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Microbial Fuel Cells as Alternate Source of Energy: Research, Advancements and Future Prospects in Indian Scenario

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Today, the world is on the verge of transformation from fossil fuels to alternative and sustainable renewable sources due to many reasons. Many plausible technologies have been developed of which, energy from biomass and biowaste is a widely accepted choice. In India too, the fuel crisis is imminent and renewable fuel sources are being developed on a large scale to meet energy requirements. However, generation of electricity from biomass and biowaste is a rather unconventional method which is less exploited. The technology that possesses immense future prospective requires collaboration of expertise from various disciplines of science. Here we present a comprehensive view of developments and novel approaches in microbial fuel cell research in Indian scenario in the backdrop of the developments on a global scale. Though the research outputs in India in terms of power density is in par with that on global scale, we lag behind in bringing a collaborative approach.

Keywords: Microbial fuel cells, Biomass, Biowastes, Electrochemically active bacteria, Conductive biofilms.

INTRODUCTION

There are frequent fluctuations in oil prices and decline in conventional fossil fuel reserves today. This scenario prompts serious deliberations on the need to target on non-conventional sources of energy. Currently, fossil fuels fulfill majority of the world energy needs and their share in the primary energy mix is on an ever increase. However, its extraction, which is uneconomical as of now-might cause grave damage to the environment [1]. These facts accentuate the prevalent impression that future energy requirements of the human race cannot be met entirely by fossil fuels. The consensus for alternate energy sources and sustainable development was strongly felt among the scientific community a few decades ago. Extraction of energy from renewable sources is one pragmatic step that can alleviate the crisis to a great extent. It seems most appropriate to discuss current strategies of fuel production from renewable sources-the non-conventional sources such as biomass and biowaste in particular.

Biomass as alternate source of energy: Global and Indian scenario: Biomass and agricultural wastes have historically been used as the solid fuel since ancient times. Even today, around 2.6 million people in Asia and Africa rely solely on solid fuels such as agricultural wastes and cow dung for their energy requirements [2]. However, the combustion systems being employed are among the least energy efficient systems and agricultural residues burnt in traditional stoves exhibit only 12 % energy efficiency [3].

Ironically, biomass stores in itself immense energy reserves that can be tapped through strategic approach and channeled to produce different forms of energy. Today, energy from biomass is extracted in a number of ways for generation of heat, power generation, thermal gasification and biofuel production [4]. International Energy Statistics published by the U.S. Energy Information Administration (EIA) shows that the leading economies of the world have been tapping electricity from energy reserves in biomass and biowaste for the past decade (Fig. 1). There has been notable increase in their use (Table-1) with China showing highest percentage increase in the use of biomass and biowaste.

Research in India focuses mainly on production of biofuels such as bioethanol [5], biodiesel [6] and methane and hydrogen [7] from biomass and remarkable advancements have been made [8]. Here, we discuss a rather unconventional approach-generation of electricity and hydrogen directly from biomass. Hydrogen has been accepted as a promising alternate fuel by the scientific world. Indian perception on hydrogen as future fuel is reflected in the comment by the famed scientist Bharat Ratna awardee Dr. C.N.R. Rao on hydrogen as the cleanest of all fuels with highest energy density per unit [9]. However, research

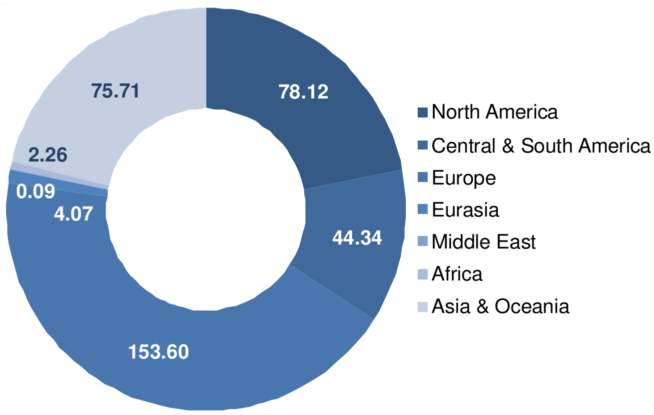

Fig. 1. Electricity Generation (Trillion Watts per hour) from biomass and biowaste by continents/geographical areas during the year, 2011. The continent Australia is included in Asia & Oceania and Antartica in Central & South America (Source: International Energy Statistics, U.S. Energy Information Administration)

