# PLANT MICROBIAL FUEL CELLS (PMFC)

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In partial fulfillment of NPRE 498 Energy Storage
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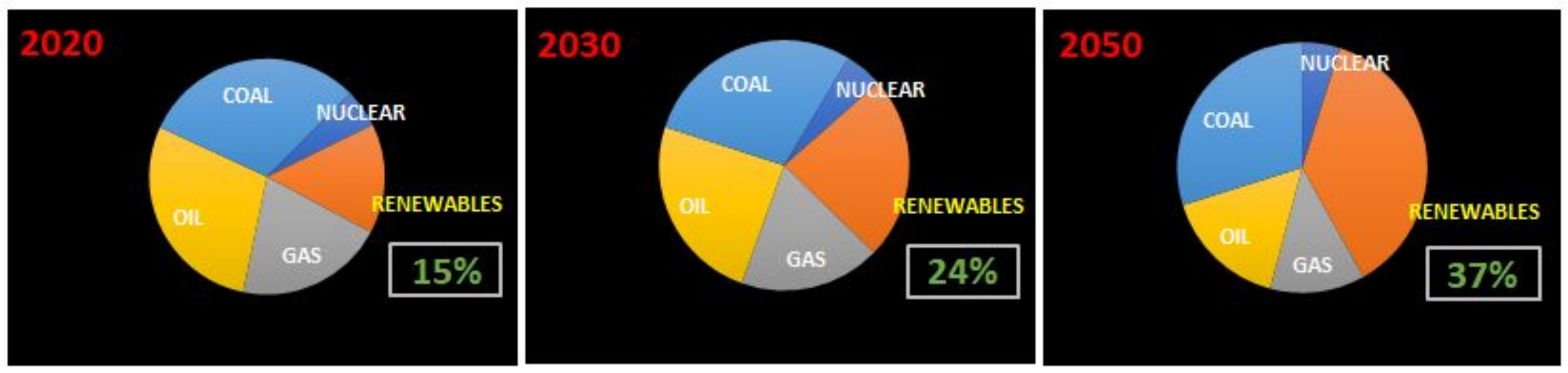
**“Pollution is nothing but resources we're not harvesting. We allow them to disperse because we've been ignorant of their value.”**

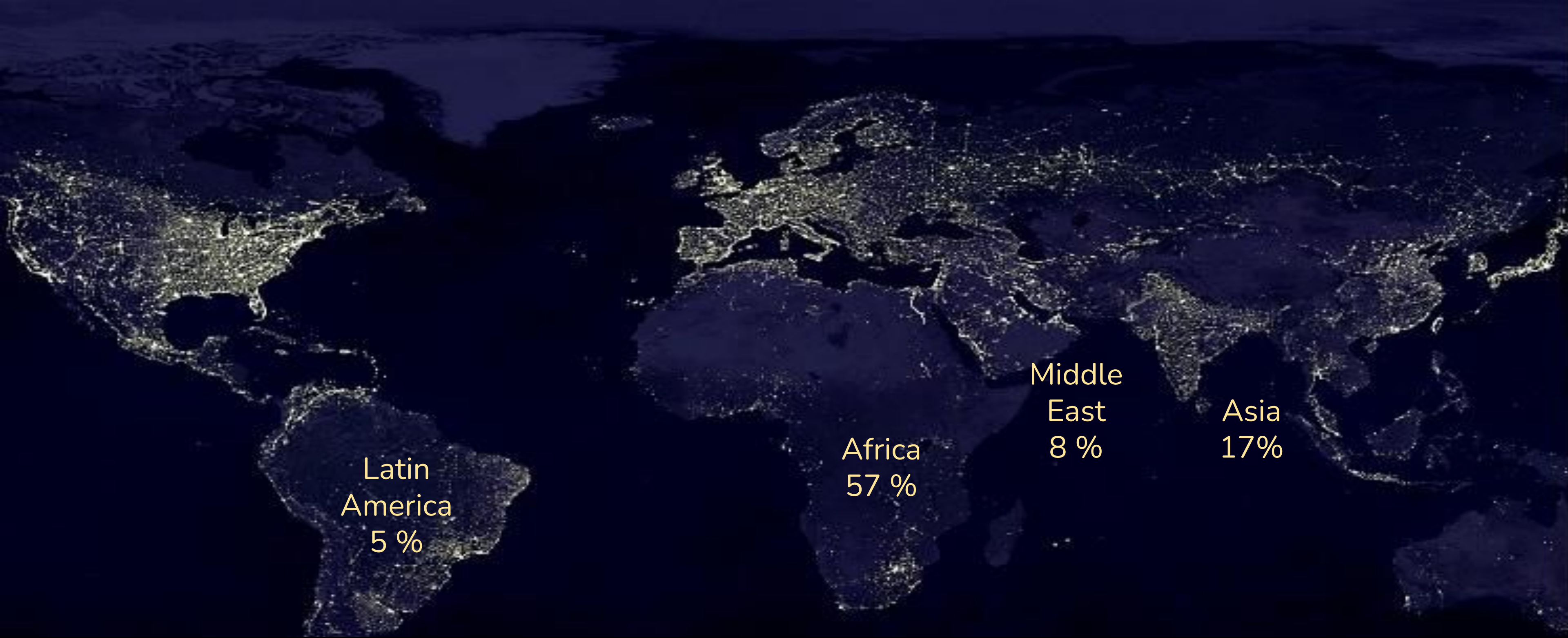
**— R. Buckminster Fuller, American engineer, architect, and futurist who developed the geodesic dome**

