Bio-electric Photosynthetic wall panels

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***Abstract*— Long-term availability of energy from sources that are accessible to all and eco-friendly are crucial for sustainable economic development. Bio electrochemical systems (BESs) have recently emerged as an exciting technology in this field. One such system which seems highly promising is a microbial fuel cell (MFC). A typical MFC is a bioreactor that uses microbes to convert biomass containing organic compounds such as glucose, fructose etc. directly to electrical energy. Generally MFCs use wastewater as source of organic compounds, which are then digested by selected microbes. Here, we investigate the possibility of building wall panels, based on the basic concepts of MFCs that use the synergistic relationship between photosynthetic and heterotrophic microbes to produce electricity from light. These panels will not only help in electricity generation but also, if their use becomes widespread, will help in reducing the atmospheric carbon dioxide (as it is used by microbes for photosynthesis). Through these panels, we plan to tackle certain core issues that plague conventional MFCs, namely low power density, large size and low self-sustainability Although these panels might currently be expensive and cumbersome for commercial manufacturing and general public use, but with the help of further research and optimization they could very well form an affordable, accessible and effective source of clean and green energy.**

***Index Terms*—Power generation, MFC, microbial mats, sustainable energy sources**

I. INTRODUCTION

A. Traditional MFCs

At a time when energy crisis is a major problem even for the developed nation, people have begun to look for alternative sources of energy that are safe, clean, reliable and ecofriendly. Microbial fuel cells have recently emerged as an exciting technology. A microbial fuel cell is a bio-electrochemical system. Bio implies bacterial species and their interactions in nature, electrochemical mean any system that drives current by the energy released from the spontaneous redox reaction. In simpler terms, a microbial fuel cell is a bio-electrochemical system that drives a current by using bacteria, by harnessing the energy present in the electrons of the bacterial electron transport system (ETS). Generally, MFCs use wastewater as source of organic compounds, which are then digested by selected microbes. It generally contains two chambers containing anode and cathode respectively, divided by a proton exchange membrane (PEM). The electrons produced by the bacteria during respiration are transferred from the anode to cathode via any conductive material like resistor (load). At the same time protons are transferred from the anode to the cathode via the PEM. In the cathode chamber, oxygen- the final electron acceptor, along with the protons and electrons (available at the cathode), forms water, thus completing the cell. And thus the bacterial ETS is harnessed to produce electricity. The bacteria doesn't always transfer their electrons directly to the electron acceptor i.e. anode. Mostly in such cases, we use mediators to help these bacteria divert the electrons to an electrode i.e. anode. Chemical mediators such as neutral red [1] etc. can be added. Although mediators are quite expensive and degrade over time, many times becoming harmful for the bacteria itself [2]. To tackle this, electrochemically active compounds are incorporated in the electrode itself. This approach has been previously tested by Park and Zeikus [3] using natural red dye and metal ions such as Fe^{3+} and Mn^{4+}. This design is much more stable and has a longer lifetime. Alternatively electrochemically active bacterial species can be used that transfer electrons to the anode efficiently enough even in the absence of any mediators or special electrodes [4]. Regarding the bacterial cultures used, mixed cultures are preferred over pure ones as mixed ones have relatively higher energy transfer efficiency [2]. The benefits of MFCs are cost efficiency, low emissions and clean source of energy Although, microbial fuel cells seem to be a good prospect of future storehouse of energy but there are many bottlenecks to be resolved in order to say that MFCs are this era's clean, green and sustainable source of energy. First and foremost since it involves a new technology, we need investors to join in hands but even before that, we have certain technicalities and issues [2] like the efficiency of the fuel cell, power output, reactor size, optimum temperature which need to be solved.