TABLE-1
COUNTRIES THAT LEAD IN USAGE OF BIOMASS AND BIOWASTE AS THE RENEWABLE ENERGY SOURCE FOR ELECTRICITY GENERATION IN THE YEAR 2012

Country	Energy from biomass and biowaste (TW h/yr)		Increase (%)
	2008	2012	
European Union	113.29	163.31	44.15
United States	66.84	71.41	6.84
Germany	29.22	44.25	51.44
China	2.35	43.56	1753.62
Brazil	19.61	34.00	73.38
Japan	22.43	23.14	3.17
United Kingdom	11.08	16.32	47.29
Italy	7.66	15.08	96.87
Canada	7.14	6.38	-10.64
India	2.00	4.12	106.00

Reference: International Energy Statistics, U.S. Energy Information Administration http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

on generation of electricity from biomass is still in its infancy. Statistics on the research output in the field disclose a prospective future for microbial fuel cell technology in India (Fig. 2).

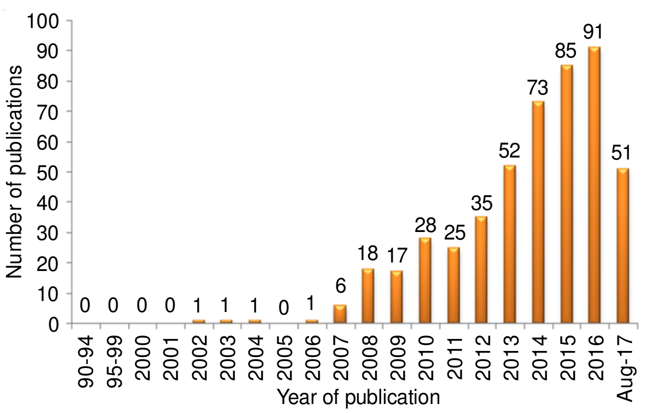

Fig. 2. Graph showing the number of publications from India since 1990 until August 2017 in topics related to Bio Electrochemical Systems. (Reference: Scopus)

Microbial fuel cells: In a broad sense, bioelectrochemical systems (BES) are systems in which biological and electrochemical processes are employed to generate hydrogen, electricity and other useful chemicals. These systems consist of anode and cathode chambers that are connected *via* an external circuit. Biological systems (usually microbial cultures) either donate electrons at the anode or capture them at the cathode. Simultaneously, they degrade enormous variety of substrates including agricultural wastes [10], sewage [11], natural water sources [12], landfill leachate [13] and other low-grade carbon sources for the recovery of energy and other products. Two prevalent technologies in BES are microbial fuel cells (MFCs) and microbial electrolytic cells (MECs). Microbial fuel cells are more efficient than MECs in energy recovery and organic waste removal. On the contrary, MECs possess proven potential for hydrogen generation in a cost-effective manner [14].

Microbial fuel cells are devices that employ electric properties of microorganisms to supply electrons to the anode to produce hydrogen and electricity (Fig. 3). Unlike conventional fuel cells in which metal catalysts generate electrons, MFCs obtain electrons produced during microbial oxidation of organic materials [15]. These electrons are captured by a suitable anode, which then combine with protons and oxygen in the cathode chamber to form water and usable electric current [16]. Most common microbes being used in MFCs are bacteria [16], yeast [17] and algae [18,19]. Microbial fuel cells are capable of harvesting more than 90 % of the electrons from organic compounds. This capacity renders them superiority over enzymatic fuel cells and abiotic fuel cells. For instance, a member of the family *Geobacteraceae, Geoalkalibacter ferrihydriticus* was reported to channel 85-95 % of electrons from acetate to electric current [20]. Moreover, bacterial culture in an MFC can constantly renew the supply of electrons while populating on the anode, thereby making the fuel cell self-sustainable [21]. A number of protein complexes are located in the bacterial cell as well as their outer membrane to facilitate the transfer of electrons through various metabolic pathways in the cell.