# Outline

# World primary energy source




**Shell Company Scenarios to 2050**




1.3 BILLION PEOPLE ARE LIVING

# IN THE DARK

# PMFCs part of the energy mix

**PMFC is a novel system to generate “bio-electricity” using living plants and bacteria.**

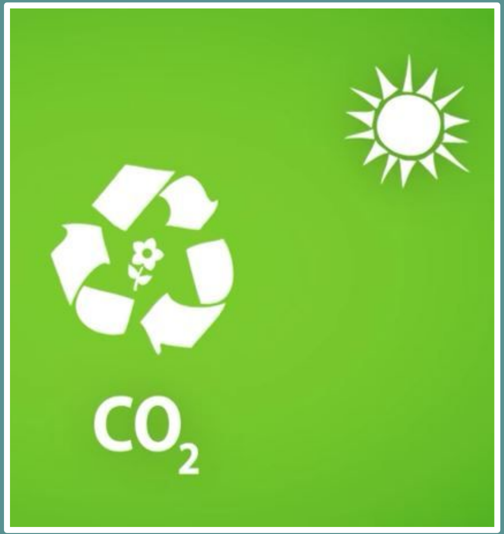
# Quick Facts about PMFCs

- Uses plant roots to fuel electroactive bacteria (EAB) at the anode by excreting rhizodeposits to generate bioelectricity
- Applications have been extended to paddy fields, wetlands, green roofs and floating water bodies
- Incorporated into agricultural lands without impact on food production
- Functional in otherwise unsuitable areas such as wastelands to harvest bioenergy
- Plants can be grown indoors, on green roofs, and rooftop gardens to generate bioelectricity, maintain air quality, and render ecosystem services

**PMFCs are capable of generating sustainable green energy with living plants as the only source of organic matter (OM)**

**PMFCs are attractive as potential source of cheap, clean and renewable bioenergy**

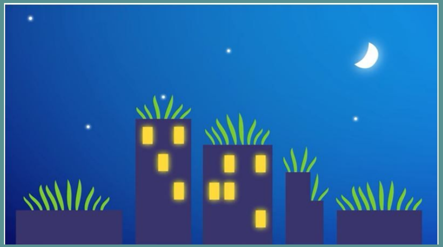
# PMFCs as sustainable technology



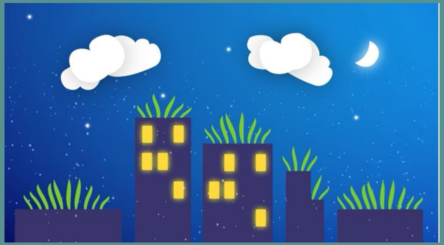
# PMFCs can provide urban energy

Natural source for electricity

Day or Night



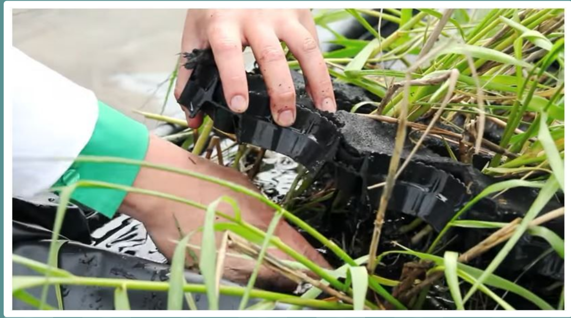
Summer or Winter



# PMFC Commercialization

Plant-Microbial Fuel Cell technology is being demonstrated at the Netherlands Institute of Ecology (NIOO-KNAW)


Plant-e
*living plants generate electricity*



Plant-e plans to commercialize roof-top Plant-Microbial Fuel Cell technology

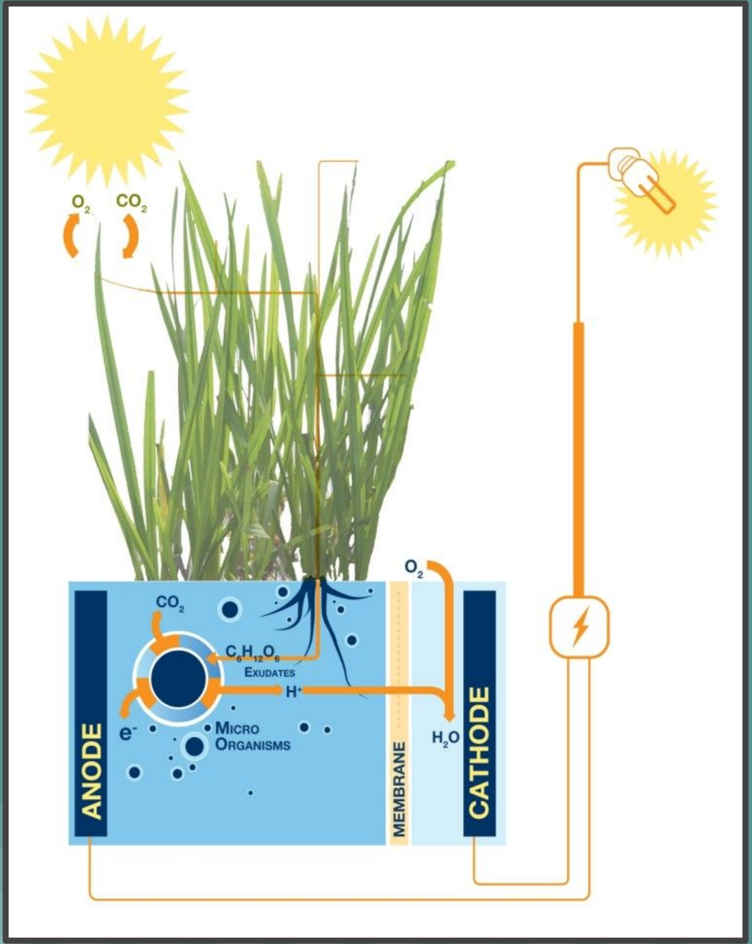
# PMFC Future - Singapore Eco-City

# PMFC concept

Figure-1. Simplified schematic of plant-microbial fuel cell.

