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A Review on Energy Harvesting Potential from Living Plants: Future Energy Resource

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Abstract- Renewable energies (RES) has been discussed and explored by researchers in the past decades, has proved that it can decline the capital cost and cost of electricity generated. Such sources such as solar energy and wind energy continue to take advantage in development, securing long-term sustainable energy for the future. Demand for these renewable energy leads to a reduction of pollution and leaning towards green energy environment. Hence, as the live tree has been discovered to be able to generate a weak source of electricity, it cannot be overlooked as those potential can be used as a power source for low-powered devices. Thus, this paper reviews the concept of living plant energy harvest in several ways and the real-life practice of the technique. Living plant energy overview is also done together for future challenges.

Keywords Plant Energy Harvest, Bioelectricity, Electrochemical Energy, Biomass, Plant-Microbial Fuel Cell, Renewable Energy.

1. Introduction

Over the decades, the growth of the world economy leads to mass consumption of non-renewable energy sources such as petroleum, coal and natural gases. Moreover, the inconsistent and rising of oil price shocks the industry as it is needed to generate electricity, run production machinery and transport the output to the market [1, 2]. Similarly, if the price of the fuel keeps on hiking, it will hinder the economic growth [3–7], while negatively effects the trade and poverty. In the future, these energy resources probably cease to deplete while causing pollution to the environment.

Consistently expanding demand for electrical energy and issues of environmental decay have been impelling electric power experts to discover economical strategies [8] of power generation. The demand for renewable energy (RE) has grown significantly over the years because of the deficiency of fossil fuels. The requirement for pollution-free green energy has made an unmistakable appeal towards renewable energy sources (RESs) [9].

Plants have become more valuable after the discovery of electrical potential inside it while reducing Carbon Dioxide (CO_2) and maintaining the surrounding temperature as the energy crisis and environmental concern become the driving force for alternative energy. It is an important aspect to study the basic properties of trees to configure it as a renewable energy source.

It is acknowledged that trees possess excitable membranes thru electrical excitations [10, 11], in the form of actions and can propagate. Electrochemical conduction [12] and excitation in living plants arose at early stages in connection with the need of broadcast of a signal about external stimulus from a part of the biological structure to another (nerve impulses). In higher plants, the trend of excitation or action potentials may be data carriers in intercellular and intercellular communication within the climate changes. According to [13, 14], fluctuation of electrical signals (electrical surge) formed when electrode inserted into plants, as a result of wounded action potentials, eventually stabilizes when allowed to rest. Normally, this reaction only makes small changes in membrane conduction or ion distribution along channels of electrical flow [10, 11, 15].

In an experiment by a team led by Koppán et. al. [16], the electric potential difference is detected and recorded by inserting a non-polarizing electrode for a period of two years. The amplitude of daily variations recorded changes between 15 – 50 mV during vegetation period. The electrical potential of plants includes their resistivity. From papers written by Fensom et. al. [17] claims that mobility of ions in plant tissue will increase the conduction with each different size and own rate by given electrochemical gradient. Another finding is the effective resistance of apoplast along the midrib of the leaf is inversely proportional to the width of leaf [18]. As the leaf dry up, resistance rises sharply. This means that resistance is higher when no water present in the plant.

From those previous research, more and more evidence of energy generation is possible through the living plant. Therefore, the aim of this paper is to review the potential of plants to become energy resource while providing theoretical principles of each proposed method. This includes the various possibilities in the implementation of current technologies to scavenge the energy. However, there is some caveat that needs to be considered in which harm that is done during the progress of energy excavation from living plant is minimal to none.

This paper is outlined as follows: Section 2 describes the concept of the harvesting methods and analysis, Section 3 provides current research involving living plant energy harvesting, while Section 4 presents the challenges and future perspective on the application of the living plant energy.

2. Energy Harvest Potential

2.1. Renewable Energy Categorisation

The emerging of renewable energies has proved to reduce the cost of power generation due to price fluctuation [19–21] of conventional fossil fuel energy. Renewable energy such as wind, hydropower, solar, geothermal and biomass [22] is able to provide sustainable energy services, which routinely available indigenous sources [23]. These renewable energies have been commercialized and accepted by the world, while able to produce an adequate amount of energy to supply consumers.

The uprising of technology also leads to the production of low-powered portable devices. Hence, micro-renewable energy [24] has gained interest from scientist and been constantly researched, for instance, piezoelectric, thermoelectric, and resonant frequency (RF). Table 1 shows the categorization of renewable energy and properties.

Table 1. Renewable energy category [25]

No Combustion Required		***Requires Combustion***
Predictable	***Unpredictable***	***By-product of Processes***
Hydropower	Solar	Biomass
Geothermal	Wind	Biofuel
Aerothermal	Ocean waves and tide	
Electrochemical	Piezo-electric	
	Thermo-electric	
	Resonant Frequency	

From the categorization of renewable energy, there is a certain concept that can be implemented to get energy from plants. That potential is discussed in the next sub-topic.

2.2. Energy Harvesting Techniques from Plants

2.2.1. Energy from Motion and Vibrations

Any type of mechanical movements such as motion and vibration will emit kinetic energy which potentially can be converted into electrical energy, with the help of electrostatic, piezoelectric or electromagnetic transducer [24, 26, 27].