B. PhotoMFCs

There are various types of MFCs that have been designed. One kind, which seems pretty interesting is photoMFCs. Typically when sunlight is converted into electricity within the metabolic reaction scheme of a MFC, we describe this system as a photo-synthetic MFC (photoMFC) [5]. PhotoMFCs were originally tested in the 1960s with metal electrocatalysts and in the 1980s with artificial electron mediators in the anode chambers [6, 7]. The rationale behind using the idea of MFC to make photoMFCs is to reduce the dependence of the MFC, for proper functioning, on external nutritional feeds for the bacteria. Besides bioelectricity generation, an additional benefit of photoMFCs is that carbon dioxide is removed from the atmosphere by the integrated photo-synthetic process [8]**.** Rosenbaum et al listed various leading approaches of coupling photosynthesis with microbial fuel cells. In their paper, "Light energy to bioelectricity: photosynthetic microbial fuel cells", they have explained about the five different conjectural models depicting photoMFCs. They are as follows:

- Photosynthetic bacteria at the anode with artificial mediators.
- Hydrogen-generating photosynthetic bacteria with an electrocatalytic anode.
- Synergism between phototrophic microorganisms and mixed heterotrophic bacteria in sediments.
- Synergism between plants and mixed heterotrophic bacteria in sediments.
- Ex situ photosynthesis coupled with mixed heterotrophic bacteria at a dark anode.
- Direct electron transfer between photosynthetic bacteria and electrodes.
- Photosynthesis at the cathode to provide oxygen

The third approach seems particularly useful. It's found that algae and certain other bacterial species, such as cyanobacteria, can supply organic matter by excreting polysaccharides [9] to heterotrophic bacteria via photosynthesis. These heterotrophic bacteria, in turn use it for respiration and are the major electron donators in the MFC. This interaction maintains synergistic communities between the two [8]. This principle is very powerful as it effectively alleviates or atleast reduces the amount of continuous "feeding" a conventional MFC requires and can be easily applied to a multitude of MFCs. As already mentioned, self-sustainability is a bottleneck that needs to be overcome in order to achieve widespread use of MFCs. Such approaches, involving use of phototrophic bacteria alongside heterotrophic ones is definitely a step in the right direction.

II. Bioelectric photosynthetic wall panels

A. Basic Structure

Our BioElectric Photosynthetic (BEP) wall panels are made up of a grid of small identical MFCs. The design of these MFCs differ from conventional H-cell configurations in order to account for the sleek profile of wall panels. **/.** The MFC unit is divided into layers. The outermost layer is a transparent plastic window that protects the MFC's internal parts from external damage but also at the same time keeps the space just below it well ventilated. Directly below it is the MFCs anodic chamber. It contains the anode, made of graphite felt. Unlike conventional designs, the anode spans entire area of cross section of the MFC. The anode is covered with a layer of microbial mat (composition of the mat discussed in detail later). Directly below the anode is the proton exchange membrane (PEM). The PEM also spans the entire area of cross section of the cell hence ensuring maximum area of contact with the anode. Just below the PEM is the cathodic chamber. The chamber consists of a cathode, also made of graphite felt, with shape and size similar to that of the PEM. Although it is not in direct contact with the PEM, rather they both are placed a little far apart. The space between them is filled with the catholyte. **Fig 1a shows an exploded side view of a single subunit of the wall panels.** The whole assembly is enclosed within a plastic encasing covering the bottom base and the right and left sides. The front part, as mentioned before, is covered with transparent plastic. The top and the bottom have been slightly modified, as shown in the **Fig 1b.** The metallic contacts electrically connect all cells in a column.. The cylindrical connections connect the catholyte of all cells of the same column. The function of the porous material is explained later. In a way, now each column of the grid now acts as a single cell. The top part of the grid is connected to 2 feeds**.** The red one contains saline water while the blue one contains the catholyte. Also the bottom most row can be modified to accommodate for periodic, controlled elution of liquids. **Fig 2 shows a comparison between conventional H cell MFCs and the BEP wall panels.** Exact dimensions of the cells can be decided upon only after conducting proper experiments. Use of currently existing MFCs, that have some aspects similar to these panels, to estimate the size of the panels has been omitted as no other current design is similar enough to provide for satisfactory accuracy.

