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# Plant Microbial Fuel Cells for Sustainable source of bioelectricity Generation

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ABSTRACT

The growing population is responsible for energy consumption all over the world resulting in the depletion of the fossil fuel reservoir. In recent decades out of many techniques, Microbial fuel cell (MFC) have served as three stop solution for electricity production, reducing global warming, producing value added products while simultaneously remediating wastewater. However, MFCs have certain limitation in terms of upscaling mainly due to exhaustion of organic matter at anode. The plant microbial fuel cell (P-MFC) having plants rooted at anode are reliable when it comes to continuous supply of organic matter at anode and thus are considered as a potential and sustainable source of green energy. Here, the solar energy gets converted into bioelectricity via electrochemical reactions in the roots of plant, at the anode separated by cathode chamber of the microbial fuel cell. The P-MFC provides clean and renewable energy, is eco-friendly and cost-effective. The P-MFC also produces, bio-methane, biohydrogen as by products, besides the products produced by plant itself. It is one of the emerging techniques for bioenergy, and also facing just like other microbial fuel cell based techniques challenge to increase the power density as well its long-term performance on commercial scale. This review discusses briefly about conventional MFC and elaborates plant-microbe consortium at rhizosphere region of a plant, for wide scope production of bioelectricity from P-MFC. Additionally, the parameters influencing P-MFC efficiency, the mechanism involved and challenges have also been narrated.

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## 1. Introduction

Energy consumption has increased all over the world due to rapid urbanisation and industrialization (Zhao & Zhang, 2018). Fossil fuel and coal being conventional and non-renewable sources are depleting rapidly. As a result, there is a tremendous demand for new renewable energy sources that are sustainable, cost efficient, and globally accessible (Elavarasan, 2019; Kataria & Khan, 2021). At the socio-economic level, the greenhouse gases emission is increasing in the environment. There is thus an urgent need of alternative sustainable source of green energy like microalgae (Van Vuuren et al., 2017; Vinayak et al., 2019). Among the diverse technologies for sustainable environment and energy production, MFC have emerged as the most promising techniques for converting wastewater to electricity via electrogenic microbes. Compared to great energy inputs as well as large land required in conventional energy generation methods such as wind, solar, geothermal and hydroelectrical requirement are of main concern, however, MFC has no such demands (Chiranjeevi et al., 2019). Thus, due to their lack of practicality, unpredictable performance, and poor power output, MFCs are regarded as a secondary technical feature employed in wastewater treatment (Khan et al., 2022b). However, recent development in MFCs have shown the scope of increasing power output at low cost. It was shown that the addition of substrates at anode in a MFC influences its power output as well as coulombic efficiency. It was seen that acetate fed MFC showed the highest coulombic efficiency (CE) of 72.3%, followed by butyrate (43.0%), propionate (36.0%) and glucose (15.0%) it thus gave researchers fresh hope for their investigation of the performance of the MFC when other additives are added (Chae et al., 2009). Multiple studies from across the world have found numerous additives for boosting the final power of MFCs (Nandy & Kundu, 2018). The evaluation of performance of MFC is not simple owing to different configuration, design and materials used for electrodes, but also depends on various environmental conditions and diverse sources. One of the key elements for evaluating MFC performance is substrate salinity. Up to a certain point, it has been shown that MFC performance improves when substrate salinity rises. In a MFC treating sulphate rich wastewater, the maximum power density (1188 $mW/m^3$) was achieved when sodium chloride was 6g/L in the anode chamber at pH 8.0 (Kumar et al., 2020). The performance of MFC is however greatly influence by the type of bacteria or inoculum used at the anode. The most frequently dominated bacteria in a MFC depends upon the type of substrate at anode. The bacterial communities found to be dominating in all MFCs were mainly *Proteobacteria*, except in propionate fed MFC in which *Firmicutes* was mainly found. Another broadly studied bacteria in MFCs are *Geobacter* and *Shewanella* spp. which have capability to accept electrons from the anode and act as electricigens so as to produce electricity (Hu et al., 2021; Ueki et al., 2018). However, the two common limitations of MFC which need to be overcomed are complete utilization of its substrate or organic biomass in wastewater by

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bacteria at anode thus resulting in low power output (Figure 1A) (Gebreslassie et al., 2021). MFC produce low voltage which limits its scaling up (Jadhav et al., 2022). To overcome the low power output in various different ways, including adding microalgae in MFC live or dead at anode and live microalgae at cathode to provide free oxygen and cost microalgal microbial fuel cells have been designed and at anode has advantage that it not only serves as tested (Khan et al., 2022b). On adding the dry algal powder not only as organic biomass but also helped in adsorbing and removing pollutants in the wastewater (Khan et al., 2022a; Rai et al., 2022a). Additionally live algal cell like diatoms at anode in a MFC have also shown recycle and reuse abilities as they not only produce bioelectricity but also produce value added compounds like biofuel, carbohydrates, pigments and proteins (Khan et al., 2022a). To upscale this technique we need microalgal mass cultivation, for simultaneous production of resources along with remediation of wastewater on which can be applied not only on earth but also on space missions to remediate biowaste in space vehicles (Rai et al., 2022b). This may however take lot of understanding with agriculturist and farmers as microalgae often face contamination in an open system. Meanwhile plants and crop plants are obviously a popular choice and necessity of agriculturist. If the plants are employed in MFC with their rhizosphere acting as a source of microbes they not only produce bioelectricity but also increases its yield as well as are resource of value added products (Helder et al., 2010). Plant MFC (P-MFC) overcomes the most challenging limitation of MFC, i.e exhaustion of organic biomass at anode (Yaqoob et al., 2021). P-MFC is promising method to generate bioelectricity and fulfil high energy demand continuously (Figure 1B) as shown by Strik et al. (Strik et al., 2008) to serve as a non-destructive and a sustainable source of bio-electricity. The first ever plant used in P-MFC was *Glyceria maxima* to produce bioelectricity with maximum power density of 67 $mW/m^2$ (Strik et al., 2008). This claim arises from the fact that for bio-energy production in a P-MFC only rhizodeposits have to be harvested and not the biomass. This avoids transportation of the biomass and depletion of nutrients in the ecosystem. The essential components of P-MFC includes living plants, conductive electrodes as anode and cathode placed in air or water and a supporting matrix (Kabutey et al., 2019). Since plants are synthesizing their own food via photosynthesis, about 40 % of it is used by plant for its own metabolism and remaining is exudated to rhizosphere. The rhizosphere is area surrounding the roots of leguminous plants which act as a biocatalyst since they are not competing with food (Sathish-Kumar et al., 2017). The roots bearing rhizosphere provides a significant carbon source for rhizobacterial populations to grow, which is good for the soil microenvironment (Buzdin et al., 2021). The bacteria in the rhizosphere make it easier for plant roots to receive nutrients in its usable form. Root exudates activate chemotaxis to encourage soil microorganisms to the rhizosphere, in addition to serving as a carbon source (Simarmata et al., 2020). The rhizobia are drawn to root hairs in the rhizosphere by chemoattractant such aromatic acids, flavonoids, dicarboxylic acids, and amino acids (Poole et al., 2018). Formic acid, succinic acid, and biotin are some root exudates and microbial metabolites which facilitate interelectron transport (Chiranjeevi et al., 2019). The organic matter in soil and compounds in wastewater undergoes chemical oxidation in rhizosphere area with the help of soil microbes and produce electrons. These electrons reach the cathode thus completing the circuit and producing bioelectricity (Maddalwar et al., 2021; Nitisoravut & Regmi, 2017). Thus by using plant rhizo deposits, the plant rhizosphere promotes a conducive milieu for bacterial metabolism and mediates the reducing equivalents of this metabolism for the purpose of capturing bioelectricity through a microbial electrochemical system(Renoud et al., 2022).