Slower energy source can be harvested by attaching one of the two parts of the transducer to one reference part and one to moving part [28]. This method usually is utilized to harvest energy from vibration [29], which in most case system is resonant by replacing moveable parts using spring. However, this method can become motion harvester [30, 31] when no spring is used. Fig. 1 show the resonant vibration harvester model.

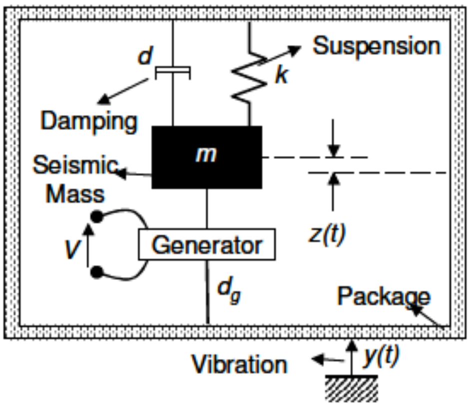


Fig. 1. Schematic overview of vibration harvester [32]

Resonant vibration harvester can be treated as velocity damped mass-spring system, described by following differential equation.

$$m\ddot{z} + (d + d_g)\dot{z} + kz = m\ddot{y} \tag{1}$$

z represents the motion of the mass, d_g the damping due to the transfer of mechanical energy to an electrical load, d the one due to parasitic effects like air, friction to sliding surfaces, k is the spring constant of the suspension, m is moving mass and y is the amplitude of the frame movement in z direction.

In this function, the maximum power can be obtained when input frequency is same as resonance frequency, f_{res}. The equation is given by [32]

$$P_{res} = \frac{m\omega_{res}\zeta_g |Y|^2}{4(\zeta + \zeta_g)^2} \tag{2}$$

Where $\zeta = d / 2m\omega$ and $\zeta_g = d_g / 2m\omega$ are non-dimensional damping factors and Y is the amplitude of the input vibration. This appears that maximum power is retrieved using the lowest damping.

Ref. [29] indicates that maximum displacement $z_{\max}$ for a well-defined damping value will produce power expressed as

$$P_{res} = 4\pi^3 m f_{res}^3 Y z_{\max} \tag{3}$$

With naturally available vibrations, the output voltage tends to be too low in the case of electromagnetic transducers and too high for electrostatic transducers. This conclusion derived from approximate analysis in [32], thus not generally valid, however, the behavior of vibration harvester can be predicted through the analysis. For a process perspective, piezoelectric harvesters are easier to fabricate.

In piezoelectric transducers (PZT), any movement or tremors will cause twist [33, 34] on piezoelectric capacitor hence generate voltages. Higher vibration frequency will lead to higher energy generation. Structural [35] and material [36] of PZT with proper battery matching [35] will improve the harvesting efficiency. This device is very small in size (about 1 – 10mm) and known as micro machine which produces small power. Any deformation or bending of the PZT crystals causing electrical polarization behaviors can be expressed in mechanical and electrical equations.

$$\delta = \frac{\sigma}{Y} + dE \tag{4}$$

$$D = \varepsilon E + d\sigma \tag{5}$$

Where δ is a strain, σ is stress, Y is Young's Modulus, d is piezoelectric strain coefficient, D is charge density, and E is the electrical field. Piezoelectric material exhibits anisotropic characteristics, which the output depends on the direction of applied force and orientation of polarization and electrodes [37]. For instance, each material is given their own set of subscripts, ij , i for the direction of excitation, j is the direction of system response. The most commonly used modes are d_{33} [38] and d_{31} [39] which the number 1, 2 and 3 represents the axis x, y and z respectively. The mode of piezoelectric strain constant d is defined as strain developed per applied electric field, E, or conversely, short circuit charged density, c per applied stress, N.

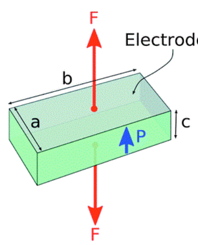
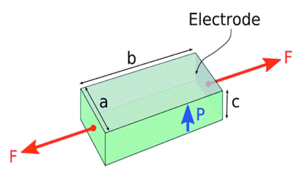
$$d = \frac{1}{E} = \frac{C}{N} \tag{6}$$

Coupling coefficient, k, which gives the efficiency of energy converted between electrical and mechanical domains.

$$k_{ij} = W_{i,e} / W_{j,m} \tag{7}$$

Where $W_{i,e}$ is the electrical energy stored in i axis and $W_{j,m}$ as mechanical input energy in j the axis. The operating modes of the piezoelectric are illustrated in Table 2.

Table 2. Comparison between d_{33} and d_{31} configuration [40]

	
d_{33} configuration	d_{31} configuration

$Q(V=0)=d_{33}F$	$Q(V=0)=d_{31}F\dfrac{b}{c}$
$V(Q=0)=\dfrac{c}{ab}g_{33}F$	$V(Q=0)=g_{31}F\dfrac{1}{a}$

Q and V is electrical charge and voltage respectively. F is applied force and P is polarization direction. g_{33} and g_{31} is the piezoelectric voltage coefficient. Fig 2. shows the fabricated piezoelectric harvesting film strip with d_{33} configuration.

