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Article

Integrating microbial fuel cells with sedum green roof for stormwater retention and renewable energy generation

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SUMMARY

Climate change brings frequent and intense storms, which challenge aging stormwater infrastructures. As a sustainable stormwater solution, green roofs are being more frequently used in urban areas. However, high installation and maintenance costs have limited applications of green roofs on a large scale. A plant microbial fuel cell (P-MFC) is a novel technology that uses bacteria living around the root of plants to generate electricity. This study explores the integration of P-MFCs with an extensive green roof module for the dual benefit of stormwater runoff reduction and renewable energy generation. While most P-MFC systems in the literature are based on flooded plants, the green roof MFC developed in this study uses sedum plants which are among the most common vegetation layers for green roof solutions. We hypothesized that MFC efficiency could be improved by introducing a water storage layer and capillary sub-irrigation. Moreover, the capillary irrigation wick can function as a salt bridge to further enhance power generation. Three prototypes were fabricated to test our hypotheses, including a control unit without sub-irrigation and two units with capillary irrigation and one with additional salt bridge configuration. Experiments demonstrated that capillary irrigation and the salt bridge configuration significantly increased P-MFC's power density and decreased the internal resistance. The research demonstrated that green roof modules with integrated P-MFCs can be a renewable energy generator, promoting the adoption of green roofs as sustainable solutions for climate resilience by simultaneously reducing storm floods, capturing carbon dioxide (CO_2) in the atmosphere, and producing green electricity.

INTRODUCTION

Global climate change is threatening the ecosystem, human health, and the economy. The changing climate is closely tied to increasing carbon dioxide (CO_2) emissions into the atmosphere, largely from burning fossil fuels to generate electricity and facilitate transportation. It has never been more important for the world to adopt renewable and eco-friendly sources of energy such as solar, wind, biomass, and geothermal power to slow down global warming, a phenomenon related to climate change (1). Climate change also causes more frequent and intense storms, which can overwhelm the aging stormwater infrastructure (2). An increase in stormwater runoff can exacerbate sewer overflow-related problems and increase pollutant concentrations in rivers, lakes, and oceans. Meanwhile, population growth and urbanization have significantly increased the demand for water, stormwater management, and wastewater treatment, which has consequently increased the energy demand. Therefore, the design and management of future water infrastructures must follow a holistic approach that considers water and energy as a nexus (3).

The impact of climate change on stormwater management is one of the highlighted topics in the Sixth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC). The new IPCC report emphasizes investing in natural or "green" infrastructures to manage the increasingly intense rainstorms by slowing down the stormwater runoff and thus protecting communities from flooding and reducing stormwater pollution (1). Roofs account for about 40~50% of the total impervious surface in developed urban areas, which contributes to a significant amount of surface runoff. A green roof is defined as a layer of vegetation planted on a rooftop. Compared to a conventional roof, a green roof can retain a large amount of rainwater in the soil layer and reduce roof stormwater runoff volume by 10–60% (4). A study showed that if 10% of rooftops in Brussels, Belgium were covered by extensive green roofs, it could reduce the runoff by 2.7% for the entire region or by 54% for individual buildings (5). Other environmental benefits of green roofs include improving thermal insulation for buildings, reducing the urban heat island effect, and reducing noise and air pollution (6). It was also demonstrated that combining green roofs and solar panels on roofs can enhance photovoltaic (PV) performance and generate 8.3% more electricity (7). Despite all these benefits, challenges such as the lack of design criteria and planning, high initial construction costs, and maintenance costs prevent the application of green roofs on a large scale (8).

The most valuable environmental service provided by vegetation should not be overlooked: they take up CO2 from the atmosphere through photosynthesis. According to recent research, the rise of CO_2 has resulted in a 12% increase in global photosynthesis over the last four decades, which has helped to slow the rate of global warming (9). Global photosynthesis converts and stores huge amounts of solar energy into chemical energy, at a rate of about 100 terawatts (10). It would be very beneficial to tap into the energy flow of photosynthesis and convert it into energy usable by society, such as electricity. A technology known as the microbial fuel cell (MFC) is one solution (11). Research over years has discovered that when bacteria break down organic matter, electrons are produced. In an aerobic environment, oxygen is the acceptor of these electrons so that bacteria can "breathe" with oxygen. However, in an anaerobic environment, some electrogenic bacteria can "breathe" onto other substances such as a conductive solid surface. In other words, electrogenic bacteria can transfer electrons to an anode. A circuit can then be designed to move electrons from the anode to cathode through a conductive wire, thus generating an electric current.