Thus these P-MFCs are different from conventional MFCs in many ways. The P-MFCs utilises living plants for their energy source while the conventional MFCs uses wastewater and organic compounds as a substrate. The P-MFCs are based on the interaction between bacteria which is electrochemically active and roots of the plant through which the electricity is produced. But in conventional MFCs these exo-electrogenic bacteria oxidised organic matter and the oxygen reduced at anode to produce electricity. Thus, the P-MFC are more environmentally friendly, efficient, and produces more clean and green electricity compared to conventional MFCs(Gupta et al., 2023; Timmers et al., 2010). This review focuses on basic functioning of P-MFC, power generation using rhizosphere bacteria, electron flow, factors which affects the performance of P-MFC and future aspects of it.

## 2. Rhizosphere Bacteria as Biocatalyst for Power Generation

A wide range of microbial communities contribute to a better understanding of the competition among electron donors in P-MFCs. As discussed briefly above that during the process of rhizodeposition the carbon from organic material utilized by roots is fed to the microbes in the form of root exudate which ultimately results in the production of bioelectricity (Guadarrama-Pérez et al., 2019). The rhizosphere zone is crucial for growth of microfauna as it provides carbon and other nutrients for their growth and in result the microbiota of rhizosphere region aid in enhancing the plant roots ability to absorb nutrients in a usable form (Renoud et al., 2022). In addition to providing source of carbon, exudate from roots of plants also act as promotor in the movement of soil microbes towards the rhizosphere zone of the soil. Soil microbes in the rhizosphere region utilize the exudate as substrate and produce electron for being used at anode either by direct transfer or by mediated transfer of electrons (Kuleshova et al., 2022). Another advantage of root exudate as substrate is that it promotes growth of microbial species in the area of roots and these microbes have ability to convert nutrients present in the soil to various ionic forms which enables the plants to utilize nutrients efficiently. Composition of microbial components in the soil is also dependent on the photosynthetic activity of the plants

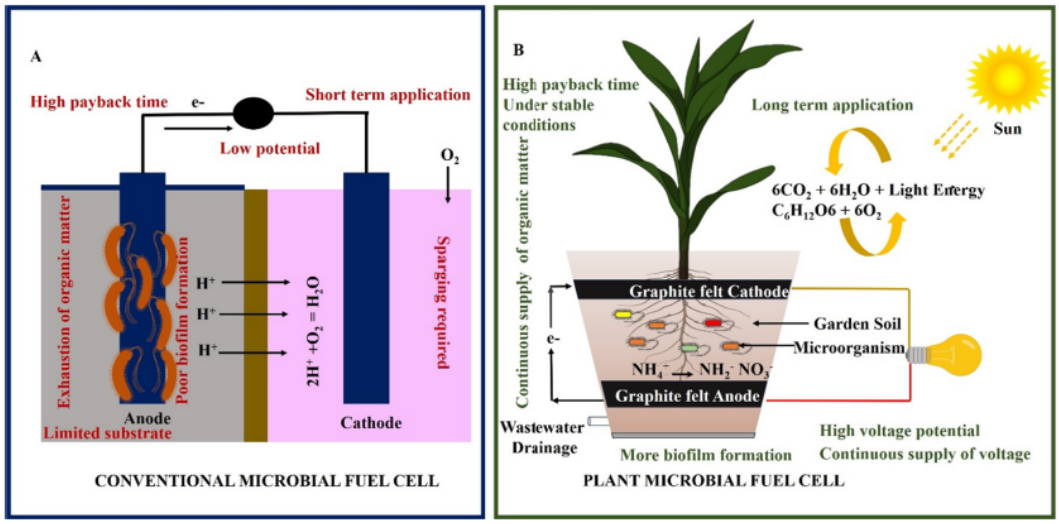



Figure 1. A schematic set up comparison of Conventional MFC and Plant MFC showing a comparison

Table 1: Different plant species used in P-MFC and their power generation

| S.No. | Plant Species used in P-MFC | Substrate | Maximum Power Output | References |
|---|---|---|---|---|
| 1. | *Canna indica* | Gravel soil bed | 22.76 $mW/m^3$ | (Sharma et al., 2021) |
| 2. | *Wachendorfia thyrsiflora* | thickened waste activated sludge (WAS) and soil | 1036 ± 59 $mW/m^3$ | (Gulamhussein & Randall, 2020) |
| 3. | *Cyperus papyrus nanus* | thickened waste activated sludge (WAS) and soil | 510 ± 92 $mW/m^3$ | (Gulamhussein & Randall, 2020) |
| 4. | *Arundo donax* | Sand matrix | 12.82 $mW/m^2$ | (Zhou et al., 2018) |
| 5. | *Sedum hybridum* (succulent plants) | mineral matrix of sand, silt, and clay | 92 $\mu W/m^2$ | (Tapia et al., 2017a) |
| 6. | *Epipremnum aureum* | bentonite clay based membrane | 15.38 $mW/m^2$ | (Sarma & Mohanty, 2018) |
| 7. | *Oryza sativa* L. | soil | 41.41 mW $/m^2$ | (Khudzari et al., 2019) |
| 8. | *Canna Stuttgart* | soil | 222 $mW/m^2$ | (Sophia & Sreeja, 2017) |
| 9. | *Brassica juncea* | soil | 69.32 $mW/m^2$ | (Sophia & Sreeja, 2017) |
| 10. | *Trigonella foenumgraecum* | soil | 80.26 $mW/m^2$ | (Sophia & Sreeja, 2017) |
| 11. | *Ipomoea aquatica* | wetland | 12.42 $mW/m^2$ | (Liu et al., 2013) |
| 12. | Grass species *Sporobolas arabicus* | Soil | 120 $mW/m^2$ | (Gilani et al., 2016) |
| 13. | Grass species *Cynodon dactylon* | Soil | 58$mW/m^2$ | (Gilani et al., 2016) |