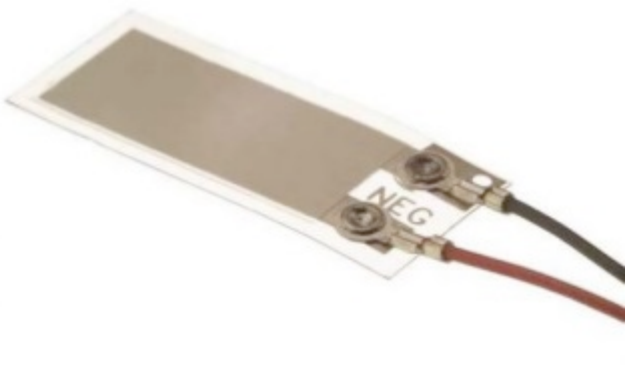


Fig. 2. Example of fabricated piezoelectric film strip [41]

In diverse application, there are studies that incorporate piezoelectricity to energy harvest from rainfall [42–45]. The recoverable energy varies from 0.8μJ/s (small rain) to 1.2mJ/s (heavy downpour), Similar evaluation performed by F. Viola et. al [46] while using advanced Arduino based measuring system to measure the actual amount of energy output. However, it is still very hard to get the desired amount of output that can power up electronics without a storage system due to the inconsistencies of raindrops.

Structure of the piezoelectric system also plays an important part in increasing the efficiencies of ambient movement harvesting. Assessment of piezoelectric structure by F. Viola et. al. [47] claims that cantilever type is more suitable to be used when dealing with the vertical movement of water droplets, while Abidin et. al. [48] claims that voltage double provides more promising energy output.

Nevertheless, from piezoelectricity perspective, the possibility and potential for plant leaves and tree trunk to vibrate and sway in a windy or raining environment using new thin film type of PZT [49] even in low frequency [37] that can generate voltages from the motion and vibration, as described in Fig. 3.

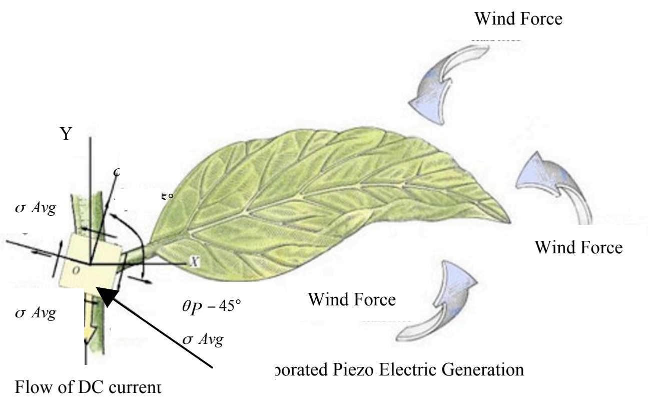


Fig. 3. Piezoelectric harvesting from tree leaf [50]

2.2.2. *Energy from Sunlight*

Under the renewable energy principle, solar power is the most popular and continuously in development. It is quoted as a future energy source and the efficiencies of photovoltaic cells ranged from 5% to 30%, depends on materials used [51]. Most solar cells today relies on silicon solar cells, which do not precisely parallel plant cells. When sunlight hits a silicon solar cell, an electron jumps across the material and moves through a wire to generate electricity. Plant cells instead take the light energy and transfer it to a protein through a chemical process.

In organic solar cells, the process of converting light into electric current is accomplished in four steps: (i) Absorption of photon leading to the formation of an excited state, the electron-hole pair (exciton). (ii) Exciton diffusion to a region, where (iii) the charge separation occurs. (iv) Finally, the charge transport to the anode (holes) and cathode (electrons), to supply a direct current for the consumer load [52].

Conventional solar cells performed almost similar as silicon solar cells, where P-type and N-type silicon are in an exchange with each other it forms a PN junction shown in Fig. 4. At this junction, a fascinating phenomenon occurs, which a basic PN junction creates a diode that allows electricity to flow in one direction but not the other. Near the PN junction, the electrons diffuse into the unoccupied holes in the P material causing a reduction zone (usually TiO_2 membrane) which stops other free electrons in the N-type silicon and holes in the P-type silicon from merging. In contrast, this causes electrical imbalance inside the crystal [51].