B. Microbial Film

The microbial mat/biofilm is made up of various communities of autotrophic as well as heterotrophic bacteria. The exact composition of the mat can be determined only after thorough experimentation. Although the key bacterial species required for proper functioning of the mat are atleast one cyanobacterial species and atleast one of the following electrochemically active bacterial species such as *Geobacter sulfurreducens, Geobacter metallireducens, Desulfuromonas acetoxidans, Rhodoferax ferrireducens, Shewanella oneidensis and Shewanella putrefaciens.* Some of them are strictly anaerobic while others are facultative anaerobes. These will be situated in the bottommost part of the mat where oxygen concentration is almost zero (depending upon the thickness and composition of the mat). At the surface, the mat will contain autotrophic bacteria such as cyanobacteria. Depending upon the interactions of various micro-organisms in the mat, certain other species of bacteria might also live in its layers, but the above mentioned species are of utmost importance to the functioning of the cell.

C. Feeds

The two previously mentioned feeds are connected only to the cells of the top row of the grid. One of them contains saline water and is connected to the porous material, while the other contains catholyte and is connected to catholyte chamber. The water is used to keep the anodes humid and a bit salty to promote bacterial growth either continuously or as and when required. Herein lies the function of the porous membranes which allow slow dripping of water into anodes from the feed till the bottom most cell in a single column. The catholyte feed distributes catholyte throughout a single column. The catholyte connectors maintain constant catholyte composition in one column. Recent research shows that common salt dissolved in water can be used as catholytes instead of conventional chemical buffers [10]. Both are connected to respective storage containers kept on the roof. Due to their clever positioning, they require only a minimal pumping force to operate, as most of the work will be done by gravity only.

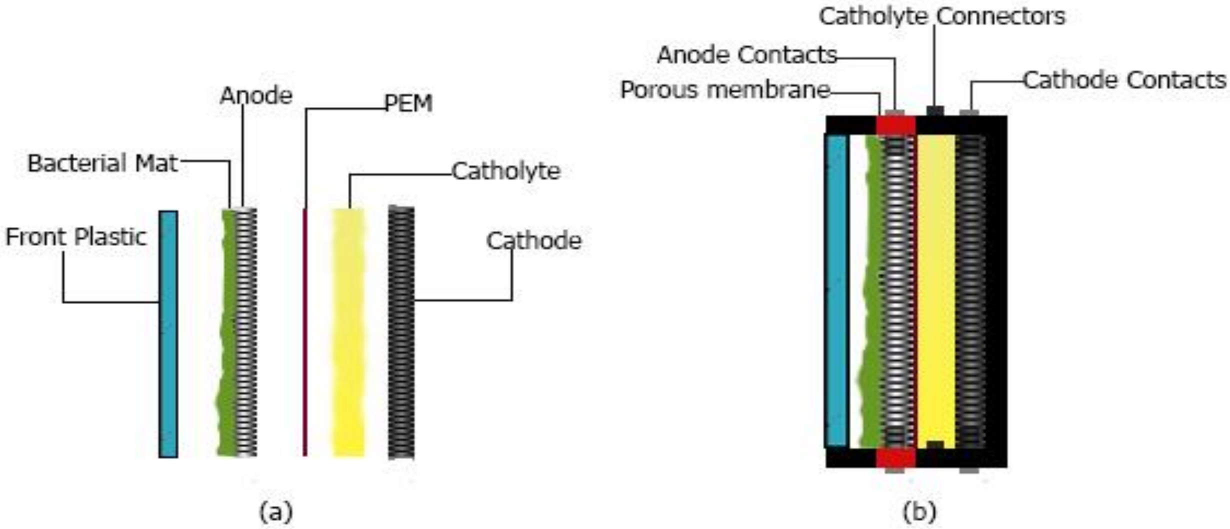

Fig 1. (a) Exploded side view of a single subunit of the panel (b) See through side view of the subunit along with the plastic casing

III. FUNCTIONING

In a functional grid, when light falls upon the microbial mat, the cyanobacteria will start producing organic molecules via photosynthesis. The excreted polysaccharides from these will be used up by the bacteria below them for respiration. During respiration, the electrochemically active bacteria, which are in contact with the anode will transfer the electrons to it.