Industrial applications of MFCs have already emerged, particularly for wastewater treatment, where microbes simultaneously degrade organic pollutants and produce electricity to save operation costs. While organic pollutants in wastewater can fuel an MFC to generate power, so can plants. Up to 70% of organic matter produced by plants through photosynthesis is emitted in the soil as root exudates, which can provide fuel for an MFC system (12). A typical plant MFC (P-MFC) system consists of an anode and cathode chamber separated by a proton exchange membrane (PEM) (**Figure 1**). In the anode chamber, organic matter released by plant roots is oxidized by bacteria living around the roots, releasing CO_2, protons, and electrons. Bacteria can donate electrons to the anode. Through the external circuit, electrons flow to the cathode. Meanwhile, protons released in the anode chamber move through the membrane to the cathode chamber, where they meet electrons and react with oxygen to produce water. This process creates a closed circuit, which generates electric power.

This study presents the integration of a green roof module with a P-MFC system to reduce urban stormwater runoff while simultaneously producing renewable energy. P-MFCs work best with flooded plants or in wetlands since underwater soil provides the anaerobic environment necessary for electrogenic bacteria to donate electrons to the anode. Additionally, wet soil promotes the transport of protons, which lowers the internal resistance (12). On the other hand, it is only practical for green roof systems to use plants that can tolerate harsh environments and require little maintenance like sedum. Sedum is a large genus of flowering succulents in the family *Crassulaceae*. While sedum plants are not perfectly ideal for P-MFCs since they thrive in well-drained soil, they are among the most common and well-developed green roof solutions thanks to their tolerance of extreme temperatures, drought, pests, and disease. Additionally, a sedum mat is usually lightweight and costs less to install and maintain.

The first objective of this research was to measure the power density of a sedum-based P-MFC system. To our knowledge, there is only one reported study on sedum MFCs, and the study found that the power density produced by their sedum MFC was between 0.015 and 0.092 mW/m^2, which is low compared to typical P-MFCs with flooded plants (5.9–240 mW/m^2) (13-14). This study also found that water content in the growth media had a positive correlation with power output (13). The second objective of this research was to examine if the output power of a sedum P-MFC could be increased by introducing a sub-irrigation system consisting of a water storage layer and a capillary wick. The extra water storage and sub-irrigation have already been implemented in some commercial sedum green roofs to increase their stormwater retention capacities. These products can be easily modified to enable P-MFC functions.

Our experiments tested two hypotheses: (A) Capillary irrigation could improve the P-MFC performance by increasing soil moisture level around the anode, (B) P-MFC power production could be further improved if the capillary wicks are brought into contact with the cathode since the wet wick can function as a "salt bridge" to provide additional transport channels for protons. Data measured in this study supported our hypotheses. Capillary irrigation, particularly with the salt bridge configuration, produced a maximum power density of 26 mW/m^2, which is substantially higher than the control without sub-irrigation, and comparable to most "wet" P-MFC systems. Our study suggests that green roof modules with integrated P-MFCs may be viable alternatives for renewable energy generation.

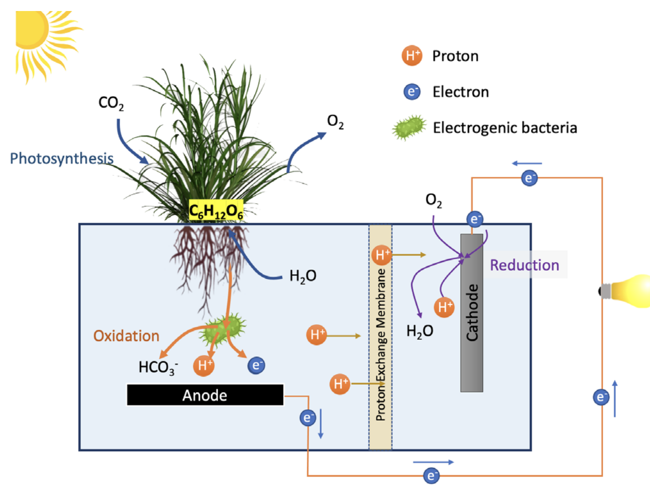

Figure 1. A typical Plant Microbial Fuel Cell (P-MFC) system. Generally, a P-MFC system consists of an anode chamber with growing plants and a cathode chamber separated from the anode chamber with a Proton Exchange Membrane (PEM) which selectively pass protons. A conducting wire connects the anode and cathode to form a close circuit.