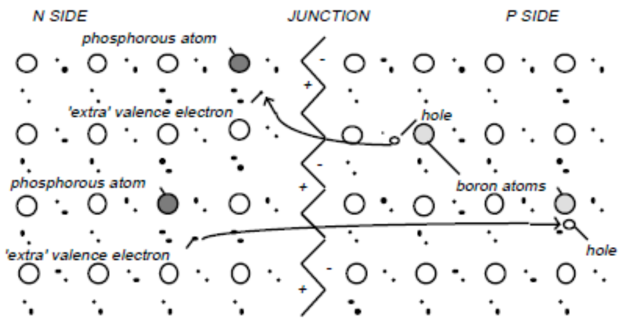


Fig. 4. Junction forming [53]

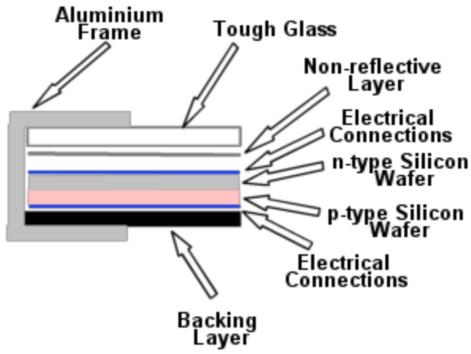


Fig. 5. Construction of photovoltaic cell

In sunlight, there is energy called photons. When a photon of light is absorbed by an atom in the N-Type silicon it will free an electron, creating a free electron and a hole. The free electron and hole have enough energy to jump out of the reduction zone. If a wire is connected from the cathode (N-type silicon) to the anode (P-type silicon) electrons will flow through the wire. The attraction of electron to the positive charge of the P-type material, causing it to travel through the external load, forming a movement of electric current. The N-type material negative charge is then attracted to the hole created and migrates to the back of electrical contact. As the electron arrives at the P-type silicon from the back electrical contact it associates with the hole reinstating the electrical neutrality [54].

Materials of photovoltaic cells are constantly researched and Coakley et. al. [55] from Stanford University managed to synthesize conjugated polymer for photovoltaic cells with optimized energy levels and higher efficiency. This polymer is then improved with 4.4% energy conversion efficiency by a group of researchers in University of California [56]. Organometal Halide Perovskites is then discovered [57], potentially as visible light sensitizers. Plant-based sensitizers such as orange and purple eggplant were also tested and successfully generate electricity with solar conversion power of 0.66mW/cm^2 [58]. Table 3 shows the photoelectrochemical properties of fruit juice and natural extracts of solar cells.

Table 3. Photoelectrochemical properties of fruit juice (plant) and natural extracts of solar cells

Dye	*P_{max} (mW/cm^2)*	*Efficiency (%)*	*Cathode (catalyst type)*	*Ref.*
Red Sicilian orange ''Moro''	0.66	0.50	Pt mirror	[58]
Strawberry	0.61	0.53	Pt mirror	[59]
Blueberry	0.52	0.34	Pt mirror	[59]
Orange	0.13	0.31	Pt mirror	[59]
Red cabbage	1.51	0.61	Pt mirror	[59]
Cochineal	1.20	0.52	Pt mirror	[59]
Skin of Jaboticaba	1.10	0.62	Pt transparent	[60]
Rosella	0.70	0.63	Pt transparent	[61]
California blackberry	0.56	-	Pt transparent	[62]
Skin of eggplant	0.48	0.40	Pt transparent	[58]
Blackrice	0.327	0.52	Pt transparent	[63]

Obviously, natural dyes show sensitization activity lower than synthetic ones and less stability, which their application is far below the industrial requirements. Nevertheless, their study is an interesting multidisciplinary exercise useful for dissemination of knowledge and to educate people on renewable energy sources.

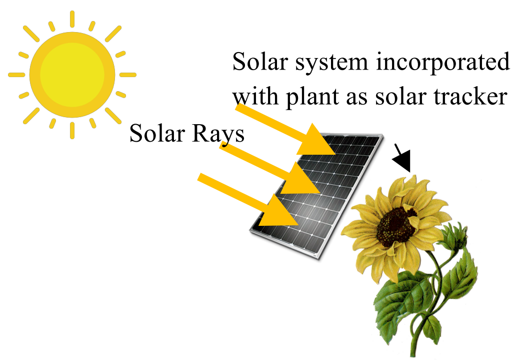


Fig. 6. Plant as a solar tracker

Indirectly, solar energy becomes a huge potential for tree energy harvesting as trees can grow in accordance with sunlight position. In Fig. 6, with the photovoltaic system installed to a plant, the solar tracker will be no longer needed as most plants always point to the sun, collecting rate of irradiance more frequently. Nonetheless, there is also a successful application of solar cell in an indoor environment, using harvesting leaves with built-in solar cell [64].

2.2.3. *Energy from Electrode Potential*

Electrode potential is defined as the potential of a cell containing the electrode acting as a cathode and the standard hydrogen electrode acting as an anode. Reduction takes place at the cathode always, and oxidation at the anode.

Electrode potential [65] can be related to electrochemical cell, which two different metals causing electric current flow as their leaning to drop electrons. For example, when zinc metal with copper metal is placed in their respective electrolyte [66], zinc will start to lose electrons through an external wire connection.

