodes for microbial fuel cells. Renewable and Sustainable Energy Reviews. 2020;**119**:109551

[59] Li Q, Fu Q, Kobayashi H, He Y, Li Z, Li J, et al. GO/PEDOT modified biocathode promoting CO2 reduction to CH4 in microbial electrosynthesis. Sustainable Energy & Fuels. 2020;**4**(6):2987-2997

[60] Olabi A, Wilberforce T, Sayed ET, Elsaid K, Rezk H, Abdelkareem MA. Recent progress of graphene based nanomaterials in bioelectrochemical systems. Science of The Total Environment. 2020;**749**:141225

[61] Shabani M, Younesi H, Pontié M, Rahimpour A, Rahimnejad M, Zinatizadeh AA. A critical review on recent proton exchange membranes applied in microbial fuel cells for renewable energy recovery. Journal of Cleaner Production. 2020;**264**:121446

[62] Mouhib M, Antonucci A, Reggente M, Amirjani A, Gillen AJ, Boghossian AA. Enhancing bioelectricity generation in microbial fuel cells and biophotovoltaics using nanomaterials. Nano Research. 2019;12(9):2184-2199. DOI: 10.1007/s12274-019-2438-0

[63] Zhang Y, Jiang J, Zhao Q, Wang K, Yu H. Analysis of functional genomes from metagenomes: Revealing the accelerated electron transfer in microbial fuel cell with rhamnolipid addition. Bioelectrochemistry. 2018a;**119**:59-67

[64] Hindatu Y, Annuar M, Gumel A. Mini-review: A node modification for improved performance of microbial fuel cell. Renewable and Sustainable Energy Reviews. 2017;**73**:236-248

[65] Kannan M. Current status, key challenges and its solutions in the design and development of graphene based ORR catalysts for the microbial fuel cell applications. Biosensors & Bioelectronics. 2016;**77**:1208-1220

[66] Ci S, Cai P, Wen Z, Li J. Graphene-based electrode materials for microbial fuel cells. Science China Materials. 2015;**58**(6):496-509

[67] Logan BE, Regan JM. Electricity-producing bacterial communities in microbial fuel cells. Trends in Microbiology. 2006;14(12):512-518

[68] Logan BE. Exoelectrogenic bacteria that power microbial fuel cells. Nature Reviews. Microbiology. 2009;**7**:375-381

[69] Logan BE, Rossi R, Saikaly PE. Electroactive microorganisms in bioelectrochemical systems. Nature Reviews. Microbiology. 2019;**17**(5):307-319

[70] Yang Q, Yang S, Liu G, Zhou B, Yu X, Yin Y. Boosting the anode performance of microbial fuel cells with a bacteria-derived biological iron oxide/carbon nanocomposite catalyst. Chemosphere. 2021;**268**:128800

[71] Slate AJ, Whitehead KA, Brownson DAC, Banks CE. Microbial fuel cells: An overview of current technology. Renewable and Sustainable Energy Reviews. 2019;**101**:60-81. DOI: 10.1016/j.rser.2018.09.044

[72] Sayed ET, Tsujiguchi T, Nakagawa N. Catalytic activity of baker's yeast in a mediatorless microbial fuel cell. Bioelectrochemistry. 2012;**86**:97-101. DOI: 10.1016/j.bioelechem.2012.02.001

[73] Schaetzle O, Barrière F, Baronian K. Bacteria and yeasts as catalysts in microbial fuel cells: Electron transfer from micro-organisms to electrodes for green electricity. Energy & Environmental Science. 2008;**1**:607-620

[74] Hemen Sarma PN, Bhattacharyya DA, Jadhav PP, Thakare M, Pandit S, Mathuriya AS. Fungal-mediated electrochemical system: Prospects, applications and challenges. Current Research in Microbial Sciences. et al., 2021;**2**:100041

[75] Patel N, Rai D, Chauhan D, Shahane S, Mishra U, Bhunia B. Carbon

nanotube based anodes and cathodes for microbial fuel cells. In: Microbial Fuel Cells: Materials and Applications. Vol. 46. Materials Research Forum LLC; 2019. pp. 125-150

[76] Salar-García M, Ortiz-Martínez V. Nanotechnology for wastewater treatment and bioenergy generation in microbial fuel cells. In: Advanced Research in Nanosciences for Water Technology. Springer; 2019. pp. 341-362

[77] Nambiar S, Togo C, Limson J. Application of multi-walled carbon nanotubes to enhance anodic performance of an Enterobacter cloacae-based fuel cell. African Journal of Biotechnology. 2009;**8**(24):6927-6932. Available from: http://www.academicjournals.org/AJB ISSN 1684-5315

[78] Jiang Q, Xing D, Zhang L, Sun R, Zhang J, Zhong Y, et al. Interaction of bacteria and archaea in a microbial fuel cell with ITO anode. RSC Advances. 2018a;**8**:28487-28495. DOI: 10.1039/c8ra01207e

[79] Yin T, Zhang H, Yang G, Wang L. Polyaniline composite TiO2 nanosheets modified carbon paper electrode as a high performance bioanode for microbial fuel cells. Synthetic Metals. 2019;**252**:8-14