PMFCs are biological cells consisting of:

- **Living plants**
- **Supporting matrix** and
- **Conductive anode** inserted into the substrate
- **Cathode** placed in air or water to convert chemical energy into bioelectricity
- **Organic Matter (OM)** chemical energy converted to $e^-$, $H^+$, and CO2 in oxidation
- **Electroactive bacteria (EAB)** attached to anode responsible for oxidation
- ($H^+$)→ medium → anode
- ($e^-$)→ anode → externally → cathode
- At cathode: O2, TEA catalyst, reduced with $H^+$ and $e^-$ to generate **bioelectricity**




Helder, Marjolein, Bioproducts and Biorefining 7, no. 1 (2013): 52–64. https://doi.org/10.1002/bbb.1373.

# Role of Plants

Plants photosynthesize to yield OM which serves as “source of carbon” in the rhizosphere for EABs activity

Removal of pollutants from ecosystems

Serve as indicator species

Removal of heavy metals

Operation PMFC, three groups of plants used in construction:

- **Vascular plants**
- **Macrophytes**
- **Wetland or marshy land grasses**

**Wetland plants** commonly used in construction of biocathodes

- Water tolerant plants
- Possess aerenchyma tissues: allow O2 from atmosphere into roots easily

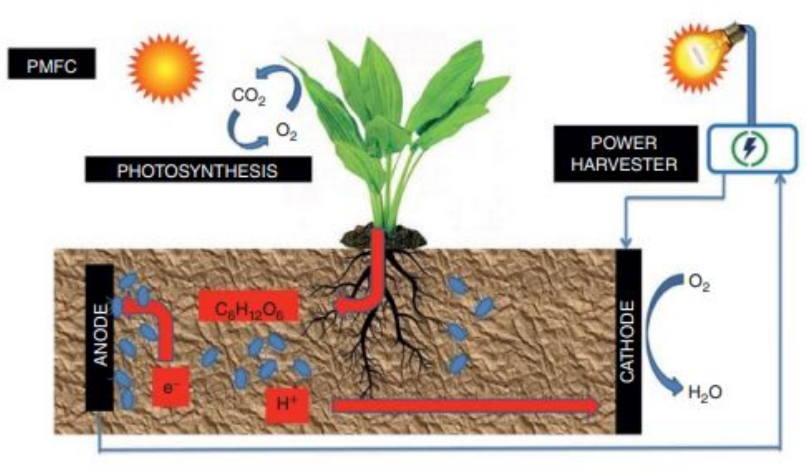



**Figure 8.1** Schematic overview of a plant microbial fuel cell (PMFC).

# Role of Plants

Selection of plants done casually

Selection of right species increases desired treatment and bioelectricity generation

Locally available species preferred to avoid introduction of invasive species

Factors for PMFC plant selection:

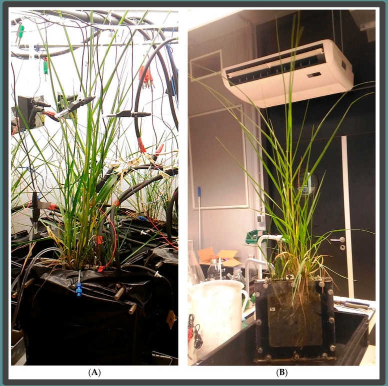
- Prefer larger amount root exudates produced
- Plant species with C4 photosynthetic pathways

**C4 plants**

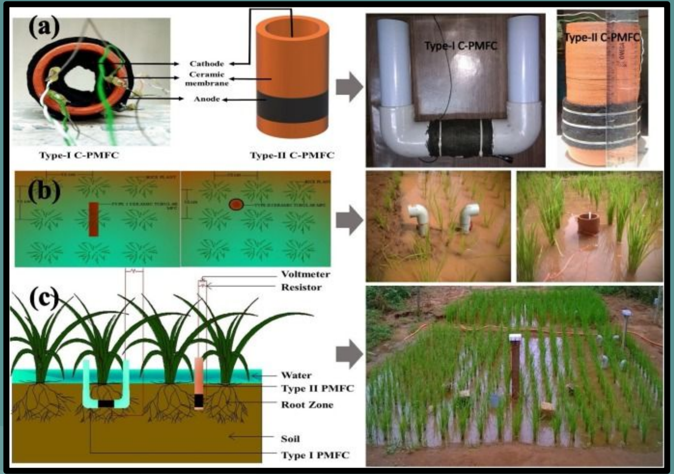
- Higher rates solar conversion and efficiency
- Increased rhizodeposition serve as substrate for microbial oxidation

**Other considerations** - hardiness, growth rate, microbial community at rhizosphere, extensiveness of root system, tolerance and bioaccumulation abilities, and local adaptability

# Role of Plants




**S. anglica** implanted PMFC achieve the highest power generation while removing pollutants




**Rice cultivars** are the most preferred plant species with easy access, adequate hardiness and flexibilities to grow under different conditions within various ecological zones


Sudirjo, Water 11, no. 9 (2019). https://doi.org/10.3390/w11091810
Kiran, Process Biochemistry 99 (December 1, 2020): 270–81. https://doi.org/10.1016/j.procbio.2020.09.015

# Supporting Matrix

Supporting matrix used in PMFC operation

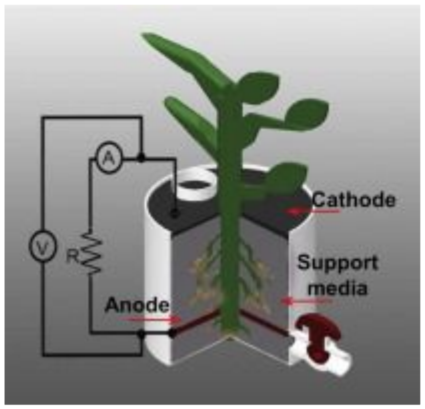
Considered during the design and operation