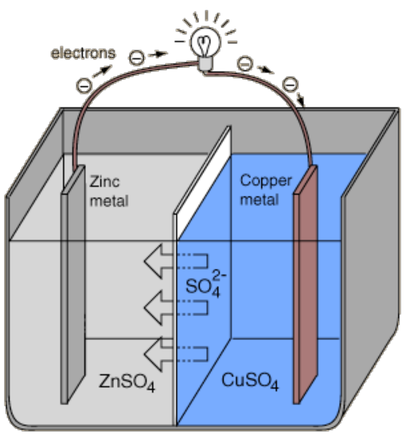


Fig. 7. Electrolysis of copper and zinc metal [67]

Fig. 7. illustrates the chemical reaction between zinc and copper separated by a porous membrane, where zinc will lose its mass, dissolving into the electrolyte and copper will gain mass from its electrolyte. The reaction can be written into the chemical equation.

$$Zn + Cu^{2+} + SO_4^{2-} \rightarrow Zn^{2+} + SO_4^{2-} + Cu \qquad (8)$$

Energy is needed to force electrons from zinc to copper and generates an electromotive force (emf), which can be expressed in volts.

$$1\ volt = 1\ joule / coulomb \qquad (9)$$

Theoretically, nutrition and water transferred from roots of trees can turn out to be an electrolyte. Hence, using electrode potential, the minerals in the soil can be utilized as a part of electrolysis, acting as fuel cell system for energy generation [68]. The efficiency of the fuel cells varies with materials [69–71]. Electrode potential of different metals is tabulated in Table 4.

Table 4. Electrode potential of different metals [72]

Metal	*Potential (Volts)*	*Metal*	*Potential (Volts)*
Calcium	+2.20	Hydrogen	0.00
Magnesium	+1.87	Antimony	-0.19
Aluminium	+1.30	Arsenic	-0.32
Manganese	+1.07	Bismuth	-0.33
Zinc	+0.758	Copper	-0.345
Chromium	+0.60	Mercury	-0.799
Iron	+0.441	Silver	-0.80
Cadmium	+0.398	Platinum	-0.863
Nickel	+0.22	Gold	-1.10

Electrode plays an important role in the plant energy harvesting system, acting as terminals completing the circuit. With correct materials, the oxidation and reduction of the electrode can generate appropriate amount of energy but with a good medium. Electrode effects will be discussed further in the next section.

3. Living Plant Energy Harvesting Systems

The plant energy is one of a kind of renewable energy resource, utilizing living plants to solve the lack of availability of power supply in remote areas. Hence, the potential of plants has been recognized and experimented by researchers with different types of variable in addition to boosting technique.

3.1. Plant-Microbial Fuel Cell (P-MFC)

A biological fuel cell, or known as MFC, is a bio-electrochemical system which includes an anaerobic anode chamber and the aerobic cathode chamber, parted by anion exchange membrane (AEM) or proton exchange membrane (PEM). MFC converts energy when microbes shift from natural electron acceptors, such as oxygen and nitrate, to an insoluble acceptor MFC anode. Oxidation of substrate in anode chamber releases electron by which is then transferred to the cathode through the outlying wire with a conductive material containing a resistor. Electrons can moves to the anode by electron mediators or shuttles [73], or direct electron transfer [74]. Fig. 8 describes the working principle of MFC.

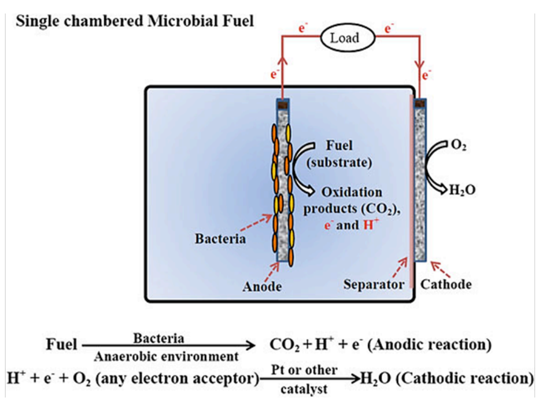


Fig. 8. Principle of single-chambered MFC [75]

The electrons flow through a load to the cathode, where electron acceptors are reduced (e.g., O_2 to H_2O), similar to the chemical fuel cell. Electrode reaction can be represented as equations using different substrate in the following equations.

Acetate as substrate:

Anode half-cell reaction:

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^- \quad (10)$$

Cathode half-cell reaction:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (11)$$

Total voltage generated from MFC can be calculated from the Nernst potential of anode and cathode.

$$E_{cell} = E^0_{cell} - \frac{RT}{nF}\ln Q_r \quad (12)$$

Where E_{cell} is = cell potential (V), E^0_{cell} = standard cell potential (V), R = universal gas constant ($8.314 J mol^{-1} K^{-1}$), T = temperature (K), n = number of electrons involved in reaction, F = Faraday's constant ($9.65\times10^4 C mol^{-1}$) and Q_r = reaction quotient of the MFC reaction.

For example, when acetate is used as substrate in anode equation (10), Nernst potential of anode is described as:

$$E_{an} = E^0_{an} - \frac{RT}{8F}\ln\left(\frac{\left[CH_3COO^-\right]}{\left[HCO_3^-\right]^2\left[H^+\right]^9}\right) \quad (13)$$

Where E_{an} is = anode Nernst potential (V), E^0_{an} = standard anode potential (V), $\left[CH_3COO^-\right]$ = acetate concentration ($mol L^{-1}$), $\left[H_2O\right]$ = water concentration ($mol L^{-1}$), $[H^+]$ = proton concentration ($mol L^{-1}$), $\left[HCO_3^-\right]$ = bicarbonate concentration ($mol L^{-1}$).