[80] Zhu W, Yao M, Gao H, Wen H, Zhao X, Zhang J, et al. Enhanced extracellular electron transfer between Shewanella putrefaciens and carbon felt electrode modified by bio-reduced graphene oxide. Science of The Total Environment. 2019;**691**:1089-1097

[81] Hernández LA, Riveros G, González DM, Gacitua M, del Valle MA. PEDOT/graphene/nickel-nanoparticles composites as electrodes for microbial fuel cells. Journal of Materials Science: Materials in Electronics. 2019;**30**(13):12001-12011

[82] Duarte KD, Frattini D, Kwon Y. High performance yeast- based microbial fuel cells by surfactant-mediated gold nanoparticles grown atop a carbon felt anode. Applied Energy. 2019;**256**:113912

[83] Truong DH, Dam MS, Bujna E, Rezessy-Szabo J, Farkas C, Vi VNH, et al. In situ fabrication of electrically conducting bacterial cellulose-polyaniline-titanium-dioxide composites with the immobilization of Shewanella xiamenensis and its application as bioanode in microbial fuel cell. Fuel. 2021;**285**:119259

[84] Zhang Q, Zhang L, Wang H, Jiang Q, Zhu X. Simultaneous efficient removal of oxyfluorfen with electricity generation in a microbial fuel cell and its microbial community analysis. Bioresource Technology. 2018b;**250**:658-665. DOI: 10.1016/j.biortech.2017.11.091

[85] Lu L, Xing D, Ren ZJ. Microbial community structure accompanied with electricity production in a constructed wetland plant microbial fuel cell. Bioresource Technology. 2015;**195**:115-121

[86] Masoudi M, Rahimnejad M, Mashkour M. Enhancing operating capacity of microbial fuel cells by using low-cost electrodes and multi anode-cathode connections in a membrane-less configuration. International Journal of Hydrogen Energy. 2021;**46**(11):8226-8238

[87] Yaqoob AA, Ibrahim MNM, Rafatullah M, Chua YS, Ahmad A, Umar K. Recent advances in anodes for microbial fuel cells: An overview. Materials. 2020;**13**:2078. DOI: 10.3390/ma1309207

[88] Aryal N, Halder A, Zhang M, Whelan PR, Tremblay PL, Chi Q, et al. Freestanding and flexible graphene papers as bioelectrochemical cathode for

selective and efficient CO2 conversion. Scientific Reports. 2017;**7**(1):1-8

[89] Bian B, Alqahtani MF, Katuri KP, Liu D, Bajracharya S, Lai Z, et al. Porous nickel hollow fiber cathodes coated with CNTs for efficient microbial electrosynthesis of acetate from CO2 using Sporomusa ovata. Journal of Materials Chemistry A. 2018;**6**(35):17201-17211

[90] Han S, Liu H, Zhou C, Ying HJ. Growth of carbon nanotubes on graphene as 3D biocathode for NAD+/NADH balance model and high-rate production in microbial electrochemical synthesis from CO2. Journal of Materials Chemistry A. 2019;**7**(3):1115-1123

[91] Choudhury P, Prasad Uday US, Bandyopadhyay TK, Ray RN, Bhunia B. Performance improvement of microbial fuel cell (MFC) using suitable electrode and Bioengineered organisms: A review. Bioengineered. 2017;**8**:471-487

[92] Kumar R, Singh L, Zularisam AW, Hai FI. Microbial fuel cell is emerging as a versatile technology: A review on its possible applications, challenges and strategies to improve the performances. International Journal of Energy Research. 2018;42(2):369-394

[93] Mashkour M, Rahimnejad M. Effect of various carbon-based cathode electrodes on the performance of microbial fuel cell. Biofuel Research Journal. 2015;**2**:296-300

[94] Xue W, Zhou Q, Li F. The feasibility of typical metal– organic framework derived Fe, Co, N co-doped carbon as a robust electrocatalyst for oxygen reduction reaction in microbial fuel cell. Electrochimica Acta. 2020;**355**:136775

[95] Wu Y, Zhang X, Li S, Lv X, Cheng Y, Wang X. Microbial biofuel cell operating 20 effectively through carbon nanotube blended with gold–titania nanocomposites 21 modified electrode. Electrochimica Acta. 2013;**109**:328-332

[96] Sun M, Zhang F, Tong Z-H, Sheng G-P, Chen Y-Z, Zhao Y, et al. A gold-sputtered carbon paper as an anode for improved electricity generation from a microbial fuel cell inoculated with *Shewanella oneidensis* MR-1. Biosensors & Bioelectronics. 2010;**26**:338-343

[97] Han HT, Khan MM, Kalathil S, Lee J, Cho MH. Simultaneous enhancement of methylene blue degradation and power generation in microbial fuel cell by gold nanoparticles, Industrial & Engineering Chemistry Research. Just Accepted Manuscript. 2013;52(24):8174-8181. DOI: 10.1021/ie4006244. Publication Date (Web): 27 May 2013 Downloaded from: http://pubs.acs.org on June 1, 2013

