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Studies on Bioelectricity Production from Industrial and Domestic Wastes: Current Trends and Future Perspective

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Abstract
Electricity is the major concern of modern era. Countries are facing power crisis because of increasing population and less non-renewable energy resources such as coal, petroleum etc. Thus, to overcome this power crisis, the industrial and domestic waste materials as a source of energy can be used. A unique kind of fuel cell with a potential in long term is the biofuel cell or microbial fuel cells (MFCs). It is a device that converts domestic and industrial waste material into generation of electricity by the action of microbes as a catalyst suchas saccharomyces cerevisiae, E. coli, Geobacter, clostridium sp-EG3 etc. The MFC work on the principle that microbes oxidized to waste material and generate carbon dioxide, electrons and protons at anode. These electrons are transferred through an external circuit which leads to the production of bioelectricity. The power density that an MFC can typically generate is 1 to 2000mW. The sewage and industrial waste showed bioelectricity production upto 594mW. The system utilizes the metabolism power of bacteria for electricity generation and MFC has a future perspective for bioelectricity production from different waste materials.

Keywords: *Bioelectricity, microbial fuel cell (MFC), geobacter, saccharomyces cerevisiae, non-renewable energy resources*

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I. Introduction

In recent years, due to globalization, higher population growth, and technological development, the global demand for energy has increased significantly. Fossil fuels have been the primary source, fulfilling 80% of this energy demand (Hasheni *et al*., 2011). To address the need for reducing fossil fuel consumption, biomass emerges as a crucial resource for producing bioelectricity, biofuel, and heat (Appels *et al*., 2011). Bioelectricity, generated from biogas produced through the anaerobic digestion of waste-derived biomass, stands out as a promising alternative to traditional fossil fuel consumption (Loganath *et al*., 2020). Additionally, anaerobic digestion plays a vital role in industrial waste management, contributing to environmental sustainability while providing clean energy (Hoo *et al*., 2018).

A promising long-term solution in the field is the biofuel cell, with recent studies exploring the use of cattle waste substrate for successful bioelectricity production through Microbial Fuel Cells (MFCs). The conversion of carbohydrates to hydrogen is facilitated by a multienzyme complex system, involving the transformation of glucose into 2 mol of NADH and 2 mol of pyruvate through the Embden-Meyerhof pathway in bacteria (Palmore *et al*., 1998). Immobilized microbial cells have demonstrated continuous hydrogen production under anaerobic conditions, although challenges exist due to poor electrical communication betweenthe cells and the electrode surface (Willner *et al*., 1996).

MFCs present a promising technique for generating electricity from microbial cells. In an MFC, anode and cathode are separated by a cation-specific membrane. Microorganisms in the anode compartment oxidize fuel, generating electrons and protons. Electrons are then transferred through an external circuit, while protons diffuse to the cathode, where they combine with electrons and oxygen to form water (Lithgow et al., 1986). Microorganisms can transfer electrons to the anode electrode through exogenous mediators, mediators produced by bacteria, or direct electron transfer from respiratory enzymes to the electrode (Bond et al., 2003). Mediators trap electrons from the respiratory chain and facilitate their transfer to the electrode via the outer cell membrane (Min *et al*., 2004).

An experimental study focused on maintaining samples in anaerobic conditions to settle solid particulate contents for analytical purposes. Two sugar sources, glucose and sucrose, were used for bioelectricity production at the laboratory scale from domestic and industrial waste. Samples were treated differentially, with duplicates designated as follows: Sample (A) - Plain diluted wastewater without treatment; Sample (B) - 10% glucose solution of plain diluted wastewater (Sample A); Sample (C) - 10% glucose and 0.5% methylene blue solution of plain diluted wastewater (Sample A); Sample (D) - 10% sucrose solution of plain diluted wastewater (Sample A); Sample (E) - 10% sucrose and 0.5% methylene blue solution of plain diluted wastewater (Sample A) (Tyagi *et al*., 2012).