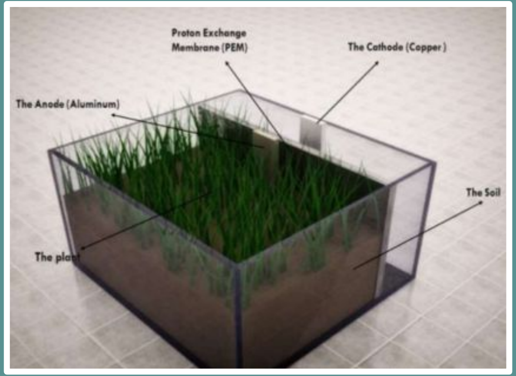
Affects the internal resistance

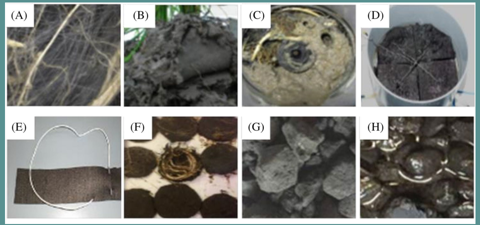
- Interfering with migration of protons (H+) between the electrodes
- Diffusion of root exudates to the anode

Supporting matrix used in PMFC operation includes flooded soils, paddy, wetland or garden soils, sediments, vermiculite, graphite granules in which the anode and the living plant are buried

Soils are the common source because of the presence of rich natural microbes




# Supporting Matrix

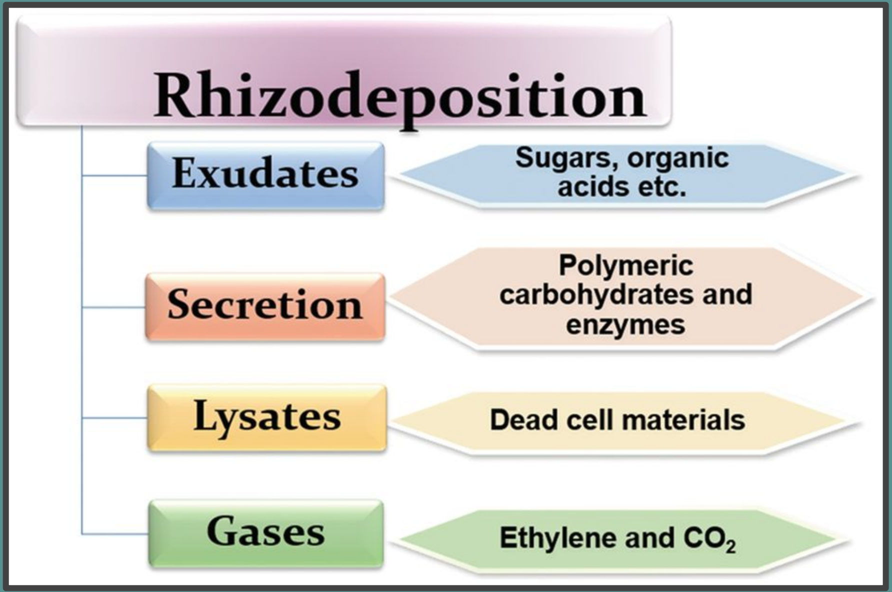
Rhizosphere provides substrates (carbon) for the growth of rhizobacterial populations

Microbiome of the rhizosphere plays a vital role in the soil microenvironment

Exudates stimulate chemotaxis which increases soil microorganisms in the rhizosphere

About 70% of carbon deposited by photosynthesis is translocated into the soil as rhizodeposition

Almost 60% of it can be recovered as energy by PMFCs




Chiranjeevi. Biomass, Biofuels and Biochemicals. Elsevier, 2019. https://doi.org/10.1016/B978-0-444-64052-9.00022-4.

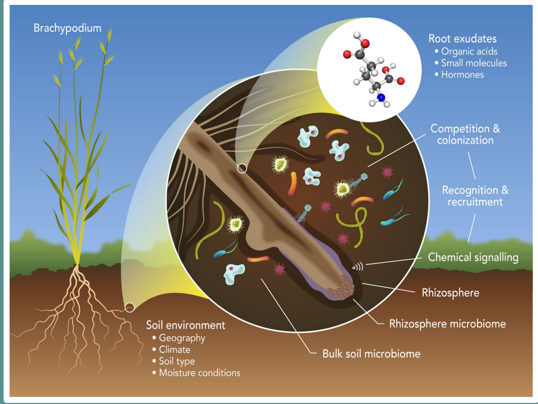
# Microorganism in rhizosphere

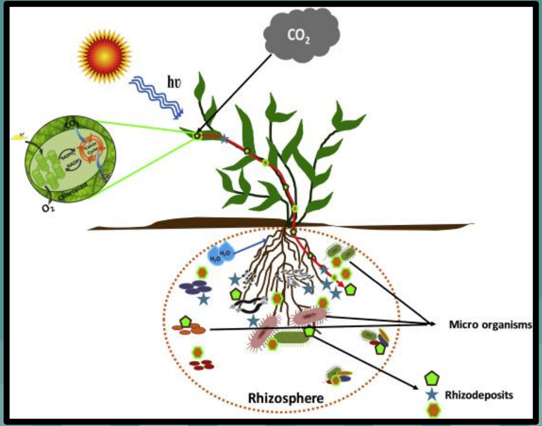
**Rhizosphere**

- Region extending about 4 mm around the roots
- Area where electrodes are inserted during PMFC operation
- Wide range of microbes and microbial activities
- Rhizodeposits in this region provide surfaces for bacterial attachment

**PMFCs microbial communities in rhizosphere are different:**

- Root exudates differs between plant species
- Microbial consortia varies with supporting matrix or inoculum and operation conditions




HowStuffWorks. "How Plant-Microbial Fuel Cells Work," January 17, 2013. https://auto.howstuffworks.com/fuel-efficiency/alternative-fuels/plant-microbial-fuel-cell.htm.