hence, plants with high rate of photosynthesis help in establishment of better microbiomes which are key in rhizosphere acclimatization and enhancements in system performance (Chiranjeevi et al., 2019). Based on the photosynthetic activity plants are classified into C3, C4 and Crassulacean acid metabolism (CAM) plants and out of these C4 plants are most efficient in converting solar energy into bioelectricity (Wang et al., 2012). CAM plants are slow and have poor adaptability compared to C3 and C4 plants. On the offset, C4 plants are advantageous to be used in P-MFC over C3 because C4 plants have better photosynthetic efficiency (Pe), 6.0% over C3 plants (4.6%). Further the greater the photosynthates formed in C4 over C3 greater are the rhizodeposits (Rp) formed in plant roots, this means more of the rhizo exudates available to microbes (Ra) 30% and fuel cell energy recovery (Er) 9% production (Deng et al., 2012). Not the least C4 plants have better adaptability to thrive in hot and humid climates –(Deng et al., 2012). The C4 plants like *Spartina anglica* and *Glyceria maxima* are well known plants which have shown good response in PMFC and are frequently preferred. At the same end *Oryza sativa* is a popular food crop but still *S. anglica* has shown better performance than *O.sativa* in terms of maximum power density due to its better photosynthetic efficiency adapted due to C4 pathway. The maximum power density reported by *O.sativa* is 20 $mW/m^2$ or lower. However, the rice fields contribute largely on methane gases (Wang et al., 2023). So, P-MFC was targeted to mitigate these issues of paddy field (Jadhav et al., 2021b). Since paddy is cultivated in waterlogged soil, it served as absolute condition for anaerobic bacteria. This favours organic degradation of carbonaceous material in the soil thus favouring paddy as one of the favourite crops for P-MFC. The P-MFC not only generates bioelectricity and crop yield but simultaneously helpful for mitigation of harmful methane gases. Further marshy grasses are better choice in P-MFC because of their high salt tolerance and high biomass (Li et al., 2021). In a study conducted where a fresh water plant *Arundinella anomola* was tested with marshy plants like *S. anglica* and *Arundo donax* for their performance in a P-MFC, it was found that showed maximum power density *S. anglica* 222 $mW/m^2$ (Helder et al., 2010). It was found that although biomass was produced in all the three P-MFCs, electricity was produced only in P-MFCs with *A. anomala* and *S. anglica.* With no stable current in case of *A. donax* (Helder et al., 2010).

On the offset, selection of plant species for P-MFC applications must adhere to a set of criteria that has previously been used by researchers, and plants with exceptional survival abilities preferred as they can be grown in environments with heavy water logging which is crucial for avoiding interruption due to oxygen in the anode chamber and thus aid in reducing fluctuations in the redox potential gradient in case of P-MFCs (Maddalwar et al., 2021). Generally for P-MFC set up, plants that have capacity to accumulate biomass rapidly and have high rate of photosynthetic activity and are preferred because such plants promote rhizodeposition which is key in utilizing the maximum potential of P-MFC for production of electricity (Nitisoravut & Regmi, 2017). A number of plants involving plants that are flower bearing monocotyledonous have been extensively studied in the P-MFC and have shown promising result (Chiranjeevi et al., 2019). In a study conducted on two nutritional crops *Amaranthus viridis* (P1) and *Triticum aestivum* (P2), to perform P-MFC for almost 180 days, with and without organic slurry (Arulmani et al., 2021). It was found that maximum current density for P2 was (185.23 ± 15.10 $mA/m^2$) without organic slurry and which increased two times about 291.23 ± 7.50 $mA/m^2$ (P2) with bioslurry. On the offset, maximum current density for P1 was 114.52 ± 20.05 $mA/m^2$ without organic slurry which increased to 185.23 ± 15.10 $mA/m^2$ with organic slurry. This also shows that organic fertilizers promote plant growth its substrates and indirectly the current density and power output. The average current density over 100-180 days for P1 and P2 was 118.23 ± 26.25 and 183.35 ± 23.32 $mA/m^2$ respectively. Similarly, the maximum power density for P1 and P2 was 118.23 ± 26.25 and 183.35 ± 23.32 $mA/m^2$ over 100-180 days. Certainly P2, P-PMFC having *T. aestivum* has shown the better power and current output together due to its high performing rhizo deposits in its $4^{th}$ order branching root system. No doubt the rhizo-exudates promote microbes in rhizosphere to alter the biochemical gradient thus enhancing the power output. Table 1 shows various other plants used in P-MFC. Indeed P-MFC is a novel and economic way of crop yielding while simultaneously remediating wastewater and producing bioelectricity.

## 3. Electron Transfer Mechanisms

A major fraction of the fixed carbon ($CO_2$) required by the plants for utilization during activity of photosynthesis is transferred to the rhizosphere in the form of root exudates which helps in growth of microbiomes in the region of rhizosphere (Chiranjeevi et al., 2019). This microbiome in the rhizosphere acts as biocatalyst and through various processes aids in conversion of complex molecules present in soil into simpler ones that can are readily available for uptake by the plant root system leading to enhanced plant growth and energy generation by the P-MFC (Rajniak et al., 2018). The electroactive bacteria (EAB) have tendency to produce reducing equivalent i.e. protons and electrons and also intermediate products of metabolic activities as a result of the synergistic interaction of plants and bacteria in the rhizosphere (Gupta et al., 2021). The plant's rhizosphere's solid noncatalyzed anode electrode receives electrons from the electroactive bacterial species, and the electrons then flow with the aid of an external load to cathode (open air) which is presented on the soil surface with humidity for the transportation of reducing equivalents (Chiranjeevi et al., 2019). As there is existence of potential gradient protons due to presence of positive charge move towards cathode where protons and electrons undergo reduction processes in the presence of oxygen acting as electron acceptor, this leads to formation of water with simultaneous production of electricity (Khan et al., 2022c). Thus P-MFC is a sustainable and efficient way of production of bioelectricity from the solar radiation (Chiranjeevi et al., 2019; Schneider et al., 2016).