Simultaneously produced protons will be transported through the PEM to the catholyte chamber. Where they will be taken up by the cathode and water shall be produced, as it happens in a conventional MFC. Thus what we get is a bacteria based, quasi-self-sustainable, electricity producing unit that, in effect, converts sunlight to electricity. Detailed analysis of self-sustained MFCs using light for electricity generation has been done previously [11]. Although the analysis is of a sediment MFC, which is quite different from these panels, but similar variation patterns in current, voltage and power are expected. Also **since the cells in one vertical column are all electrically connected in series and also share the same catholyte, we can say that each individual column actually acts as one single big cell.**

IV. ADVANTAGES

A. Flexibility

As we mentioned earlier, each vertical column acts as one single MFC. Now, each of the big cells (columns) can be connected in various combinations of parallel and serial connections to have fine tune control over the output voltage and current. For example, consider a 3x4 grid of cells, like that of **fig 2**. The grid will contain 3 big cells (4x1) each made of 4 smaller cells. Let the open circuit voltage across each of the so formed vertical cells be V volts and short circuit current be i amperes. Also let the net internal resistance of each column be "r". Irrespective of the pattern of connections of these 4 cells, the power produced by the grid shall be same. But the amount of voltage and current produced is different for each configuration. As can be clearly seen from **fig 3** putting all 3 in series gives maximum voltage and putting all 3 in parallel gives maximum current. Other combinations can be obtained by putting 2 in series and then 1 in parallel or 2 in parallel with 1 in series. **By varying the pattern in which the vertical cells are connected, the net voltage and current output of the grid can be varied without affecting the net power output.** Hence what we get is flexible control over the combination of current and voltage we can extract.

B. Miniaturization

One key, although not very intuitive, aspect of the BEP panels that make them better than conventional MFCs is their size. Although the whole panel might be very large, but it is actually made of small MFCs. It has been very well noted previously [12] that creating miniature MFCs by use of extensively porous/folded electrodes (e.g. Graphite felt), so as to provide a very high surface area to volume ratio provides

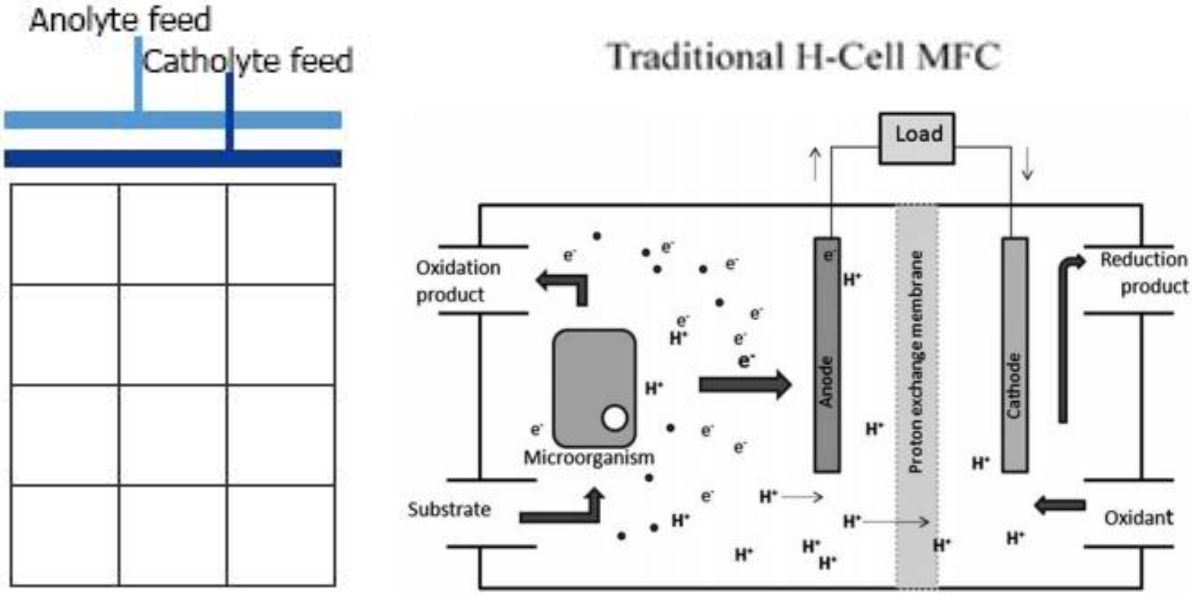

Fig 2. A schematic comparison between a BEP wall panel and a conventional MFC [13]. Notice the catholyte and the anolyte feeds at the top of the panel.