Set up of a microbial fuel cell

Microbes: Use of microbial inocula rich in electrochemically active bacteria (EAB) that possess immense ability for extracellular electron transfer (EET) is one key point in determining the performance of an MFC. Microbial fuel cell inoculated with EAB-enriched culture shows lesser internal resistance than that inoculated with an unfettered culture, such as, sulfur reducing bacteria [22]. Bacterial culture can be either a pure type containing single type of bacteria or a mixed culture, usually obtained from nature [23]. When microbial consortia are used, they may also contain electrically inert bacteria. These passive members contribute to synergistic electrogenic biofilm formation on the anode, thereby enhancing the electron donation by EAB [24]. Such synergistic activities are also known to enhance the otherwise slow natural degradation processes in addition to electricity generation [25]. EAB's possess special structures on their cell surface that facilitates electron efflux [26] from various substrates ranging from acetate [27] to lignocellulosic biomass [28]. Most extensively studied EAB so far are Gram-negative proteobacteria such as, *Shewanella oneidensis* and *Geobacter sulfurreducens* owing to their excellent electricigenic properties. More examples are listed in Table-2.

TABLE-2
LIST OF PROMINENT MICROBES EMPLOYED IN SOME DISTINCT MFC RESEARCH WORKS FOR PAST FIVE YEARS. ELECTRODES EMPLOYED, MAXIMUM POWER/CURRENT DENSITY GENERATED AND OTHER DISTINCTIVE FEATURES OF EACH WORK ARE MENTIONED

Organism	Anode	Cathode	Power	Current	Remarks	Ref.
S. japonica (from mussels of Sea of Japan); can degrade complex polysaccharides unlike other *Shewanella*	Low density graphite felt (0.13 g)	Uncoated graphite felt	–	0.66 mA/cm^3	Direct conversion of polysaccharides and agar to electricity with maximum after 75 h of MFC operation	[101]
Anaerobic sludge from Sewage Treatment Plant	Graphite felt with nanopolypyrrole	Carbon cloth containing 0.35 mg/m^2 Pt catalyst (7 cm^2)	430 mW/m^2	–	Demonstrates electropolymerization of anode material as an efficient method to enhance MFC performance	[102]
Shewanella frigidimarina (isolated from Antarctic Sea)	Graphite felt+ Titanium wire	Graphite felt+ Titanium wire	0.28 ?W/cm^2	0.56 ± 0.2 mA/cm^2	High current generation capacity when cultured in the presence of divalent cations such as Mg^{2+} and Ca^{2+} and under marine conditions.	[103]
Mixed slurry of kitchen waste, anaerobic compost and recyclable paper waste in semi-continuous stirred bioreactors	Carbon felt (10 cm^2)	Non-platinized Teflon-bonded carbon air cathode	22.26 mW/m^2	65.33 mA/m^2	The two-step continuous process with hydrogen/VFA (volatile fatty acids) produces hydrogen in the first step and electricity in the second step.	[104]
Heat-treated anaerobic sludge along with synthetic waste water	Stainless steel wire mesh (surface area 576 cm^2)	Carbon felt (surface area 1428 cm^2)	6.57 W/m^3	10.91 mA/m^2 at cathode	Power generation when sodium hypochlorite was used as catholyte was 9 times greater than that obtained when oxygen was used.	[105]
Aquaculture sediment with cellulose added at different concentrations	Graphite plates (projected surface area 1418 cm^2)	Graphite plates (projected surface area 1418 cm^2)	8.47 mW/m^2	–	Demonstrated effective cellulose degradation at a cellulose concentration of 2 % (w/w)	[106]
High pure H_2 and O_2 were used as the fuel and oxidant to maintain anhydrous conditions	Carbon cloth pre-treated and loaded with Pt catalyst (0.125 mg/cm^2)	Carbon cloth pretreated and loaded with Pt catalyst (0.375 mg/cm^2)	203 mW/cm^2 at 145 °C	–	A membrane electrode assembly of SPEEK/50 % IL doped composite membrane supported effective anhydrous proton transport membrane for fuel cells	[84]
	CNF-skinned Micropillar embedded film	–	~2496 mW/m^2	–	Power density ~ 10 times greater than that in pristine carbon film based electrodes	[80]

Electrodes: An ideal electrode should facilitate microbial colonization, substrate transport to attached microorganisms, removal of waste products, efficient transfer of electrons from the microorganisms to the electrode surface and efficient collection of current from all regions of the electrode [29]. Most commonly used electrodes are carbonaceous in nature [30], *viz.*, graphite fiber brushes [31], graphite plates [31], graphite felt [32] graphite rods, carbon mesh [33], carbon cloth [34] and carbon felt [35]. In addition, a number of novel materials are being experimented for their potential for generation of electricity in a sustainable and reliable manner (Table-2). For instance, glass wafers sputtered with Cr and Au in micron-scale proved to be ideal for rapid onset of current generation [36]. Some other modified electrodes recently reported are multi-walled carbon nanotubes [19] and their composites [29] and multilayered graphene foil [37]. Graphene and graphene based compounds have proven to be good choices for anodes in enzyme-based biofuel cells too, due to its excellent electrical communication properties as redox active conducting polymers [38].