## 4. Factors affecting P-MFC performance over time

P-MFC has widened its scope since years of research, the bibliometric database from year 2014 to 2024, shows great potential in this field for further innovation and sustainability as seen in figure 2, however its efficiency depends upon many factors which needs to be kept in mind. Many factors, such as plant species employed in P-MFCs, are identified by various studies throughout the globe which affect P-MFC performance, various operations, features and qualities of usable wastewater, kind of available microbiological inoculum, and design configuration and conformations (Ahirwar et al.,

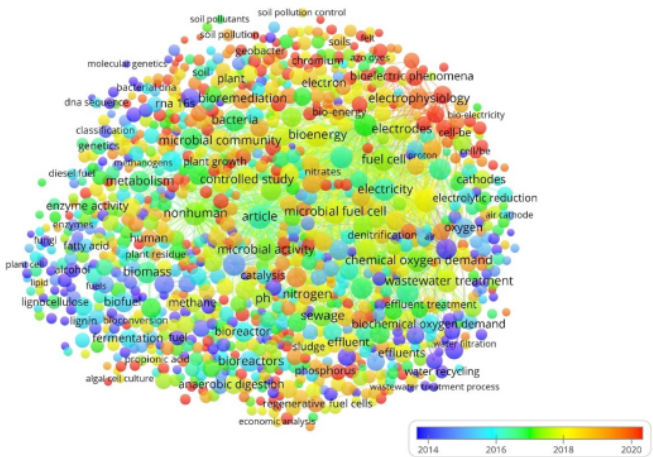



Figure 2. Overlay visualisation of database in the field of plant microbial fuel cells published from year 2014 to 2024 using LinLog/modularity method

2023; Jadhav et al., 2021a). Before pursuing the optimal design and performance standards for P-MFC, several other minor problems in the systems must be extensively identified (Maddalwar et al., 2021).

*4.1 Intensity of light*

Photosynthetic active radiation (PAR) light intensity and $CO_2$ are the key factors of the photosynthesis process of the P-MFC. Photosynthesis using solar radiations is the most important factor that lead to the power production in any type of photosynthetic MFC (Vinayak et al., 2021). PAR is defined as electromagnetic radiations in the 400-700 Hz waveband (Das, 2015). There are different ways to determine how much sunlight will reach a part of the plant canopy: either using direct flux, diffuse fluxes, or both. The direct flux is produced when photons travel through the atmosphere unscathed. However, when photons scatter owing to different obstacles such as suspended particles in the atmosphere such as aerosols, and clouds resulting the flux to partially reach to the plant they produce diffuse flux (Packard et al., 2019).

*4.2 Impact of a higher $CO_2$ concentration in the atmosphere on P-MFC performance-*

Rising atmospheric $CO_2$ concentration is one of the key elements contributing to the increase of global warming. Since last five decades rapid industrialization led the elevation in $CO_2$ concentration in environment of the earth (Khan, Singh et al. 2022). According to current figures, the $CO_2$ proportion in the environment has increased from 320 to 390 ppmv (parts per million volume) throughout this time period (Rae, Zhang et al. 2021). Increased concentration of $CO_2$ in the atmosphere cause a significant rise in the photosynthesis activity of the plants due to $CO_2$ fertilization effect of high concentrations of $CO_2$ (Thompson, Gamage et al. 2017, Wang, Zhang et al. 2020). This enhanced photosynthesis rate increases the production of metabolites and also helps in plant growth thus having a direct relationship with the performance of PMFC. In recent times various studies conducted on crops such as *Saccharum officinarum* and zea mays have shown that under elevated $CO_2$ concentration plants show enhanced metabolite formation and growth (Iqbal, Hussain et al. 2020, Liu, Hochberg et al. 2024). This shows that atmospheric concentration of $CO_2$ is a key controlling factor of performance of P-MFC as $CO_2$ plays a crucial role in the growth of plants. Further as discussed earlier sections C3 and C4 plants show different physiological response towards increased $CO_2$ levels and thus plants should be carefully chosen to enhance the performance of PFMC under given conditions (Vanlerberghe, Dahal et al. 2020).

*4.3 Soil microbes*

The rhizosphere is the area immediately surrounding the roots and their surface. (Al-Ghussain, 2019). It acts as the location of rhizodeposition by plant roots, which gives bacteria a place to attach. It also serves as the scene of microbial activity, and a vast variety of microorganisms live there. Thus, the rhizosphere's microbial diversity fluctuates in accordance with the inoculum, the supporting medium, and the nutritional requirements. Bacteria *Geobacter* sp. and *Desulfobulbus* sp. had substantial abundances of colonies in soil on anode surface when utilised as the inoculum in the rhizosphere P-MFC with rice plants. Additionally, it has been observed that a few bacterial species, including *Natronocella acetinitrilica*, *Beijerinckiaceae, Rhizobiales,* and *Rhodobacter gluconicum* have a dominating place on the anode in rice paddy field assisted P-MFC (Maddalwar et al., 2021).

*4.4 Surface area and the type of electrode*

The properties of anode material for an effective operation includes good conductivity, nontoxic to the microorganisms and plants, chemically stable and cost-effective. Among a variety of electrode material metal electrodes such as non-corrosive stainless steel can give a great favour in operation over the metals like copper due to its toxic effect on microorganism (Yaqoob et al., 2020b). A variety of carbon electrodes such as graphite plates, carbon cloth, rods and paper felt are worthwhile as anode electrode material. Electrodes with higher surface area provides better attachment and surface for biofilm formation. (Liu et al., 2020). However, the porous nature must be preserved for protons to reach the ion exchange membrane completing the circuit and maintaining the redox gradient in the system. The resistance of the material will determine the type of electrode to be utilised in the P-MFC. In P-MFC applications, the least resistant materials are often used. However, due to the high cost of highly effective electrodes such as platinum or platinum coated electrodes, their usage is not practicable. Its performance is hindered because the anode's resistance increases the total resistance of the P-MFC (Jadhav et al., 2021c).

*4.4.1 Plane structure of electrode*

Carbon paper, carbon cloth and graphite plates are the most often used anode materials in MFC research labs. The different forms of electrodes display favourable and unfavourable performance with respect to a particular type of MFC for instance graphite felts or sheets perform better than carbon paper (Smaisim et al., 2022). On the other hand, irregular surface of graphite electrodes showed more power output as compared to flat graphite electrodes. To invent cost effective and more viable carbon cloth and carbon paper replacements, carbon mesh treated with ammonia gas has been used as anode. In comparison to carbon cloth and carbon paper, it consequently produced more power density. In comparison to electrode designs with smooth surfaces, the power generated per unit of geometric anode surface area increases as anode porosity increases. In the porous anode setup, the increase in surface area accessible for bacterial species per unit volume of anode chamber increases (Guo et al., 2015).

*4.4.2 Packed structure of electrode*

Packing materials such as glass beads, granular graphite rods and activated carbon of different shapes are used as packing material at the anode chamber which provide the larger surface area for bacterial biofilm (Tan et al., 2021). To improve long-term performance, the whole bed must be made conductive by closely stacking the materials adjacent to each other. Although these tightly packed electrodes porosity ranges from 30 % to 50 %, after a while the pores begin to block, reducing the long-term effectiveness of MFC.

It was reported that the graphite felt gave the better performance over the graphite granules of size 2 and 5 mm, and resulted the higher power output up to 386 $W/m^3$ (Caizán-Juanarena et al., 2020). It has been observed that granular activated carbon (GAC) has a higher power density in a MFC system, than having carbon cloth as anode by a factor of 2.5, demonstrating the efficiency of GAC in power production and its application (Matsena et al., 2021).