# Microorganism in rhizosphere

EABs are electron donors in association in PMFC operations

Microbes grouped according to their locations (on the anode or cathode) or the role they play in electron transfer

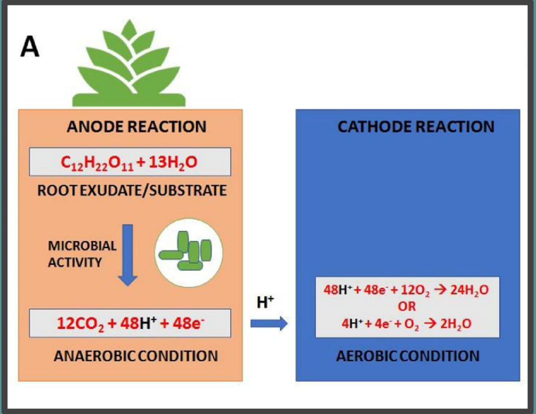
- Classified as electricigens, anodophiles and exoelectrogens

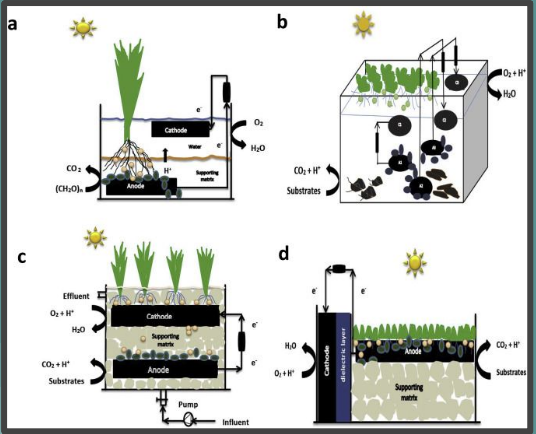
**Anode** contain anaerobic microbes

**Cathode** contain both aerobes and anaerobes

**Aerobes** use oxygen as the oxidant to assist the oxidation of transitional catalysts such as manganese (II) or iron (II) for electron delivery to oxygen

**Anaerobes** uses nitrate, sulphate, iron, manganese, carbon dioxide for their reduction




Kabutey, Renewable and Sustainable Energy Reviews 110 (August 1, 2019): 402–14. https://doi.org/10.1016/j.rser.2019.05.016.

# Substrate conversion

**Organic matter (OM)** in the supporting matrix

Substrate and a source of energy for EABs during PMFC operation

Impacts performance of the system in power generation and coulombic efficiency

**Other reactions involved**:

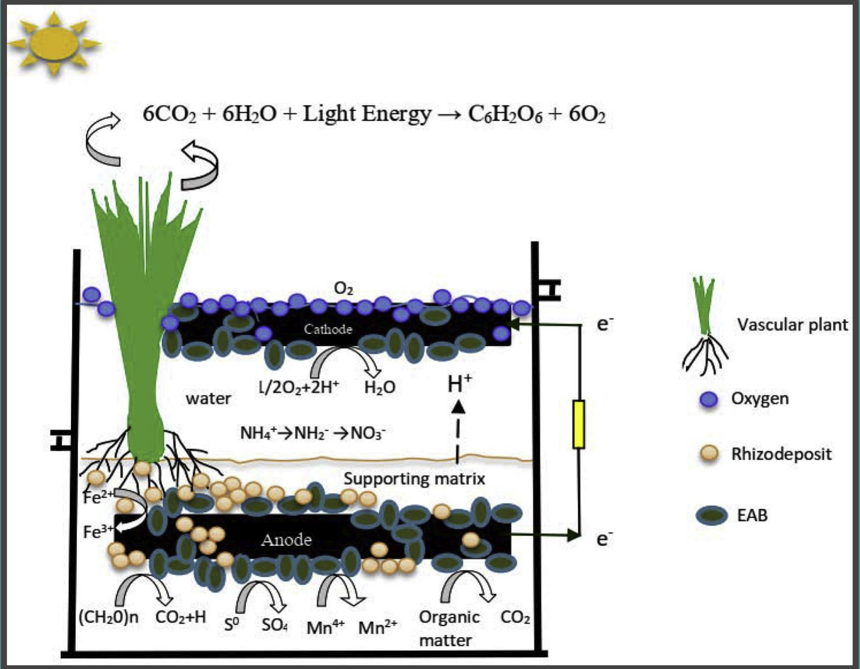
Chemical oxidation of microbially produced reductants
Microbial oxidation of sulphur to sulphate

Oxidation of ammonia to nitrite/nitrate

Conversion of carbonate into organic carbon

Hydrolysis of carbohydrates to acetate

**Reactions produce electrons which are transferred to the anode for bioelectricity generation**




Kabutey, Renewable and Sustainable Energy Reviews 110 (August 1, 2019): 402–14. https://doi.org/10.1016/j.rser.2019.05.016.