Proton exchange membrane: While the electrons donated by the bacteria at the anode reaches the cathode through external circuit, the protons migrate through the solution across a proton exchange membrane that separates the cathode and anode chambers in a typical MFC [39]. Oh and Logan [40] demonstrated that power generation in a typical MFC is a function of surface areas of proton exchange membrane and the cathode relative to that of the anode. However, most of the customary proton exchange membranes, such as Nafion, are costly and uneconomical for practical applications and also have some disadvantages [41]. Mayahil *et al.* [42] developed a fuel cell membrane electrode assembly made of PtRu active species supported on mesoporous carbon nitride material. This enabled enhanced hydrogen absorbing capacity and greater efficiency of the fuel cell.

Mechanism of electron transfer: Many microorganisms have electrical properties and can pump electrons to the exterior. Thus, they are competent with conductive polymers and can act as supercapacitors and transistors. Bacteria transfer from electron extraneous substrates to the electrodes through three different modes. Extensive research has been done for the past decade to unravel the molecular mechanisms behind bacterial electron donation to the anode. These electron shuttle mechanisms and the components involved have routinely been reviewed explicitly by research groups led by Lovley [43-46] and Logan *et al.* [15,39,47,48]. Three predominant modes of bacterial electron transfer are *via* cytochromes, nanowires, soluble mediators and conductive biofilms (Fig. 3).