*4.4.3. Brush structure of electrode*

Graphite brush electrodes are an excellent choice for anodes in MFC due to their large surface area, current gathering and porosity. These electrodes are constructed by twisting required length carbon fibres over two non-corrosive titanium wires (Yaqoob et al., 2020a). The smaller one graphite brush with the properties like length, porosity and surface area brush volume was 2.5 cm, 95%

porous and 18,200 $m^3$ respectively. Another one was larger in size with length, diameter, porosity, and surface area brush volume of 7 cm, 5 cm, 98% and 7170 $m^3$ respectively. The study with smaller brush size, larger brush size and plain carbon paper as electrode at anode gave the power density 2400 $mW/m^2$ (Yaqoob et al., 2020a), 1430 $mW/m^2$ and 600 $mW/m^2$ respectively (Nandy & Kundu, 2018).. Henceforth, it is crucial to carry out thorough studies understanding for long-term performance in P-MFC, using porous electrodes.

## 5. Challenges and future prospective

There are many challenges which come across in P-MFC such as short lifespan of a plant, lack of consistent voltage production, low voltage generation, type of plant used, design and configuration of MFC, lack of data to analyse, etc. These shortcomings of P-MFC prevents it from being commercialized (Khan et al., 2022c). Therefore, more study is needed to refine each possible aspect. High power generation and low prime battery technology are two crucial factors that must be extensively explored before comparing P-MFCs to other popular renewable energy resource based on utilization of solar radiation, wind energy and hydro energy. Some of these factors are discussed here (Aftab et al., 2020).

### *5.1 Long term operation*

Many plant species used in the P-MFC to date are wild grass species or plants with extremely low economic value. As a result, it is quite difficult to accurately determine the efficiency of P-MFC over a longer time durations. Certain limitations, such as plant ageing and plant physiological parameters affecting the structure of the microbial population in the rhizosphere over time, limit the usage of P-MFC for extended periods of time (Aftab et al., 2020). Two of the most important issues for long-term operation of P-MFCs are maintaining plant vitality while simultaneously maintaining a constant and consistent power output and inhibiting degradation of electrode material over time due to action of various environmental components. In this regard, selecting an appropriate plant as well as long-lasting, low-cost electrode materials that resist fouling may be critical. Perennial and vigorous plants with large root biomass that can resist adverse environmental conditions thrive best in P-MFCs (Nitisoravut & Regmi, 2017). Another key issue that has been seen in the consistent power generation from the P-MFC is increase in internal resistance due to formation of a biofilm by microbes on the electrodes which leads to significant drop in the power generation capacity of P-MFC and thus it becomes necessary to replace electrodes after a certain period of time leading to increase in running cost of P-MFC (Aftab et al., 2020).

### *5.2. Standardization of design for P-MFC*

The goal should be to better understand the function of the plant-microbe connection in the performance of P-MFCs by unravelling the world of the rhizosphere. Understanding plant ecophysiology, as well as engineering aspects, is an essential requirement for this (Nitisoravut & Regmi, 2017). For commercializing the P-MFC technology several key factors involving material of electrode, composition of catholytes and anolytes, identification of microorganism with greater abilities to produce high power, spacing of electrodes must be standardized (Vinayak et al., 2021). Apart from this it is also important that various parameters for media which carries the substrate upon which microbiota acts is standardized so that required internal resistance can be achieved for certain values of pH and soil porosity (Lu et al., 2020). In addition, numerous aspects like the introduction of innovative catalysts, employment of bio-cathode, or the utilizing specific operations should be standardised and explored for enhancing economic viability and sustainability of P-MFC.

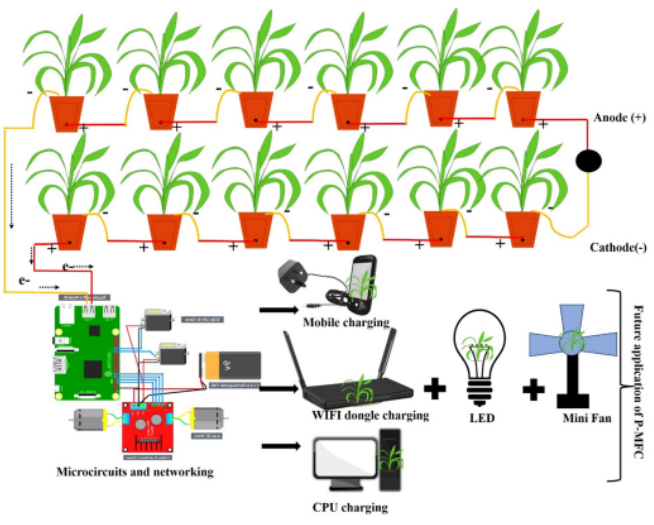



Figure 3. Stacking Plant MFC for increasing energy output

### *5.3. Optimizing various functional aspects*

P-MFCs should be investigated using various operational settings relating to organic loading as well as physicochemical factors (light, humidity, temperature, pH, and conductivity). There have been some documented works on P-MFC optimization, however they are all associated with distinct setups, designs, and plant species. As a result, designing a standard optimization methodology for the P-MFC is difficult (Yadav et al., 2021). Optimization factors must be altered depending on geographic location, PAR, wavelength of light, $CO_2$ concentration in the environment, atmospheric temperature, and composition of microbes employed at anode and cathode (Raychaudhuri & Behera, 2020). The primary purpose of this optimization is to obtain a steady and sustainable power generation over long period of time and making the technology commercially viable and cost effective.

However, the power output of the P-MFC is still low and there is a need of developing innovative techniques for enhancing the power output to make it economical as well as sustainable source of energy (Shaikh et al., 2021). To address this enormous issue, stacking the P-MFC could be a possible technology to collect energy (Figure 3). By transforming plant energy into electrical energy, it can then be used in multiple of ways to store energy while simultaneously remediating wastewater.

According to the findings of many research it is believed that the P-MFC is a sustainable, eco-friendly, cost-effective approach in bio electrochemical systems which uses plants and microbial communities to treat different wastewater, and produces renewable bio-electricity. Furthermore, these P-MFCs can also use as a power source for wireless sensor (Bataillou et al., 2024). In another study the P-MFC used as a sensor for sensing soil water content using sedum species in Green roofs to monitor water content (Tapia et al., 2017b).