Chemicals and Microorganisms

Chemicals and microorganisms are employed based on the source to generate bioelectricity from various substrates. In the research conducted by Tyagi *et al.* (2012), wastewater samples were collected from industrial areas in Moradabad, U.P., India. All chemicals used were of analytical grade and obtained fromSigma Aldrich Co. The microorganisms utilized included Bacillus subtitles (MTCC-121), Clostridium acetobutylicum (MTCC-481), Escherichia coli (MTCC-2939), Saccharomyces aureus (MTCC-96),Saccharomyces cerevisiae (MTCC-178), and Proteus vulgaris (MTCC-742). In another study by Mehmet et al. (2010), S. aureus and S. cerevisiae were grown aerobically in a defined medium, followed by appropriate inoculation, and the samples were incubated for 72 hours at 28°C.

Recently, researchers have embraced the challenge of using algae in conjunction with bacterial communities to provide an organic carbon fuel source for Microbial Fuel Cells (MFCs) (Enamala *et al*., 2020).

Substrate

In Tyagi *et al.* (2012) study, glucose-rich molasses and sucrose-rich domestic wastewater served as fermentation substrates in the reaction mixture medium. Additionally, specific mediators such as methylene blue, crystal violet, Commassie brilliant blue, and cresol red were used in three sets of experiments with triplicates each. These experiments were designed for the optimization of voltage and current.

In Abbasi *et al.* (2015) study, wastewater samples from various industries, including vegetable oil, metalworks, glass and marble, chemical industries, and industrial effluents, were collected. Each sample was treated for 98 hours in an MFC. Various substrates were used, including non-fermentable substrates like acetate and butyrate (Liu *et al*., 2005), fermentable substrates such as glucose, xylose, and sucrose (Catal *et al*., 2008), and even complex substrates containing both non-fermentable and fermentable components, such as corn stover hydrolysate, domestic wastewater, food process wastewater, paper recycled wastewater, and aquatic sediment organic matter (Holmes *et al*., 2004; Huang *et al*., 2008; Oh and Logan *et al*., 2005; Zuo *et al*., 2006).

From the above data it is shown that the best results were show by Escherichia coli, up to maximum power density 760mW/m^2 produced by applying the composite electrode (graphite/TTFE) and glucose as substrate for this particular organism in the single chambered MFC (Rahman *et al.*, 2021).

Various parameters used for bioelectricity production with the application of certain microorganisms have been listed in the Table 1.

Table 1. Details of strain, substrate, electrode, MFC type, and max power density used for Bioelectricity production using various microorganisms.

Substrate	Anode	Microbes	Type of MFC	Max power density (mW/m^2)	Refs.
Glucose	Carbon cloth	*Geobacter*SPP	Two-chambered	40.3	Jung *et al*. (2007)
Glucose	Graphite	*Saccharomyces cerevisiae*	Two-chambered	16	Rahimnejad *et al*.(2009)
Sewage sludge	Graphite with Mn^{4+}	*Escherichia coli*	Single-chambered	91	Nevin *et al*. (2008)
Glucose	Composite electrodes	*Escherichia coli*	Single-chambered	760	Rahimnejadet al.(2011)
Lactate	Carbon cloth	*Geobacter* SPP	Two-chambered	52	Jung *et al*. (2007)
Acetate	Carbon cloth	*G. sulfurreducens*	Two-chambered	48.4	Jung *et al* .(2007)
Glucose	Graphite plate	Mixed culture	2-chambered air cathode MFC	283	Rahimnejad *et al*. (2011)
Glucose	Carbon cloth with CNTs	*Escherichia coli*	DCMFC	228	Zou *et al*. (2008)