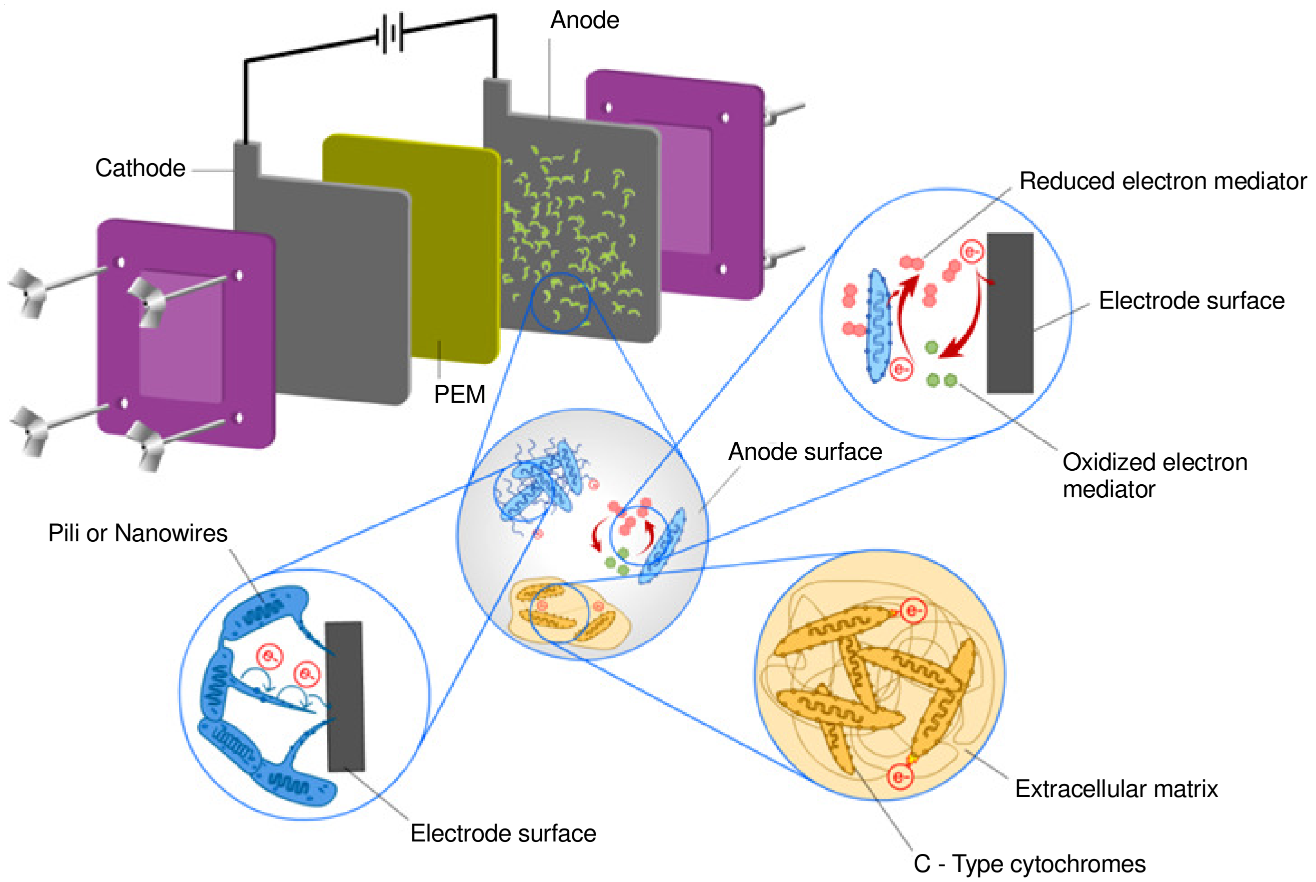

Fig. 3. A typical microbial fuel cell. Bacterial biofilm is formed on the anode surface that transfers electrons through any of the three modes: redox molecules, extracellular matrix, or pili. Cathode and anode are separated by proton exchange membrane

Cytochromes: Cytochromes are membrane bound heme-proteins that are actively involved in external electron transfer and ATP generation. Multiple lines of evidences suggest that, of all types of cytochromes, c-type cytochromes are the key determinant in direct transfer of electrons (DET) from the respiratory chain to the anode [15,49,50]. Apart from the outer membrane, c-type cytochromes were detected in other locations such as along the length of pili [51] and in conductive biofilms. Interestingly, these proteins exhibit high degree of conservation across different species.

Richter *et al.* [50] presented a comprehensive list of protein complexes and corresponding genes that assist c-type cytochromes in DET. In *Shewanella oneidensis* MR-1, majority of electron transfer takes place en route cytochrome complexes dispersed throughout the cytoplasm, outer membrane and periplasmic space. The electron flow occurs through a series of multi-heme cytochromes with overlapping potential windows, to pump electrons from higher potential to lower potential outside the cell. *S. oneidensis* possess genetic information for 42 distinct c-type cytochromes [52].

Geobacter has similar network of membrane proteins designated as OmCB, OmCZ, OmCE and OmCS [50]. However, these complexes in *Geobacter* species exhibit lesser degree of conservation, probably due to co-occurrence of multiple molecular strategies in these bacteria for electron transfer [20].

C-type cytochromes on the outer membranes can also form long chains or networks that can serve as electrical linkages between Fe-oxide (α-Fe_2O_3 and α-FeOOH) nanocolloids. This phenomenon allows cell populations to exploit semiconductor-mediated electron hopping, enabling efficient electron transport to the anodes [53].

Pili or nanowires: They are comparable with synthetic metallic nanostructures and can conduct signals for distances in centimeter scale. Nanowires or pilin nanofilaments of *Geobacter sulfurreducens* have electronic conductivity in the range of 5 mS cm^{-1}, which is comparable to that of synthetic nanowires [54]. The study revealed the formation of a confluent biofilm that spread across non-conductive gap. *Geobacter sulfurreducens* transfer electrons to Fe(III) mainly through nano conductive pili [54] which have aromatic amino acids in the C-terminus that account for conductivity of the pili and increased current production by the bacteria [55]. Recently, data from ambient electrostatic force microscopy revealed that electron transfer takes place *via* delocalized charges across pilus [51] and not through hopping mechanism as previously thought [56].

Other prominent bacteria that use nanowires are *Shewanella oneidensis* MR-1. They were found to be electrically conductive along micrometer length scale with electron transport rate up to 10^9/s at 100 mV and resistivity of the order 1 Ωcm [57].

Extracellular mediators: Many planktonic bacteria secrete soluble extracellular mediators that can function as electron shuttles between the electrode and the cell (Fig. 2), such as, phenazine derivatives produced by *Pseudomonas aeruginosa* [58] and quinone derivatives produced by in *Lactococcus lactis* [59] and *Geobacter metallireducens* [60]. Rabaey *et al.* [58]

discovered that *Pseudomonas aeruginosa* KRP1 secretes pyocyanin and phenazine-1-carboxamide [58] that is effective in transporting electrons to bacteria belonging to other genera too. This was the first report on the ability of bacteria in a mixed culture to utilize derivatives of other members for growth and electron shuttle.