## 6. Conclusion

Plant Microbial Fuel Cell approach is among one of the most promising novel methods of producing bio-electricity by utilizing photosynthetic activity of plants and association of plants with rhizosphere microbial community. There are several limiting factors which are responsible for the efficiency of P-MFC and lots still needs to be done. The low power and durability are its major drawbacks hence stacking the cells seems to be the reason to increase its efficiency in terms of bioelectricity and power density generation. The P-MFC however seems to work in conjunction with its rhizome bacteria for remediating wastewater producing bioelectricity and increasing the biomass of plants. It has many applications, yet further study is needed. Efforts in research can be made to enhance the efficiency of P-MFC, by developing new methods, change in electrode materials, plant selection, larger agriculture, and industrial settings. The P-MFC can be scaled up for production of bio-electricity on larger scale which can be used in various agricultural sensors, wireless, etc. Further the P-MFC approach can be utilised in reduction of global warming, purification of atmospheric air, and environmental monitoring in future.

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## Reference

1. Aftab, S., Shah, A., Nisar, J., Ashiq, M.N., Akhter, M.S., Shah, A.H. 2020. Marketability prospects of microbial fuel cells for sustainable energy generation. *Energy & Fuels*, **34**(8), 9108-9136.
2. Ahirwar, A., Das, S., Das, S., Yang, Y.-H., Bhatia, S.K., Vinayak, V., Ghangrekar, M.M. 2023. Photosynthetic microbial fuel cell for bioenergy and valuable production: A review of circular bio-economy approach. *Algal Research*, **70**, 102973.
3. Al-Ghussain, L. 2019. Global warming: Review on driving forces and mitigation. *Environmental Progress & Sustainable Energy*, **38**(1), 13-21.
4. Arulmani, S.R.B., Gnanamuthu, H.L., Kandasamy, S., Govindarajan, G., Alsehli, M., Elfasakhany, A., Pugazhendhi, A., Zhang, H. 2021. Sustainable bioelectricity production from Amaranthus viridis and Triticum aestivum mediated plant microbial fuel cells with efficient electrogenic bacteria selections. *Process Biochemistry*, **107**, 27-37.
5. Bataillou, G., Ondel, O., Haddour, N. 2024. 900-Days long term study of plant microbial fuel cells and complete application for powering wireless sensors. *Journal of Power Sources*, **593**, 233965.
6. Buzdin, A.V., Patrushev, M.V., Sverdlov, E.D. 2021. Will Plant Genome Editing Play a Decisive Role in "Quantum-Leap" Improvements in Crop Yield to Feed an Increasing Global Human Population? *Plants*, **10**(8), 1667.
7. Caizán-Juanarena, L., Sleutels, T., Borsje, C., ter Heijne, A. 2020. Considerations for application of granular activated carbon as capacitive bioanode in bioelectrochemical systems. *Renewable Energy*, **157**, 782-792.
8. Chae, K.-J., Choi, M.-J., Lee, J.-W., Kim, K.-Y., Kim, I.S. 2009. Effect of different substrates on the performance, bacterial diversity, and bacterial viability in microbial fuel cells. *Bioresource technology*, **100**(14), 3518-3525.
9. Chiranjeevi, P., Yeruva, D.K., Kumar, A.K., Mohan, S.V., Varjani, S. 2019. Plant-microbial fuel cell technology. in: Microbial Electrochemical Technology, *Elsevier*, pp. 549-564.
10. Das, D. 2015. Algal biorefinery: an integrated approach. *Springer.*
11. Das, S., Raj, R., Das, S., Ghangrekar, M.M. 2022. Evaluating application of photosynthetic microbial fuel cell to exhibit efficient carbon sequestration with concomitant value-added product recovery from wastewater: *A review. Environmental Science and Pollution Research*, 1-18.
12. Deng, H., Chen, Z., Zhao, F. 2012. Energy from plants and microorganisms: progress in plant–microbial fuel cells. *ChemSusChem*, **5**(6), 1006-1011.
13. Elavarasan, R.M. 2019. The motivation for renewable energy and its comparison with other energy sources: A review. *European Journal of sustainable Development research*, **3**(1), em0076.
14. Gebreslassie, T.R., Nguyen, P.K.T., Yoon, H.H., Kim, J. 2021. Co-production of hydrogen and electricity from macroalgae by simultaneous dark fermentation and microbial fuel cell. *Bioresource Technology*, **336**, 125269.
15. Gilani, S.R., Yaseen, A., Zaidi, S.R.A., Zahra, M., Mahmood, Z. 2016. Photocurrent Generation through Plant Microbial Fuel Cell by Varying Electrode Materials. *Journal of the Chemical Society of Pakistan*, **38**(1).
16. Guadarrama-Pérez, O., Gutiérrez-Macías, T., García-Sánchez, L., Guadarrama-Pérez, V.H., Estrada-Arriaga, E.B. 2019. Recent advances in constructed wetland-microbial fuel cells for simultaneous bioelectricity production and wastewater treatment: a review. *International Journal of Energy Research*, **43**(10), 5106-5127.
17. Gulamhussein, M., Randall, D.G. 2020. Design and operation of plant microbial fuel cells using municipal sludge. *Journal of Water Process Engineering*, **38**, 101653.
18. Guo, K., Prévoteau, A., Patil, S.A., Rabaey, K. 2015. Engineering electrodes for microbial electrocatalysis. *Current opinion in biotechnology*, **33**, 149-156.
19. Gupta, S., Patro, A., Mittal, Y., Dwivedi, S., Saket, P., Panja, R., Saeed, T., Martínez, F., Yadav, A.K. 2023. The race between classical microbial fuel cells, sediment-microbial fuel cells, plant-microbial fuel cells, and constructed wetlands-microbial fuel cells: Applications and technology readiness level. *Science of The Total Environment*, **879**, 162757.