Since the concentration and composition of the organic substrate in MFC are mainly unknown, the precise Nernst potential of the anode is hard to determine. Hence, standard open cell potential of anode E^0_{an} is used which is typically -0.289 V vs. standard hydrogen electrode [76].

Ideally, the reduction process in the cathode is, oxygen reduced in water equation (11), the Nernst potential can be determined as:

$$E_{cath} = E^0_{cath} - \frac{RT}{4F}\ln\left(\frac{1}{pO_2\left[H^+\right]^4}\right) \quad (14)$$

Where E_{cath} is = cathode Nernst potential (V), E^0_{cath} = standard cathode potential (V), pO_2 = partial oxygen pressure (Pa), $[H^+]$ = proton concentration ($mol L^{-1}$).

The standard cathode potential with oxygen reduction is typically +0.805 V vs standard hydrogen electrode [76].

Ideally, the MFC with oxygen reduction at the cathode would have a maximum cell voltage of 1.1 V according to [77]:

$$E_{cell} = E_{cath} - E_{an} \quad (15)$$

The maximum cell potential is reached when no internal potential losses occur and are advanced by the open circuit potential (when no current is generated) [78]. The variation between open circuit potential and the Nernst potential is the cause of thermodynamic losses due to the anabolic reaction in the electrochemically active bacteria (EAB), and the chemical reduction of alternative electron acceptors resulting in a mixed potential [79].

However, theoretical maximum cell voltage is usually higher than the measured cell potential. This is due to the internal resistance of the MFC. The internal resistance of the MFC is approximated to the open cell potential, the current and the internal resistance [78].

$$E_{cell} = E_{OC} - R_{\text{int}} I \quad (16)$$

Where E_{OC}= open cell potential (V), R_{int} = internal resistance (Ω), and I = current density (A).

In the year 2008, Strik et. al. [80] proposed and proof the concept using experimentation with Reed mannagrass (Glyceria maxima), which carbon dioxide from plant freed out as rhizodeposits, consumed by bacteria (micro-organisms) and release carbon dioxide into the atmosphere. This method uses biodegradable substance from waste into electricity [81–84]. Metabolic energy transferred to bacteria in electron form via anode, which linked to an electrical circuit to the cathode where electron flows through to generate electricity [85]. Oxygen is reduced in the cathode, releasing electrons and receiving protons that permit through the membrane separating anode and cathode, forming water at the cathode side. This process is described in Fig. 9.

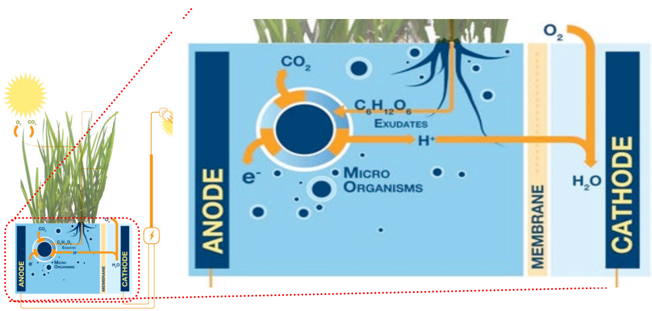


Fig. 9. The reaction of rhizodeposits in P-MFC [80]

Glyceria maxima and Spartina anglica P-MFC [86, 87] have electrochemically active bacteria (EAB) on the root surface that hydrolyze the cellulose that is the one which generates current. Deng et. al. [88] summarize that the potential of P-MFC to power biosensors in wetlands, whereas reducing methane emission and increasing nutrient obtainability in root exudates.

In 2012, Timmers et. al. [89] found out that polarization in cathode increases the internal resistance of P-MFC, triggered by membrane resistance and interrupt the maximum power output prediction. Hence, ammonium-bicarbonate buffer (new medium) was added in P-MFC by Helder et. al. [90] and bio-cathode by Chen et. al. [91] which aim to deliver oxygen electrons to roots for increased power output.

Using graphite felt rather than graphite granule, the anode material is reduced while generating the same power output per square meter of P-MFC membrane [92]. Consequently, Liu et. al. [93] claimed that photosynthate from Ipomoea aquatic plant coupled with a constructed wetland microbial fuel cell (P-CW-MFC) and sunlight photosynthesis process increases power output density.

Firstly, the plant will release O_2 and $C_6H_{12}O_6$ [94, 95]. Next, the anode will produce electrons from anaerobic degradation of $C_6H_{12}O_6$. At the same time, nitrifying bacteria in rhizosphere altered NH_4^+ to NO_3^-. Both O_2 and NO_3^- then utilized as electron acceptors near the cathode.

Sustainability and resilience of the P-MFC also tested in the Netherlands under the natural condition on rooftops [96], and after a period of 221 days suggesting weather climate causing a big influence on the power generation. Increase in solar radiation and temperature will likely increase the power output [97]. Table 5 describes the previous P-MFC system with the maximum power density that can be generated.