Similarly, *Shewanella* can transfer electron to the electrodes located > 50 μm from the cells with the aid of flavins secreted by them. Flavins have also been shown to remain adsorbed to the electrode surfaces especially when they are colonized by biofilms [61]. Okamotoa *et al.* [62] suggests that flavin/outer membrane c-type cytochrome interaction regulates the extent of extracellular electron transport in *S. oneidensis*.

Xu *et al.* [63] reported the use of dye decolorized intermediates such as bicyclic aromatics-1-amino 2-naphthol and 4-amino 1-naphthol as artificial and cost-effective mediators to improve the power output by MFC.

Conductive biofilms: Electron shuttle is more robust when bacteria remains closely adhered to the electrode surface by forming conductive biofilms. This is because, effective transfer of electrons from the cell to an insoluble extraneous material such as an electrode requires intimate contact with the cell and the electrode. In contrast, when the bacteria reduce insoluble minerals such as Fe(III) oxides, they become planktonic and move around, using flagella to search for the mineral deposits [46].

The role of electrogenic biofilms is indisputable [15] and a number of mechanisms have been proposed to explain electron transport *via* biofilms. Cytochromes, nanowires and mediators [15] generally mediate electron transport in biofilms.

Novel perspectives

Powering electrical instruments: First-ever commercial application of microbial fuel cell to power an electrical instrument was reported by Tender *et al.* [31]. The team demonstrated powering of a metereological buoy with 18 mW average consumption, using a benthic microbial fuel cell (BMFC) that weighed 16 kg and had a volume of 0.03 m^3. The BMFC deployed in a salt marsh in New Jersey, USA, could operate successfully incurring a cheaper cost. This was an indication of the potent application of MFC's for long-term operations of electric and electronic devices.

Electrosynthesis: BES technology enables synthesis of liquid carbon fuels and other organic commodities by electrically activating microorganisms. Most commonly, the role of the electrode reaction in the whole system of catalysis is to maintain a redox enzyme in its active oxidation state to facilitate synthesis of organic compounds. Microbes that inhabit the cathode reduce carbon dioxide forming products of commercial and industrial application. This novel route of chemical synthesis is highly attractive and involves the integration of microbiology and electrochemistry [64]. It was shown by Eerten-Jansen *et al.* [65] that electrons generated at the cathode of a bioelectrochemical system with -0.9 V *vs.* NHE cathode potential can be used for synthesis of medium chain fatty acids such as caproate and caprylate from acetate.

Geobattery: Microbial batteries can act to recover energy from natural energy reservoirs such as marine benthic zones and wastewater reservoirs, which would otherwise turn out to be green house producers when left unattended. Xie *et al.* [66] describes the significance of microbial batteries for recovery of energy from reservoirs of organic matter, such as wastewater. Next generation battery technology may be dominated by microbial fuel cells at nanoscale. A group of scientists from Carnegie Mellon University, Pennsylvania designed the smallest MFC reported to date, with a total volume of 0.3 μL [36].

Photo MFC's: Photosynthesis can be linked with bacterial electricity generation to tap solar energy for electrochemical purposes. Electric current from sunlight can be generated by electrocatalysis of heterotrophic bacteria at the anode [67]. Illumination at the cathode is also prospective in generating products of interest.

Nanotechnological applications: Nanotechnology has a significant role to play in improving the charge-transfer efficiency of microbial fuel cells. A number of renowned laboratories have switched their focus onto exploring potential of nanotechnology. Dr. Alivisatos' research group in University of California is one such leading group in nanotechnological research.

Generation of hydrogen: Hydrogen generation is one potential application, the development and commercialization of which, is hampered by difficulty in storage and transportation. Nielsen *et al.* [68] suggests a robust method to overcome this obstacle. Molecular hydrogen can be converted to produce electricity in a low-temperature proton-exchange MFC. To achieve sustainable hydrogen production and its conversion to energy (hydrogen economy), hydrogen can be stored in methanol. It can later be recovered through low-temperature aqueous-phase methanol dehydrogenation process with the help of ruthenium complexes. Through this process, hydrogen can be generated at 65-95 °C and ambient pressure. Hence, hydrogen storage and recovery can be made feasible.