20. Gupta, S., Srivastava, P., Patil, S.A., Yadav, A.K. 2021. A comprehensive review on emerging constructed wetland coupled microbial fuel cell technology: potential applications and challenges. *Bioresource Technology*, **320**, 124376.
21. Helder, M., Strik, D., Hamelers, H., Kuhn, A., Blok, C., Buisman, C. 2010. Concurrent bio-electricity and biomass production in three Plant-Microbial Fuel Cells using Spartina anglica, Arundinella anomala and Arundo donax. *Bioresource technology*, **101**(10), 3541-3547.
22. Hu, Y., Wang, Y., Han, X., Shan, Y., Li, F., Shi, L. 2021. Biofilm biology and engineering of Geobacter and Shewanella spp. for energy applications. *Frontiers in Bioengineering and Biotechnology*, **9**, 786416.
23. Jadhav, D., Ghosal, D., Chendake, A., Pandit, S., Sajana, T. 2021a. Plant microbial fuel cell as a biomass conversion technology for sustainable development. in: Catalysis for Clean Energy and Environmental Sustainability, *Springer*, pp. 135-147.
24. Jadhav, D., Ghosal, D., Chendake, A., Pandit, S., Sajana, T. 2021b. Plant microbial fuel cell as a biomass conversion technology for sustainable development. Catalysis for Clean Energy and Environmental Sustainability: *Biomass Conversion and Green Chemistry*-Volume 1, 135-147.
25. Jadhav, D.A., Chendake, A.D., Vinayak, V., Atabani, A., Abdelkareem, M.A., Chae, K.-J. 2022. Scale-up of the bioelectrochemical system: Strategic perspectives and normalization of performance indices. *Bioresource Technology*, 127935.
26. Jadhav, D.A., Mungray, A.K., Arkatkar, A., Kumar, S.S. 2021c. Recent advancement in scaling-up applications of microbial fuel cells: From reality to practicability. *Sustainable Energy Technologies and Assessments*, **45**, 101226.
27. Kabutey, F.T., Zhao, Q., Wei, L., Ding, J., Antwi, P., Quashie, F.K., Wang, W. 2019. An overview of plant microbial fuel cells (PMFCs): Configurations and applications. *Renewable and Sustainable Energy Reviews*, **110**, 402-414.
28. Kataria, A., Khan, T. 2021. Necessity of Paradigm Shift from Non-renewable Sources to Renewable Sources for Energy Demand. in: Urban Growth and Environmental Issues in India, *Springer*, pp. 337-352.
29. Khan, M.J., Das, S., Vinayak, V., Pant, D., Ghangrekar, M. 2022a. Live diatoms as potential biocatalyst in a microbial fuel cell for harvesting continuous diafuel, carotenoids and bioelectricity. *Chemosphere*, **291**, 132841.
30. Khan, M.J., Singh, N., Mishra, S., Ahirwar, A., Bast, F., Varjani, S., Schoefs, B., Marchand, J., Rajendran, K., Banu, J.R. 2022b. Impact of light on microalgal photosynthetic microbial fuel cells and removal of pollutants by nanoadsorbent biopolymers: Updates, challenges and innovations. *Chemosphere*, **288**, 132589.
31. Khan, M.J., Suryavanshi, V.J., Joshi, K.B., Gangadharan, P., Vinayak, V. 2022c. Photosynthetic microalgal microbial fuel cells and its future upscaling aspects. in: Handbook of algal biofuels, *Elsevier*, pp. 363-384.
32. Khudzari, J.M., Gariépy, Y., Kurian, J., Tartakovsky, B., Raghavan, G.V. 2019. Effects of biochar anodes in rice plant microbial fuel cells on the production of bioelectricity, biomass, and methane. *Biochemical engineering journal*, **141**, 190-199.
33. Kuleshova, T., Rao, A., Bhadra, S., Garlapati, V.K., Sharma, S., Kaushik, A., Goswami, P., Sreekirshnan, T., Sevda, S. 2022. Plant microbial fuel cells as an innovative, versatile agro-technology for green energy generation combined with wastewater treatment and food production. *Biomass and Bioenergy*, **167**, 106629.
34. Kumar, S.S., Kumar, V., Gude, V.G., Malyan, S.K., Pugazhendhi, A. 2020. Alkalinity and salinity favor bioelectricity generation potential of Clostridium, Tetrathiobacter and Desulfovibrio consortium in Microbial Fuel Cells (MFC) treating sulfate-laden wastewater. *Bioresource technology*, **306**, 123110.
35. Li, K., Qi, J., Zhang, F., Miwornunyuie, N., Amaniampong, P.S., Koomson, D.A., Chen, L., Yan, Y., Dong, Y., Setordjie, V.E. 2021. The role of wetland plants on wastewater treatment and electricity generation in constructed wetland coupled with microbial fuel cell. *Applied Sciences*, **11**(16), 7454.
36. Liu, S., Song, H., Li, X., Yang, F. 2013. Power generation enhancement by utilizing plant photosynthate in microbial fuel cell coupled constructed wetland system. *International Journal of Photoenergy*, 2013.
37. Liu, Y., Zhang, X., Zhang, Q., Li, C. 2020. Microbial fuel cells: nanomaterials based on anode and their application. *Energy Technology*, **8**(9), 2000206.
38. Lu, Z., Yin, D., Chen, P., Wang, H., Yang, Y., Huang, G., Cai, L., Zhang, L. 2020. Power-generating trees: Direct bioelectricity production from plants with microbial fuel cells. *Applied energy*, **268**, 115040.
39. Maddalwar, S., Nayak, K.K., Kumar, M., Singh, L. 2021. Plant microbial fuel cell: opportunities, challenges, and prospects. *Bioresource Technology*, **341**, 125772.
40. Matsena, M.T., Mabuse, M., Tichapondwa, S.M., Chirwa, E.M. 2021. Improved performance and cost efficiency by surface area optimization of granular activated carbon in air-cathode microbial fuel cell. *Chemosphere*, **281**, 130941.