# Electron Transfer in PMFC

Rhizodeposition form from plant's photosynthetic activity

Microbes oxidize the rhizodeposits for growth

Convert substrates into CO2, (H+) and (e–) donated to the anode

Electrons captured by the anode are transferred to the cathode where oxygen is reduced to water

Transfer of electrons to the anode has three pathways:

(i) direct electron transfer by biofilm-forming bacteria (Fig. a)
(ii) mediated electron transfer (Fig. b)
(iii) electron transfer through nanowires (Fig. c)

Supporting matrix can serve as an electron donor

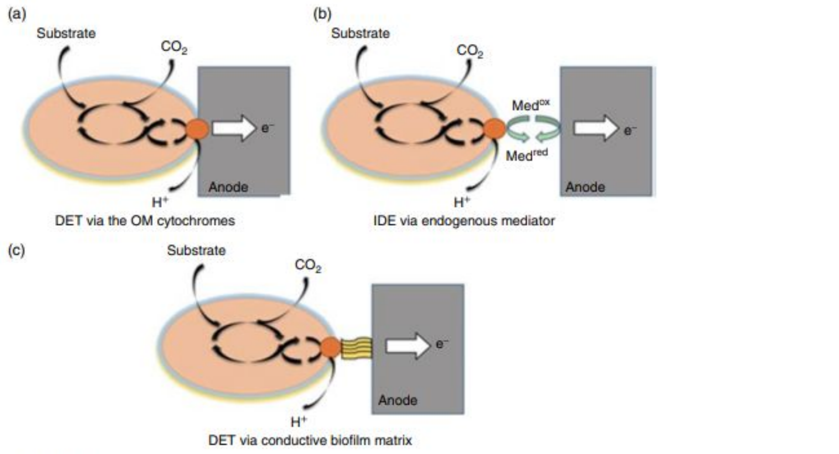



**Figure 8.2** Three main mechanisms for extracellular electron transfer (EET) proposed by several researchers, including (a) direct electron transfer (DET) via outer-membrane cytochromes, (b) indirect electron transfer (IET) via an exogenous or endogenous mediator, and (c) DET via a conductive biofilm matrix. *Source:* Winaikij et al. (2018).

# PMFC Applications

**WASTEWATER**

PMFCs bioelectricity generation from wastewater

Mohan et al. used miniature floating macrophyte ecosystem to generate bioelectricity using domestic sewage and fermented distillery

Removal of COD (86.67%) and VFA (72.32%) and bioelectricity generation of (224.93 mA/m2)

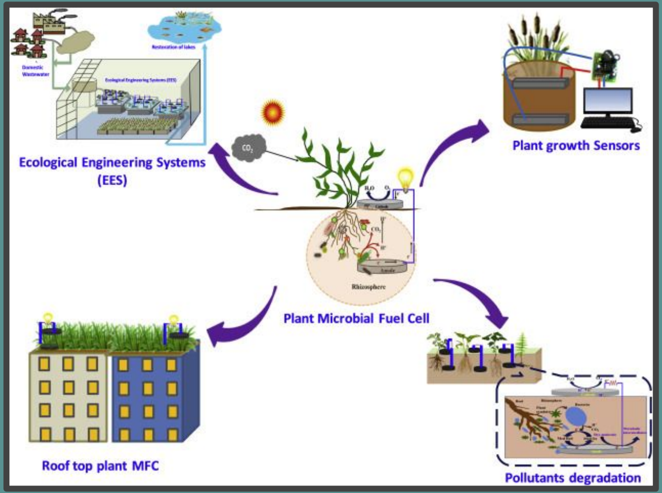
**Greenhouse Gas Mitigation**

PMFCs installed in wetlands and paddy fields to reduce methane gas emission

**Biosensing**

Fuel cells to power devices for detection of environmental pollutants

PMFC constructed to serve as a source of energy and biosensor for a wireless electronic system produced maximum voltage output of 502 mV and maximum current of 590 µA

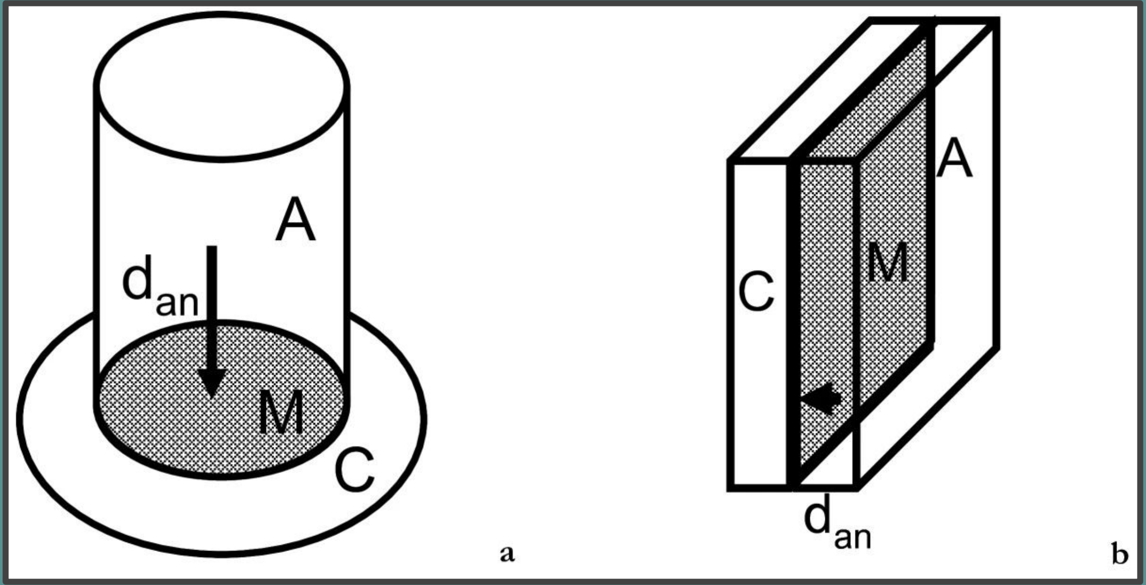



Kabutey, Renewable and Sustainable Energy Reviews 110 (August 1, 2019): 402–14. https://doi.org/10.1016/j.rser.2019.05.016.

# PMFC flat-plate

Tubular (2a) and flat-plate (2b) design of a Plant Microbial Fuel Cell, in which A = anode, C = cathode, M = membrane, d an = average distance between anode and membrane.

Distance between anode and membrane is shorter in flat-plate design than in tubular design.