Hybrid Technologies: MFC's can be used in combination with other technologies for power generation. For example, Logan and Elimelech [16] described a combinatorial development of technologies such as MFC, Reverse electrodialyis (RED) and Pressure Retarded Osmosis. The maximum power density from an MFC using a forward-osmosis membrane (called an osmotic MFC) was 15 % higher with a 35 g L^{-1} sodium-chloride solution than from the MFC alone. Microbial desalination cells (MDS) is another hybrid technology wherein, electrodialysis, in combination with MFC is employed in groundwater remediation- by removing salinity and hardness of water and generates hydrogen [69].

Microbial fuel cell research in India: In India demand for energy expected to rise by 6 % in the next decade. In the current technological environment when there is a wave of transformation around the globe, it is most appropriate for Indian science to initiate, promote and gain a foothold on novel and prospective technologies such as MFC's. IPCC special report on renewable energy sources and climate change mitigation (SRREN) [70] emphasizes on the significance of policies adopted by the developing countries in determining the future of fuel technology. Even though the country's geographical state is appropriate for tapping various renewable sources, optimal efficiency can be achieved only when there is a strategic approach towards it. The scenario in India is promising. There is an arousal among scientists and policy makers for adopting these technologies. As rightly said by Dr. C.N.R. Rao, we should focus more on hydrogen, fuel cell and renewable energy technologies that hold much promise for future. As the country is facing severe deficit in terms of energy, we should be able to generate 3,50,000 to 4,00,000 MW of electricity by 2030 to meet the ever-increasing need. Therefore, it is high time to generate power through hydrogen.

Material advances

Microbial diversity: Most of the MFC studies done in India employed mixed cultures, probably due to their high power generating capacity. Geetha and Raj [71] demonstrated that mixed culture had better prospects in MFC's in terms of complex substrate utilization. Bacteria studied so far include *Pseudomonas aeruginosa* [72], *Lysinibacillus sphaericus* [73], co-culture of *Acetobacter aceti* and *Gluconobacter roseus* [74], consortium of sulfate reducing bacteria [75], binary culture of *Bacillus tequilensis* DMR-5 and *P. aeruginosa* DMR-3 [76].

Selvaraj *et al.* [77] identified the role of at least 11 newly predicted ABC transporter proteins in respiration and biofilm formation- and in turn, electricity generation- by *Geobacter sulfurreducens* PCA. In a novel approach to developing MFC's with better performance, Gupta *et al.* [78] utilized the potential that develop during interaction between negatively charged *Klebsiella pneumoniae* (Kp6) and positively charged phage (p-Kp6) for generation of electricity. When both the cells were pumped through a fuel cell fitted with copper electrodes, the interaction resulted in an open circuit potential.

Electrodes: There is a need for good electrode materials that are low-cost, biocompatible and easy to use to make MFC technology cheaper and viable. Jayapriya and Ramamurthi [72] tested different electrode combinations and discovered that of all the combinations of carbonaceous and metal-salt doped epoxy composites tested, Fe^{3+} graphite cathode produced significant power output. In a similar approach, Geetha and Raj [71] proved that $KMnO_4$ could perform as better cathodic electron acceptor (Power Density 6.26 mW/m^2) than $K_4[Fe(CN)_6]$ and dissolved oxygen. A team led by Das and Pradhan [79] of IIT-K demonstrated convincingly that polypyrrole is a better conducting support than conventionally used Vulcan XC and they can improve the efficiency of energy recovery by manganese cobaltite nanorods when mixed *in situ*. Khare *et al.* [80] demonstrated that N-enriched Ni/carbon micropillar-embedded carbon film, when used as electrode, could produce approximately 10 times greater power density (about 2496 mW/m^2) than that by pristine carbon film-based electrodes. The choice of coatings for anode varied from goethite [81] to carbon supported nickel-phthalocyanine/MnOx [82]. Some other research outputs are listed in Table-3.

Membrane systems: Development of membrane systems is one thrust area of active research. Ayyaru and Dharmalingam [83] introduced a novel material for the enhancement of PEM performance. They used sulfonated TiO_2 (S-TiO_2)/polystyrene ethylene butylenes polystyrene (SPSEBS) as nanocomposite membranes. This new membrane was shown to deliver 4-folds higher power density than Nafion 117 membrane. Jothy and Dharmalingam [84] showed that a similar material, simple combination of a phosphate based alkylimidazolium ionic liquid in sulfonated poly (ether ether ketone) polymer matrix could be a promising anhydrous PEM. Modifications of these composites with improved performance were also reported by Prabhu and Sangeetha [85]. Pardeshi and Mungray [86] suggested that high flux layer by layer polyelectrolyte forward osmosis membranes with improved performance could be synthesized to reduce their cost.