41. Nandy, A., Kundu, P.P. 2018. Configurations of microbial fuel cells. Progress and Recent Trends in Microbial Fuel Cells, 1st ed.; Dutta, K., Kundu, PP, Eds, **464**.
42. Nitisoravut, R., Regmi, R. 2017. Plant microbial fuel cells: A promising biosystems engineering. *Renewable and Sustainable Energy Reviews*, **76**, 81-89.
43. Packard, C.D., Larsen, M.L., Cantrell, W.H., Shaw, R.A. 2019. Light scattering in a spatially-correlated particle field: Role of the radial distribution function. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **236**, 106601.
44. Poole, P., Ramachandran, V., Terpolilli, J. 2018. Rhizobia: from saprophytes to endosymbionts. *Nature Reviews Microbiology*, **16**(5), 291-303.
45. Rae, J.W., Zhang, Y.G., Liu, X., Foster, G.L., Stoll, H.M., Whiteford, R.D. 2021. Atmospheric CO2 over the past 66 million years from marine archives. *Annual Review of Earth and Planetary Sciences*, **49**.
46. Rai, A., Sirotiya, V., Mourya, M., Khan, M.J., Ahirwar, A., Sharma, A.K., Kawatra, R., Marchand, J., Schoefs, B., Varjani, S. 2022a. Sustainable treatment of dye wastewater by recycling microalgal and diatom biogenic materials: Biorefinery perspectives. *Chemosphere*, 135371.
47. Rai, I., Ahirwar, A., Rai, A., Varjani, S., Vinayak, V. 2022b. Biowaste recycling strategies for regenerative life support system: An overview. *Sustainable Energy Technologies and Assessments*, **53**, 102525.
48. Rajniak, J., Giehl, R.F., Chang, E., Murgia, I., von Wirén, N., Sattely, E.S. 2018. Biosynthesis of redox-active metabolites in response to iron deficiency in plants. *Nature chemical biology*, **14**(5), 442-450.
49. Raychaudhuri, A., Behera, M. 2020. Review of the process optimization in microbial fuel cell using design of experiment methodology. *Journal of Hazardous, Toxic, and Radioactive Waste*, **24**(3), 04020013.
50. Renoud, S., Vacheron, J., Abrouk, D., Prigent-Combaret, C., Legendre, L., Muller, D., Moënne-Loccoz, Y. 2022. Field site-specific effects of an Azospirillum seed inoculant on key microbial functional groups in the rhizosphere. *Frontiers in microbiology*, **12**, 760512.
51. Sarma, P.J., Mohanty, K. 2018. Epipremnum aureum and Dracaena braunii as indoor plants for enhanced bio-electricity generation in a plant microbial fuel cell with electrochemically modified carbon fiber brush anode. *Journal of bioscience and bioengineering*, **126**(3), 404-410.
52. Sathish-Kumar, K., Vignesh, V., Caballero-Briones, F. 2017. Sustainable power production from plant-mediated microbial fuel cells. in: Sustainable Agriculture towards Food Security, *Springer*, pp. 85-107.
53. Schneider, K., Thorne, R.J., Cameron, P.J. 2016. An investigation of anode and cathode materials in photomicrobial fuel cells. Philosophical Transactions of the Royal Society A: *Mathematical, Physical and Engineering Sciences*, **374**(2061), 20150080.
54. Shaikh, R., Rizvi, A., Quraishi, M., Pandit, S., Mathuriya, A.S., Gupta, P.K., Singh, J., Prasad, R. 2021. Bioelectricity production using plant-microbial fuel cell: Present state of art. *South African Journal of Botany*, **140**, 393-408.
55. Sharma, A., Gajbhiye, S., Chauhan, S., Chhabra, M. 2021. Effect of cathodic culture on wastewater treatment and power generation in a photosynthetic sediment microbial fuel cell (SMFC): Canna indica v/s Chlorella vulgaris. *Bioresource Technology*, **340**, 125645.
56. Simarmata, T., Setiawati, M.R., Fitriatin, B.N., Herdiyantoro, D. 2020. Rhizomicrobiome for Sustainable Crop Growth and Health Management. *The Plant Microbiome in Sustainable Agriculture*, 157-194.
57. Smaisim, G.F., Abed, A.M., Al-Madhhachi, H., Hadrawi, S.K., Al-Khateeb, H.M.M., Kianfar, E. 2022. Graphene-Based Important Carbon Structures and Nanomaterials for Energy Storage Applications as Chemical Capacitors and Supercapacitor Electrodes: a Review. *BioNanoScience*, 1-30.
58. Sophia, A.C., Sreeja, S. 2017. Green energy generation from plant microbial fuel cells (PMFC) using compost and a novel clay separator. *Sustainable Energy Technologies and Assessments*, **21**, 59-66.
59. Strik, D.P., Hamelers, H., Snel, J.F., Buisman, C.J. 2008. Green electricity production with living plants and bacteria in a fuel cell. *International journal of energy research*, **32**(9), 870-876.
60. Tan, S.-M., Ong, S.-A., Ho, L.-N., Wong, Y.-S., Abidin, C.Z.A., Thung, W.-E., Teoh, T.-P. 2021. Polypropylene biofilm carrier and fabricated stainless steel mesh supporting activated carbon: Integrated configuration for performances enhancement of microbial fuel cell. *Sustainable Energy Technologies and Assessments*, **46**, 101268.
61. Tapia, N.F., Rojas, C., Bonilla, C.A., Vargas, I.T. 2017a. Evaluation of Sedum as driver for plant microbial fuel cells in a semi-arid green roof ecosystem. *Ecological Engineering*, **108**, 203-210.
62. Tapia, N.F., Rojas, C., Bonilla, C.A., Vargas, I.T. 2017b. A new method for sensing soil water content in green roofs using plant microbial fuel cells. *Sensors*, **18**(1), 71.
63. Timmers, R.A., Strik, D.P., Hamelers, H.V., Buisman, C.J. 2010. Long-term performance of a plant microbial fuel cell with Spartina anglica. *Applied microbiology and biotechnology*, **86**, 973-981.
64. Ueki, T., Nevin, K.P., Woodard, T.L., Aklujkar, M.A., Holmes, D.E., Lovley, D.R. 2018. Construction of a Geobacter strain with exceptional growth on cathodes. *Frontiers in microbiology*, **9**, 393377.
65. Van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., Van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y. 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237-250.
66. Vinayak, V., Joshi, K.B., Sarma, P.M. 2019. Diafuel™(diatom biofuel) vs electric vehicles, a basic comparison: a high potential renewable energy source to make India energy independent. Diatoms: Fundamentals and Applications, 537-582.
67. Vinayak, V., Khan, M.J., Varjani, S., Saratale, G.D., Saratale, R.G., Bhatia, S.K. 2021. Microbial fuel cells for remediation of environmental pollutants and value addition: special focus on coupling diatom microbial fuel cells with photocatalytic and photoelectric fuel cells. *Journal of Biotechnology*, **338**, 5-19.
68. Wang, C., Guo, L., Li, Y., Wang, Z. 2012. Systematic comparison of C3 and C4 plants based on metabolic network analysis. *BMC systems biology. Springer*. pp. 1-14.
69. Wang, J., Ciais, P., Smith, P., Yan, X., Kuzyakov, Y., Liu, S., Li, T., Zou, J. 2023. The role of rice cultivation in changes in atmospheric methane concentration and the Global Methane Pledge. *Global Change Biology*, **29**(10), 2776-2789.
70. Yadav, G., Mishra, A., Ghosh, P., Sindhu, R., Vinayak, V., Pugazhendhi, A. 2021. Technical, economic and environmental feasibility of resource recovery technologies from wastewater. *Science of The Total Environment*, **796**, 149022.
71. Yaqoob, A.A., Ibrahim, M.N.M., Guerrero-Barajas, C. 2021. Modern trend of anodes in microbial fuel cells (MFCs): an overview. *Environmental technology & innovation*, **23**, 101579.
72. Yaqoob, A.A., Ibrahim, M.N.M., Rodríguez-Couto, S. 2020a. Development and modification of materials to build cost-effective anodes for microbial fuel cells (MFCs): An overview. *Biochemical Engineering Journal*, **164**, 107779.
73. Yaqoob, A.A., Mohamad Ibrahim, M.N., Rafatullah, M., Chua, Y.S., Ahmad, A., Umar, K. 2020b. Recent advances in anodes for microbial fuel cells: An overview. *Materials*, **13**(9), 2078.
74. Zhao, P., Zhang, M. 2018. The impact of urbanisation on energy consumption: A 30-year review in China. *Urban climate*, **24**, 940-953.
75. Zhou, Y., Xu, D., Xiao, E., Xu, D., Xu, P., Zhang, X., Zhou, Q., He, F., Wu, Z. 2018. Relationship between electrogenic performance and physiological change of four wetland plants in constructed wetland-microbial fuel cells during non-growing seasons. *Journal of Environmental Sciences*, **70**, 54-62.