Table 5. P-MFC system previous research

Plant species	***Anode***	***Cathode***	***Growth Medium/ Substrate***	***Operating Environment***	***Maximum Power Density (mW/m^2)***	***Ref.***
A. anomola	Graphite rod	Graphite felt	Hoagland solution	Climate chamber	22	[98]
A. calamus	Graphite felt	Graphite felt	Pyrene and benzo pyrene rich water	Climate chamber	-	[99]
C. indica	Graphite disk	Carbon cloth	Tap water	Constructed wetland	18	[100]
C. involucratus	Graphite felt	Graphite felt	Lotus soil and wastewater	Ambient	5.9	[101]
E. crassieps	Graphite disk	Graphite disk	Domestic and fermented distillery wastewater	Miniature benthic system	224.93	[102]
G. maxima	Graphite granules, Graphite felt	Graphite felt	Hoagland solution, Ammonium rich ½ Hoagland solution	Climate chamber	12-80	[80, 86, 92]
I. aquatica	Granular activated carbon (GAC)	Stainless steel with GAC	Anaerobic sludge from municipal wastewater	Constructed wetland	12.42	[93]
I. perenne	Graphite granules	Carbon felt	Hoagland solution	Green House	55	[103]
O. sativa	Graphite felt, Carbon fiber, Graphite granules	Graphite felt, Carbon/ polytetrafluorethylene coated, stainless steel, Graphite granules	NPK fertilizer/acetate solution, Glucose/acetate, professional growing medium, Vermiculite, Soil, Onada soil	Rice field, Climate chamber, Greenhouse, Ambient	6–80	[104–111]
P. setaceum	Graphite plate	Graphite plate	Red soil	Ambient	163	[112]
S. anglica	Graphite rod, Graphite granules, Graphite felt	Graphite felt	Hoagland solution, Nitrate less Ammonium rich medium, Growth Medium	Climate chamber	110-240	[87, 98, 113, 114]
T. latifolia	Carbon felt	Carbon felt, porous air spargers	Sludge from glove manufacturing company	Constructed wetland	6.12	[115]

The organic degradation [100] will be affected by anaerobic methanogens and denitrifying bacteria in a small part. For instance, electron donor competitive partners are hydrogenotrophic methanogens and thermophilic archaea.

In summary, P-MFC technology is an interesting source of sustainable and renewable energy. However, electrode ingredients, operation structures, plant, and soil type ultimately alter system performance. Voltage generation of P-MFC is affected by nature exudation by microbes, root morphology and biomass [116, 117]. A plant that is more resistant and robust which have reliable rhizodeposition and structure of electron transfer rate which is effectively engineered would make sure a future practical application of this technology.

3.2. Living Plant Bio-Energy Fuel Cell

Apart from the microbial fuel cell, trees have been discovered to have electrical properties [13, 17, 18, 118–122] making it an interesting source of energy to harvest from. Started in 2006, Cainan et. al. [123] claimed to have obtained electricity of 0.8V – 1.2V by inserting half an inch of aluminium roofing nail to tree and copper water pipe seven inches into the ground [124] illustrated in Fig. 10. These voltage differences have been used in attempts to monitor plant activity and have been hypothesized to be due to various sources, most prominent of which appears to be the ‘‘streaming potential’’ mechanism [118]. Since then, speculation of the report instantly become the driving force for researchers to reveal the sustainability of the renewable energy source.

Fig. 10. Embedding electrodes to the tree to harvest energy

“Streaming potential” mechanism which explains the voltage generation due to the flow of sap [125, 126] written as

$$V_{sapstream} = \frac{\varepsilon_0 \varepsilon_r}{\sigma \eta} \Delta P.\xi \quad (17)$$

Where ΔP is a pressure difference between ends of the capillary, σ is typical conductivity, η is viscosity and Zeta (ξ) is voltage difference due to flow difference in centre of capillary [127]. Voltage variation also leading more to Nernst equation, which is pH concentration value.

$$V = V' - \frac{RT}{nF}[\Delta pH] \quad (18)$$

Where R is the universal gas constant = 8.314 J K^{-1} mol^{-1}, T is the temperature in degrees Kelvin, F is the electronic charge times Avogadro’s number (Faraday’s constant) = 9.6486104C mol^{-1} and $[\Delta pH]$ is the difference in pH between two reservoirs.

Transroot potential occurs when charged ion gradients like H^+, K^+, and Ca^{2+} [128, 129] reacting inside the xylem sap. K^+ activity can cause an increase of 50mV in transroot potentials [130], similar to glucose and H^+ when moving in the opposite direction [131]. Electrical signaling in plant [121] can also cause the short duration of electrical pulses.

Air relative humidity, soil temperature and material of electrode affected the bioelectricity in the xylem [132]. Lower temperature reduces bioelectricity, while higher moisture increases current [133]. Optimization attempted by using sunlight as an energy source for show increase of power output [134].

Referring to those research, it is convinced that the tree itself has the potential to generate electricity. By using the right electrode material and tree with compatible electrochemical properties, it should be able to generate a significant amount of energy to be harnessed by low powered electronic devices.