MFC Construction and Operation

Before delving into the utilization of Microbial Fuel Cells (MFCs), it's essential to understand the construction of these cells. MFCs were primarily designed with the incorporation of electrodes in a two- chamber glass vessel interconnected by a nitrocellulose membrane, polyvinyl chloride membrane, salt bridge, orcotton cloth under defined experimental conditions. Figure 1 illustrates the schematic configuration of the MFC-fabricated chamber. The beakers were connected by a glass bridge containing a proton exchange membrane, specifically Nitrocellulose and Polyvinyl Chloride, secured by a clamp between the flattened ends ofthe two glass tubes fitted with rubber gaskets. Electrodes underwent cleaning with 1.0 N NaOH followed by 1.0 N HCl, and after each experiment, they were stored in sterile distilled water. Watertight electrical connections were established, and the liquid volume in each chamber was maintained at approximately 500 ml and 100 ml, with a headspace of about 200 ml and 440 ml, respectively. Flushing was implemented to maintain anaerobic conditions in the chambers. In the cathode chamber, 30mM Tris buffer (pH7) was used and continuously flushed with sterile, water-saturated air. For power output determination, a variable resistance (0.1 to 3.0 Ω) was employed as an external load. All experiments were conducted at a temperature of 37°C, and current and voltage were measured using a Digital Multimeter (Tyagi *et al*., 2012; Fig. 1). The choice of membrane is a critical factor in MFC development, responsible for transferring required ions while preventing the undesired ones, commonly used on cost and efficiency considerations. While salt bridges can be used, they are generally less efficient than

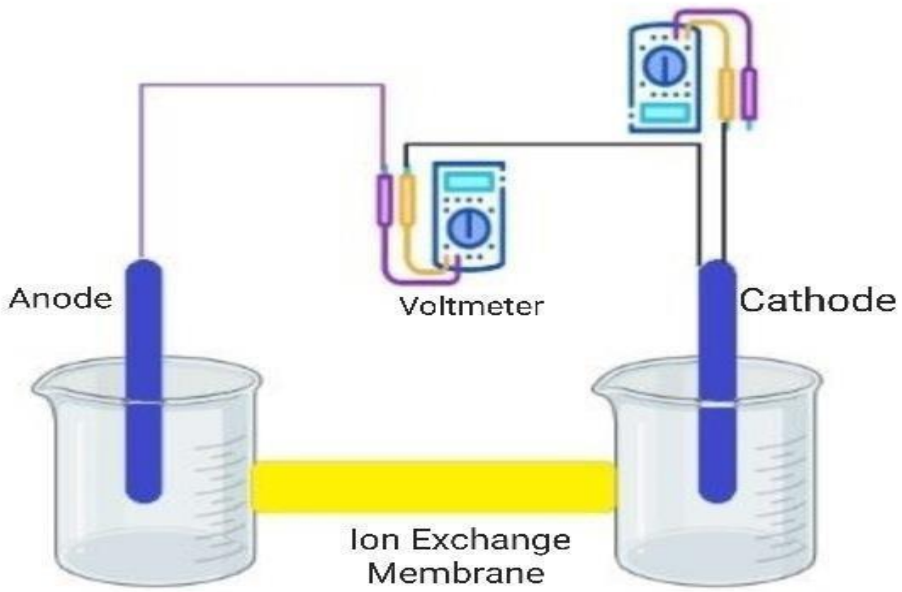

Figure 1. Schematic diagram of MFC fabricated chamber system with two chambers, anodic chamber containing MFC is interconnected with membrane (Nitrocellulose/Poly-vinyl Chloride) to cathodic chamber containing chemicals. An ammeter and voltmeter is connected to the chambers. (c.f. Tyagi *et al.*, 2012)

membranes. Mediators, such as methylene blue, crystal violet, commassie brilliant blue, and cresol red, are potential factors influencing MFC performance. Various electrodes, including graphite, carbon cloth, charcoal, and platinum, are employed based on their efficiency and cost. Platinum, despite being costly, offers high efficiency. MFC efficiency relies on several factors, with notable considerations being the surface area of electrodes, internal resistance of the system, open circuit voltage, and closed circuit voltage. Thus, during MFC development, it is crucial to consider all these factors to create an overall efficient MFC system. Drawing insights from studies by Lu *et al*. (2009), Min *et al*. (2005), and Zheng *et al*. (2010), the current model reflects an efficient MFC system for bioelectricity production, aligning with waste recycling objectives. Ongoing laboratory progress focuses on comprehending biotechnological applications related to these concepts (Lu *et al*., 2009).