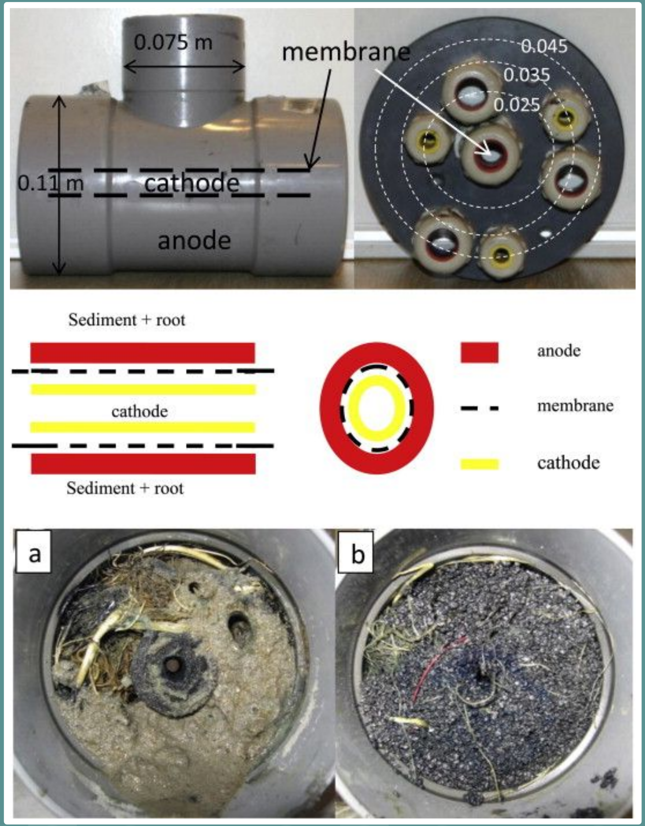

Helder, Biotechnology for Biofuels 5, no. 1 (September 21, 2012): 70. https://doi.org/10.1186/1754-6834-5-70.

# PMFC setup

Fig. 1. Picture and schematic representation of the tubular plant microbial fuel cell.

a) anode compartment with graphite felt,

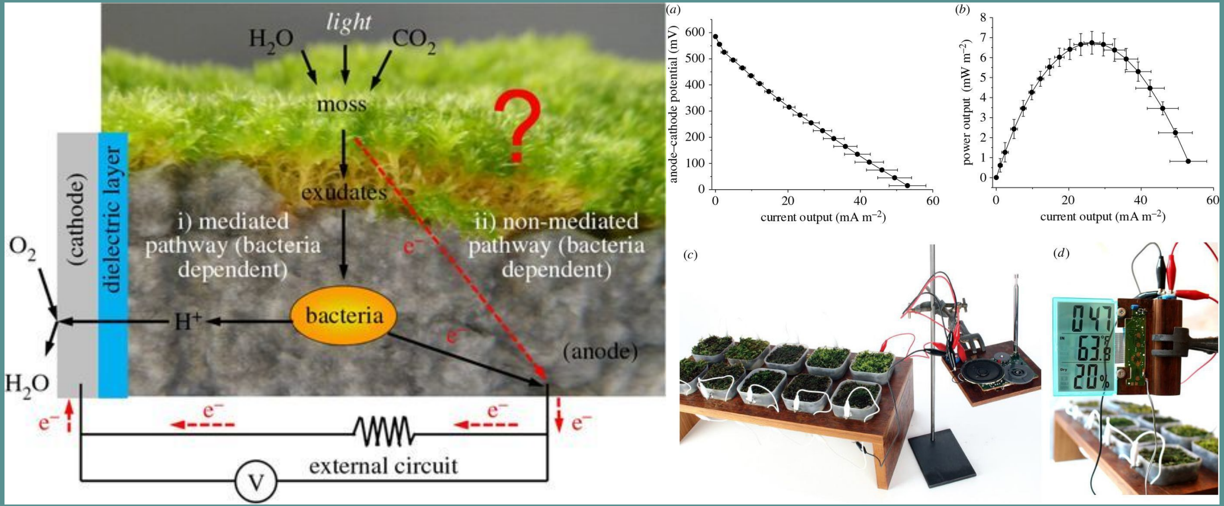
b) anode compartment with graphite granules.




“Flora Health Wireless Monitoring with Plant-Microbial Fuel Cell.” Procedia Engineering 168 (January 1, 2016): 1646–50. https://doi.org/10.1016/j.proeng.2016.11.481.

# PMFC setup

Fig. 1. Characterization of the MossFM. The figure shows polarization (a) and power (b) curves for the bio-electrochemical systems forming the Moss FM (n = 10), as well as the actual Moss FM powering a commercial radio (c) and a digital LCD environmental sensor (d).




Bombelli, Royal Society Open Science 3, no. 10 (n.d.): 160249. https://doi.org/10.1098/rsos.160249.