[98] Rong H, Zhang S, Muhammad S, Zhang J. Noble metal-based nanocomposites for fuel cells. Novel Nanomaterials. London, UK: IntechOpen; 2018. pp. 291-310. DOI: 10.5772/intechopen.71949

[99] Zhang H, Lu HY, Hu NF. Fabrication of electroactive layer-by-layer films of myoglobin with gold nanoparticles of different sizes. The Journal of Physical Chemistry B. 2006;**110**:2171-2179

[100] Dessie Y, Tadesse S. Advancements in bioelectricity generation through nanomaterial-modified anode electrodes in microbial fuel cells. Review published: 17 May 2022 doi: 10.3389/fnano.2022.876014, Frontiers in Nano Technology

[101] Guo W, Pi Y, Song H, Tang W, Sun J. Layer-by-layer assembled gold nanoparticles modified anode and its application in microbial fuel cells. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2012;415:105-111

[102] Kalathil S, Jintae Lee, and Moo Hwan Cho. 2013. Gold nanoparticles produced in situ mediate bioelectricity and hydrogen production in a microbial fuel cell by quantized capacitance charging ChemSusChem 2013, 6, 246 – 250 247, DOI: 10.1002/cssc.201200747

[103] Cheng Y, Mallavarapu M, Naidu R, Chen Z. In situ fabrication of green reduced graphene-based biocompatible anode for efficient energy recycle. Chemosphere. 2018;**193**:618-624

[104] Richter H, McCarthy K, Nevin KP, Johnson JP, Rotello VM, Lovley DR. Electricity generation by Geobacter sulfurreducens attached to gold electrodes. Langmuir. 2008;**24**:4376

[105] Amirdehi MA, Saem S, Zarabadi MP, Moran-Mirabal JM, Greener J. Microstructured anodes by surface wrinkling for studies of direct electron transfer biofilms in microbial fuel cells. Advanced Materials Interfaces. 2018:1800290

[106] Gu HY, Fu C-C, Su C-H, Hung T-C, Hsieh C-H, Suryani D, et al. Effects of biomass weight and light intensity on the performance of photosynthetic microbial fuel cells with Spirulina platensis. Bioresource Technology. 2009;**100**:4183-4186

[107] Lin H, Wu X, Nelson C, Miller, Zhu J. Electricity generation and nutrients 30 removal from high-strength liquid manure by air-cathode microbial fuel cells, Journal of Environmental Science and Health Part A, 2016;**51**(3):240-250

[108] Chen S, Chen X, Hou S, Xiong P, Xiong Y, Zhang F, et al. A gold microarray electrode on a poly(methylmethacrylate) substrate to improve the performance of microbial fuel cells by modifying biofilm formation. RSC Advances. 2016;**6**:114937-114943. DOI: 10.1039/C6RA22152A

[109] Alatraktchi FA, Zhang Y, Noori JS, Angelidaki I. Surface area expansion of electrodes with grass-like nanostructures and gold nanoparticles to enhance electricity generation in microbial fuel cells. Bioresource Technology. 2012;**123**:177-183

[110] Kasem E, Tsujiguchi T, Nakagawa N. Effect of metal modification to carbon paper anodes on the performance of yeast-based microbial fuel cells part II: In the case with exogenous mediator, methylene blue. Key Engineering Materials. 2013;**534**:82-87

[111] Chandra R, Venkata Mohan S, Roberto P-S, Ritmann BE, Cornejo RAS. Biophotovoltaics: Conversion of Light Energy to Bioelectricity through Photosynthetic Microbial Fuel Cell Technology. Microbial Fuel Cell. 2017:373-387. DOI: 10.1007/978-3-319-66793-5_19

[112] Regmi R, Nitisoravut R, Charoenroongtavee S, Yimkhaophong W, Phanthurat O. Earthen pot-plant microbial fuel cell powered by vetiver for bioelectricity production and wastewater treatment. Clean. - Soil, Air, Water. 2018a;**46**:1700193. DOI: 10.1002/clen.201700193

[113] Feng J, Qian Y, Wang Z, Wang X, Xu S, Chen K, et al. Enhancing the performance of *Escherichia coli*-inoculated microbial fuel cells by introduction of the phenazine-1-carboxylic acid pathway. Journal of Biotechnology. 2018;**275**:1-6

[114] Cui Y, Lai B, Tang X. Microbial fuel cell-based biosensors. Biosensors. 2019;**9**(3):92

[115] Chen L, Tremblay PL, Mohanty S, Xu K, Zhang T. Electrosynthesis

of acetate from CO2 by a highly structured biofilm assembled with reduced graphene oxide–tetraethylene pentamine. Journal of Materials Chemistry A. 2016;**4**(21):8395-8401

[116] Do MH, Ngo HH, Guo W, Chang SW, Nguyen DD, Liu Y, et al. Microbial fuel cell-based biosensor for online monitoring wastewater quality: A critical review. Science of the Total Environment. 2020;**712**:135612

IntechOpen
IntechOpen