II. Conclusion

From the above study we came to know about different types of microorganisms and different type of sources were usedfor bioelectricity production.There are some moresources from which bioelectricity can be generated by using MFCs. For example, (Rahman *et al*., 2021) used mango, banana, and orange waste as substrate in their single chamber, fuel cells, achieving peak voltages of 0.350 V for the orange substrate and adding glucose at 0.5 V (Kondaveeti *et al.*, 2019). Likewise, (Kondaveeti *et al*., 2019) used citrus peels as substrates in their single-chamber cells managing to generate 0.250 V and 72 mW/cm^2 Voltage and power density values (Rahman *et al*., 2021). (Prasidha *et al*., 2020) used food waste leachates as substrate in their double chamber fuel cells, managing to generate 0.410 V and 0.23 mA /cm^2 voltage and current density, concluding that aeration of the cathode chamber increases the energy values (Rahman *et al*., 2021). Various types of agro-waste can be found in the environment, which depends upon the source and availability. They can be derived from many different sources such as municipal solid waste works, livestock excrements, lignocellulosic and agro-wastes, food crops, etc. Thus, such waste can be classified into four main generation based on their ability to produce different types of products (Pandit *et al*., 2021): (a) First generation: This comprises various food crops such as Wheat, corn, rice, and sorghum. Fuel production is viewed to be of a higher return on investment than food production; (b) Second generation: This generation generally consists of lignocellulosic wastes like sugar-cane bagasse, wood chips, crop residues, and organic waste that can be employed to generate bioenergy using different waste management techniques; (c) Third generation: Microalgalbiomass, which is used in engineered energy source production as a feedstock. Hence, its cultivation can easily be achieved in lagoons and open ponds using a high nitrogenous compound containing agro-waste containing waste water; (iv) Fourth generation: This type of biomass is from metabolically engineered species such as bacteria, including algae generated from cleaner disposals, or emissions control processes such as CO2 capture systems (ElMekawy *et al*., 2015).

MFC development is a global undertaking driven by its notable ability to recycle pollutants while concurrently generating a substantial amount of electricity. Consequently, contributing to the advancement of MFCs has been a primary objective among various ongoing endeavors. The process of MFC development involves meticulous consideration of numerous factors, paving the way for the creation of more efficient and effective MFC systems. The convergence of environmental sustainability through pollutant recycling and electricity production propels this field into a promising and impactful realm.

III. Future Perspectives

Looking ahead, the ongoing research and development in MFC technology offer promising future prospects for the efficient generation of bioelectricity from organic wastes and wastewater. As highlighted by Logrono et al. (2014), MFCs have already been investigated as devices to harness bioelectricity from such sources. Moreover, the application of MFCs for pollutant treatment, including substances like phenol, demonstrates the versatility and potential impact of this technology (Moqsud et al., 2013).

Addressing the current challenge of low power densities in MFC operation, future endeavors will likely focus on optimizing the design to mitigate losses caused by activation, ohmic, and concentration overpotentials (Nastro et al., 2015). Enhancing the system's volumetric capacity through direct oxidation and other approaches may help minimize internal energy losses. The utilization of MFCs is anticipated to be a common strategy to avoid significant losses, emphasizing the need to elevate exoelectrogenic microbial population density. This may involve bioaugmentation and leveraging potential field effects within the electrode, capitalizing on its morphology and conductivity.

Future research efforts will likely be directed towards overcoming limitations in microbial attachment positions on the electrode surface, potentially through bioaugmentation and addressing field effects. Modifying electrode surfaces and employing active catalyst coatings are avenues being explored to establish more efficient electron transfer mechanisms between the electrode and the biocatalyst. These advancements aim to optimize MFC performance and enhance overall bioelectricity output.

In summary, the evolving landscape of MFC technology presents new insights and opportunities for the development of a pivotal platform. The ongoing efforts and advancements provide a foundation for exploring possibilities for upgrading output through more advanced MFC technologies, fostering a greener and more sustainable approach to energy generation and wastewater treatment in the future.

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