for some rather unexpected advantages as compared to conventional MFCs. We shall mention a few of them. In conventional MFCs, the anode and the PEM are situated far apart which slows the process of proton transfer from anode to PEM. In an MFC as small as ours, both the anode and the PEM are in direct contact of each other. In standard H configurations MFCs, even though there may be 50–104 cm^2 of electrode surface area in the anode chamber of a cell, there is usually a relatively narrow pathway (2–5 cm^2) for protons to traverse across the proton exchange membrane (PEM). Therefore, electron transfer to the anode can be highly efficient while proton throughput across the PEM is highly inefficient. In our design, the area of PEM is same as the apparent area of cross section of the anode. This ensures high area of contact between the anode and the PEM, and hence more efficient proton diffusion. Another peculiar advantage of a miniature MFC is increased power density. Although the power generated per unit area of anode might not increase drastically, but since a large surface area of anode is fitted into a very small chamber, so the power per unit area of the MFC (or per unit volume) increases drastically. Previous experiments [12] have reported upto 750 times higher current density and upto **10^4 times higher power density for a mini-MFC versus an H-cell reactor for similar conditions and culture of bacteria**. Also since the panel is divided into such small independently functioning units, damage to one does not require the whole panel to be changed.

C. Environment friendly

As it is with most MFCs, BEP panels are very much eco-friendly and practically no harmful emissions. Since the power production is done by bacteria, only emission could be some by product of bacterial metabolism.

D. Variability of use

These power generating units are based off of bacteria. Theoretically speaking, with slight changes in design, they can be used almost anywhere where bacteria can thrive, which is almost impossible for any other power source.

V. Disadvantages

A. Costly

As of now, creation of such large panels can prove to be quite costly, although not completely unfeasible. We feel that as the technology gets adopted by commercial companies, cost effective ways of mass production will be devised. Also, cheaper alternatives of current MFC components are being studied [14], but still need a lot of optimization and research before they can be properly implemented.

B. Cumbersome to maintain

As of now, these small MFCs can prove to be pretty cumbersome when it comes to maintenance. Although they are more long lasting unlike simple MFCs, but only to an extent. The feeds might need periodic regulation and would need to be refilled eventually. Also the bacterial film might prove to be a bit unstable. Although as of now, nothing much can be said about the bacterial film, its stability or longevity. Proper experimentation needs to be performed before concluding anything.

C. Low Power

MFCs in general have a very low power density [2, 11]. Although the BEP panels are bound to have a higher power density than conventional MFCs, due to reasons discussed above, but they still can't dominate other alternative sources such as solar power in this particular area.

VI. Further Research and Applications

The study performed by us has been purely theoretical. Although some of the concepts used by us have been tested