# PMFC setup

Example of PMFC biosensing system

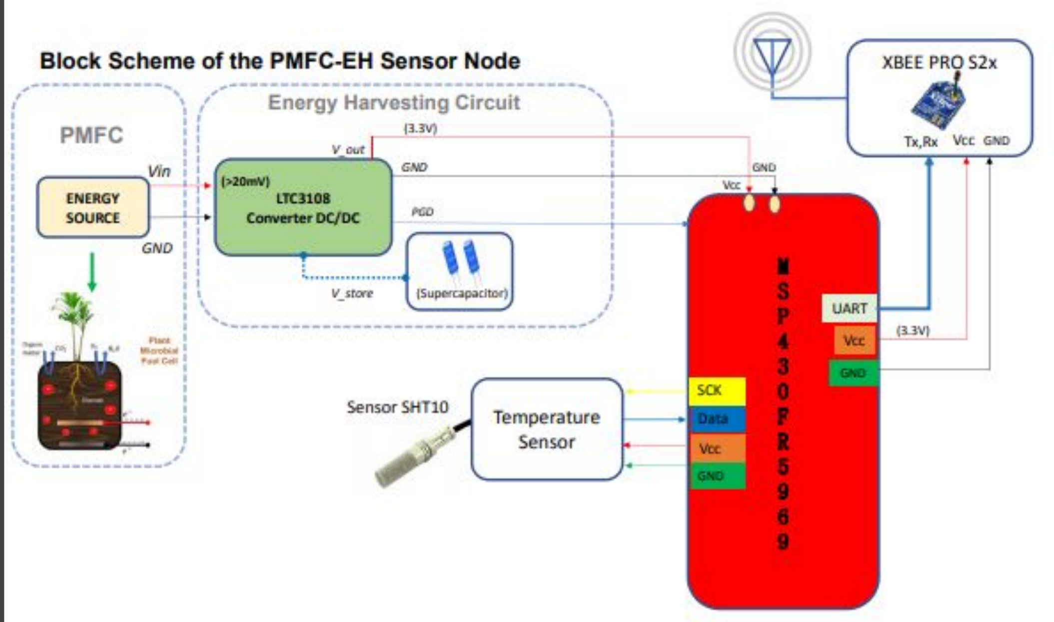



**Figure 2.** Conceptual PMFC-EH system for the IoT applications proposed in this paper.

Osorio de la Rosa, Sensors 19, no. 6 (March 20, 2019): 1378. https://doi.org/10.3390/s19061378.

# PMFC how much power?

**Plants are inefficient at converting solar energy into biomass**

- Quantum factors affecting photosynthesis
- Chloroplasts only absorbs light in the 400-700 nm band,
- Accounts for about 45 percent of incoming solar radiation

C3 and C4 two most prevalent photosynthesizing plants (named from number of carbon atoms in the first molecules they form during $CO_2$ breakdown)

Theoretical conversion limit:

- C3 plants (95% plants on Earth) = 4.6 %,
- C4 plants = 6 %

These plants achieve only 70 % of theoretical conversion limit

[source: Deng, Chen and Zhao]; [sources: Deng, Chen and Zhao; Miyamoto; SERC].

# PMFC how much power?

Any machine loses some energy in running the works

For PMFCs energy is lost in growing the plant

Only 20 % of biomass from photosynthesis reaches the rhizosphere

Only 30 % of that becomes available to microbes as food

PMFCs convert 9 % of the energy from microbial metabolism as electricity

SO,

**PMFC solar-to-electrical conversion rate:**

**for C3 plants** = (70 %) x (4.6 % conversion rate) x (20 %) x (30%) x (9 %) = **0.017 %**

**for C4 plants =** (0.70 x 6.0 x 0.20 x 0.30 x 0.09) = **0.022 %**

[source: Deng, Chen and Zhao]; [sources: Deng, Chen and Zhao; Miyamoto; SERC].

# PMFC how much power?

**How much energy they can PMFC produce?**

According to a 2008 estimate 21 gigajoules (5,800 kilowatt-hours) per hectare (2.5 acres) each year

Estimated that number could go as high 1,000 gigajoules per hectare [source: Strik et al.].

So,

Europe has approximately 13.7 million farmers each farm averaging 12 hectares (29.6 acres)

America has 2 million farmers averaging 180 hectares (444.6 acres)

**If 1 % of U.S. and European farmlands were converted to PMFCs:**

Europe: generate 34.5 million gigajoules (9.58 billion kilowatt-hours) annually

America: generate 75.6 million gigajoules (20.9 billion kilowatt-hours) annually

source: Strik et al.; sources: BP; European Commission

# Prospects and challenges of PMFCs

**Prospects** of PMFCs include:

1) Provide continuous sustainable bioelectricity generation without harvesting the plant
2) Produce stable power all year round
3) Coupled to power biosensing devices to monitor ecological quality
4) Remediate the ecosystem in addition to electricity generation
5) Deployable on green roofs and wetlands areas unsuitable for food production
6) Add aesthetic value to parks and gardens
7) Installed indoors to reduce GHG emissions

**Challenges** for PMFCs to optimize operational conditions for commercial application:

1) Low power output compared to the theoretical

   Estimated net power output of 3.2 mW $m^{-2}$ per geometric planting area (280,000 kWh $ha^{-1}$ $year^{-1}$)

   OM limitation for EAB oxidation and higher internal resistance at the anode

2) Plant species with increased rhizodeposition
3) EABs with high metabolic ability (extracellular electron transfer)

# PMFC Future


SOLARPUNK
ATOMHAWK
Plants and micro organisms can generate electicity in a **Biological Fuel Cell**
- Solar energy are converted by plants and microbes to produce electrons. The electrons can be used as electrical energy.
Solar Panels
ELECTRON MULTIPLIER
POWERED BY PEN


SOLARWOOD
16A
ASHERBENALPAY


SUN

# Conclusion on PMFCs

“Directly or indirectly nearly all life on Earth is solar-powered

Plants convert sunlight into organic compounds that, when consumed by other life, pass on the sun's energy to the rest of the food web. As humans, we access this stored energy through digestion and by burning raw or processed plants. Petroleum is just long-dead organic matter transformed by geological forces, and first-generation biofuels are ginned up from corn, sugar cane and vegetable oil.

Unfortunately, petroleum is as packed with environmental and security problems as it is energy, and first-generation biofuels -- which are refined by burning other fuels -- fall well short of carbon neutrality. Worse, as global food crops literally lose ground to biofuel production, mounting scarcity drives up food prices, hunger and political instability .

But what if there were a way to have our rice and burn it, too? What if we could derive energy from crops without killing them, or generate power using plants and land not needed for food, all through the power of microbes? That's the idea behind plant-microbial fuel cells (PMFCs).”

[source: The New York Times].

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# Thank You

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