4. The perspective of living plant energy

4.1. The potential for future applications

4.1.1. Plant health/ Fire monitoring system

In modern countries, the number of forests is declining. This is due to the deforestation activities from human and natural causes such as forest fire, ecological activities, and diseases. Therefore, there should be a system to monitor the surrounding heat and humidity that operates on low power utilizing the energy from trees. Though the electrical energy from plant today is low, it is viable to be utilized when being connected in series-parallel, increasing its potential difference which is a promising future for later generations.

4.1.2. Network coverage and reporting system

The growth of communication system has produced devices such as smartphones with the need of network coverage for it to work. By incorporating the wireless system which uses low power with energy from trees, this can be a good way to expand the coverage with natural resources, while reducing the deforestation. Reporting system also seems to be an interesting application which can be used by hikers in mountains to send distress signals to when they got lost. However, to achieve these plant energy systems still have many challenges to be overcome.

4.2. Challenge of living plant energy harvesting

4.2.1. Long-term operation

Keeping a plant healthy along with constant generation of voltage and prevention of electrode failing is the main challenge for long-term operation of plant energy. Therefore, the selection of plant and electrode which resists damage and aging become an important aspect. Notably, ceaseless and robust plants that can withstand severe climate conditions with good electrical characteristics can accomplish better.

4.2.2. Controlling the variables

Living plant power output is highly influenced by physiochemical parameters (pH, temperature, moisture, light, soil nutrition, conductivity and etc.) and environmental climate. For this, scientists from multidisciplinary should investigate the effects of each variable and determine the optimal setting for harnessing the maximum energy from the plants.

5. Conclusion

This study presents living plants as an appealing source of renewable energy. This underutilized organic energy can be scavenged in many ways, either from motion, surrounding environment or even electrochemical element potential. However, most of the possible harvesting technique still needs to be adjusted to suit the characteristic of the plant. There are several factors that affect the energy generation of plants, including temperature, moisture, soil pH, electrode types, and environment properties. Overview, the plant energy harvest managed to produce electrical voltages of few millivolts to hundreds of millivolts. Plant and soil types will alter the power output. The variables such as pH, temperature, and moisture still need to be researched to make sure the harvesting operation is controllable. It is important to understand the concept used to scavenge the energy from trees as a pioneer to step in towards practical application of this renewable energy. It is a challenge for engineers to manipulate and improve the harvested energy while using proper algorithms [135] to make it utilizable.

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6. Abbreviations

Section	***Symbol/ Abbreviations***	***Explanation***
2.2.1 (Vibration harvester)	d	Damping due to parasitic effects like air or friction to sliding surfaces
	d_g	Damping due to the transfer of mechanical energy to an electrical load
	f_{res}	Resonance frequency
	k	Spring constant of the suspension
	m	Moving mass
	P_{res}	Resonance power
	ω	Angular frequency
	ω_{res}	Angular resonance frequency
	y	Amplitude of the frame movement in z direction
	Y	Amplitude of the input vibration
	z	Displacement of motion of the mass
	$z_{\max}$	Maximum displacement
	ξ	Non-dimensional damping factors
(Piezoelectric harvester)	c	Short circuit charged density
	d	Piezoelectric strain coefficient
	D	Charge density
	E	Electrical field
	ε	Permittivity
	F	Applied force
	k	Coupling coefficient
	N	Applied stress
	PZT	Piezoelectric transducer
	Q	Electrical charge
	V	Voltage
	$W_{i,e}$	Electrical energy stored in i axis
	$W_{j,m}$	Mechanical input energy in j the axis
	Y	Young's Modulus
	δ	Strain
	σ	Stress

2.2.2 (Energy from sunlight)	P-type	Positive type
	Pt	Platinum
	N-type	Negative type
2.2.3 (Energy from electrode potential)	Zn	Zinc
	Cu	Copper
	SO	Sulfate Oxide (electrolyte)
3.1 (Plant Microbial Fuel Cell)	AEM	Anion Exchange Membrane
	CH_3COO	Acetate
	e^-	Electron
	E_{an}	Anode potential (V)
	E_{an}^0	Standard anode potential (V)
	E_{cath}	Cathode potential (V)
	E_{cath}^0	Standard cathode potential (V)
	E_{cell}	Cell potential (V)
	E_{cell}^0	Standard cell potential (V)
	E_{OC}	Open cell potential (V)
	EAB	Electrochemically Active Bacteria
	F	Faraday's constant ($9.65\times10^4 Cmol^{-1}$)
	H^+	Hydrogen ion
	H_2O	Water
	I	Current density (A)
	MFC	Microbial Fuel Cell
	n	Number of electrons involved in reaction
	O_2	Oxygen
	p	Pressure
	PEM	Proton Exchange Membrane
	P-MFC	Plant Microbial Fuel Cell
	Q_r	Reaction quotient
	R	Universal gas constant ($8.314 Jmol^{-1}K^{-1}$)
	R_{int}	Internal resistance (Ω)
	T	Temperature (K)
3.2 (Living Plant Bio-energy fuel cell)	Ca^{2+}	Calcium
	K^+	Potassium
	$V_{sapstream}$	Streaming Potential
	ΔP	Pressure difference between ends of the capillary
	ΔpH	Difference in pH between two reservoirs
	η	Viscosity
	σ	Typical conductivity
	ζ	Voltage difference due to flow difference in centre of capillary

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