Sabina *et al.* [87] recently demonstrated a novel application of MFC principle with huge future prospects. The team developed a microbial desalination cell in which *Bacillus subtilis* degraded waste engine oil with considerable power production (3.1 ± 0.3 mW/m^2) along with desalination and enhanced biodegradation. Masih *et al.* [88] demonstrated that bioremediation of river water can be collaborated with MFC performance. More focus is needed towards development of effective hybrid technologies. Rahman *et al.* [89] developed an integrated electrolytic-electrodialytic apparatus in which hydrogen evolution was combined with removal of metal ions from waste water streams. The invention, which was patented in 2006, could bring down the concentration of metal ions in wastewater from thousands of ppm to a few ppm.

There is a trend in Indian research towards combining electricity generation with waste management. Considerable research has been carried out in this regard [90-100]. Advancements in the field of biofuel cells, another type of BES employing enzymes as electron donors are equally important. Its

TABLE-3
SOME PROMINENT RESEARCH OUTPUTS BY VARIOUS RESEARCH GROUPS IN INDIA WITH REGARD TO MATERIAL DEVELOPMENT OF MFC's

Component	Modification	Power density	Ref.
Cathode	Activated carbon fabric with stainless steel mesh	23.11 mW/m^2	[75]
Anode	Activated carbon nanofiber	3.50 ± 0.46 W/m^3	[108]
Cathode	α-MnO_2 nanotube/graphene oxide	3359 mWm^{-2}	[109]
Cathode	Sodium hypochlorite (NaOCl)	6.57 W/m^3	[105]
Cathode	Air-cathode modified with vanillin + PVA binder	233 mW/m^3	[91]
Anode	Goethite heat treated at 550 °C coated over stainless steel anode	17.1 W/m^3 at 20 Ω	[81]
Cathode	Liquid crystal coated polaroid glass electrode (LCPGE)	10 mW/m^2	[97]
Catholyte	Hypochlorite	8.7 W/m^3	[104]
Catalyst	Ceria (CeO_2) nanoparticles coated on graphite	~ 2403 mW/m^3	[110]
Proton exchange membrane	Oxy-polybenzimidazole (OPBI) and its sulfonated analogue (S-OPBI)	87.8 mW/m^2	[111]
Substrate	Cow's urine	5.23 W/m^3	[112]
Membrane/catalyst binder cathode	Quaternized polysulphone (QPSU)	810 mW/m^2	[113]
environment	Aqueous $KMnO_4$ at pH 6.86	7.8 W/m^3	[114]
Cathode	Carbon supported nickel-phthalocyanine/MnOx	10.58 Wm^{-3}	[82]

versatility, especially, ability to perform in miniature forms ensures its wide applications in biomedical devices, genetic engineering and biosensing [38].

The progress of the technology in India is evident from increasing number of publications on the topic. Scopus publications have increased from 1 in 2002 to more than 90 in 2016. In 2017 so far we have more than 50 publications in leading journals. Moreover, our results in terms of power generation are comparable with those in other foreign laboratories (Table-2).

Conclusion

R&D in MFC in India is in par with the pace of research in developed countries, though the number of institutions giving prime consideration for the technology is only a few. These institutions focus on development of better electrodes, cheaper and versatile membrane systems and wastewater treatment apart from exploration of energy generation potential by organisms other than bacteria. Still, there is a significant lack of path-breaking achievements apart from a few innovations from IIT Kharagpur, which have been filed for patents.

The current scenario underscores the high potential for development of the technology in India. Nonetheless, research institutes should produce worthier results and explore the potential of MFC in applications other than wastewater treatment. Areas that remain less explored include improvement of performance of microorganisms through biotechnology, photo MFCs, algal systems, micro MFCs with microfluidic technology, nanocompounds as membranes and electrodes, potential of other biosystems as energy source and development of technologies for hydrogen storage. Though MFC technology cannot subdue wind or hydropower, it can surely contribute to the expanding body of possible energy sources. The success of a technology depends on the optimized satisfaction of all the stake holder perspectives. Thus, success of MFC lies not only in the excellence of research, but also on various other factors. These include satisfaction of various facets such as commercial success, technological system optimization, optimal satisfaction of market share and profits, options for the government to generate loyalties and taxes along with stimulation of natural resource development, in addition to free and easily accessible energy for consumers of different status.

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