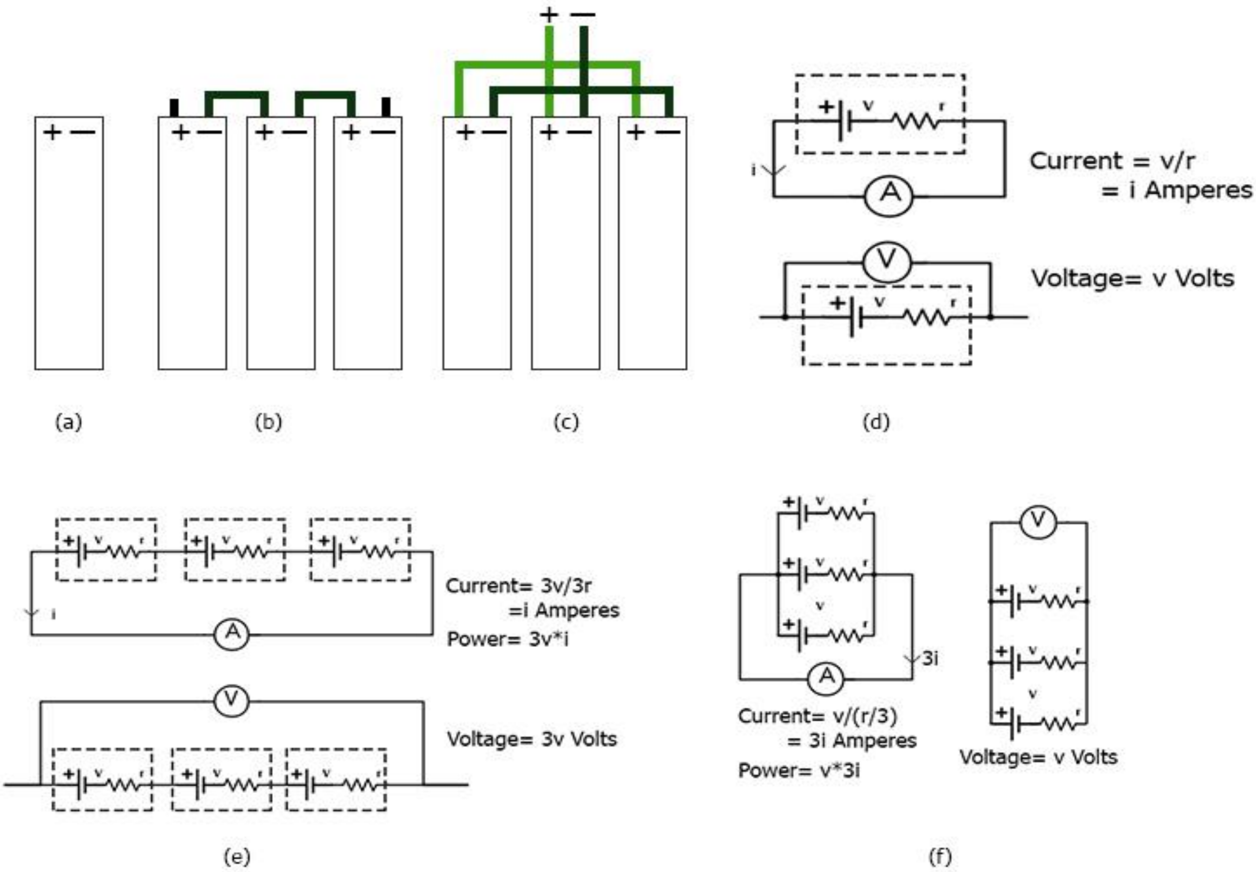

Fig 3 (a) a single column (b) three columns in series (c) three columns in parallel; circuit diagrams for (d) a single column (e) three columns in series (f) three columns in parallel

by others in some form of the other [8, 11, 12]. So, the idea is backed by only indirect experimentation. Extensive research needs to be performed, with particular focus on the construction and sustainability of the bacterial mats, proper optimization of sizes of all components to get maximum power per cost ratio.

As mentioned before, these MFCs can be used theoretically anywhere where bacteria can thrive. They can be used as floating power generating units beneath the water surface in the oceans and seas. They can be buried in mud and used to generate power. In many cases, such as burying in mud, the use of photosynthetic bacteria can be omitted as the electrochemically active bacteria could obtain nutrition directly from the surroundings.

VII. Conclusion

The study we presented here is based on theories and logical deductions. Proper experiments for optimization and verification of the concepts shall be performed. Micro-organisms are present all around us and are an untapped resource for numerous possibilities. They have played a key role in shaping and modifying this planet since the onset of life. Future of technology lies in systems that work in harmony with these microbes. Microbial fuel cells, though might appear a bit odd at first sight, are a step in that very direction. Through BEP panels we want to propose an idea, a new approach to MFCs. The key of building successful MFCs does not lie in fitting them into conventional electrochemical cell designs, but to rather design cells from the ground up to complement the concept of MFCs. This is the basic design philosophy behind BEP panels. They are intricate enough to sustain within themselves living microbes, yet simple enough to maintain a sleek profile. Although at a very primitive stage currently, these BEP have the potential to be one of the most effective alternative sources of energy in the future.

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