RESULTS

To test our hypotheses, three green roof prototypes were designed to study the sedum-based P-MFC (**Figure 2**). All three units were single-chamber P-MFC systems with an air cathode attached immediately below a proton exchange membrane (PEM) on the bottom of the soil container. The anode was buried in the soil media near the sedum roots and was placed immediately above the PEM. The PEM selectively allowed protons to pass through while blocking oxygen and electrons. The baseline system is denoted as the control unit. The second unit is the baseline with a water storage layer added below the green roof module with capillary wicks for the sub-irrigation function. Hereafter it is denoted as the CAP-IRR unit (i.e., capillary irrigation). This configuration serves dual purposes: 1) to increase stormwater retention capacity and 2) to maintain soil moisture through capillary irrigation wicks, thus improving the fuel cell's efficiency. The third unit is similar to CAP-IRR but with the capillary wicks being brought into contact with the air cathode to serve as a salt bridge. Hereafter, it is denoted as the CAP-IRR-SB unit (i.e., capillary irrigation with salt bridge configuration).

We observed that water in the storage layer of the control unit was depleted in about three weeks due to evaporation, while it took about two weeks for CAP-IRR and CAP-IRR-SB units. This demonstrated that capillary irrigation could effectively withdraw water from the storage layer to moisturize

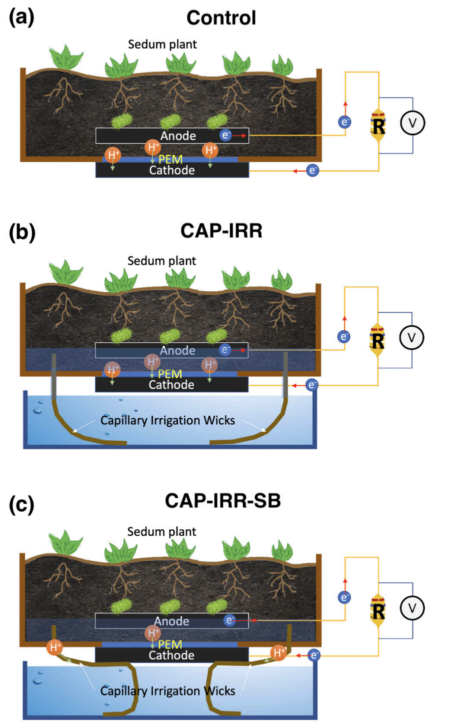

Figure 2. Experimental designs of three sedum-based green roof P-MFC systems. (a) Control unit as the baseline system with a single chamber air cathode configuration. **(b)** CAP-IRR system with the additional water storage layer and capillary irrigation. **(c)** CAP-IRR-SB system which is similar to CAP-IRR, except capillary wicks were brought into contact with the cathode, serving as a salt bridge.

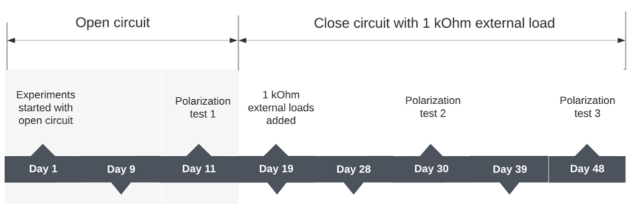

Figure 3. Timeline of experiments. P-MFC voltage was measured at a 30-min interval for 48 days. Circuits remained open for the first 18 days and closed by adding 1 kOhm external loads since day 19. Polarization tests were conducted on day 11, 30 and 48. Plants were watered on day 9, 19, 28 and 39.

the plant's soil. All storage tanks were refilled after they dried. Sedum plants in all three units demonstrated visible growth during the experiment; however, the growth of succulent leaves was not recorded in this study.

Experiments were conducted in late winter for 48 days, and the timeline of events is presented (**Figure 3**). To evaluate the power generation performance of the three systems, electric potential (voltage) between the anodes and the cathodes and soil moisture were measured every 30 minutes. For the first 18 days, circuits remained open to allow electrogenic bacteria to incubate. The open circuit voltage (OCV), which is an indicator of the P-MFC's electric potential due to the bacteria's bioelectrochemical processes, was evaluated daily. About 11 days after the start of the experiment, the

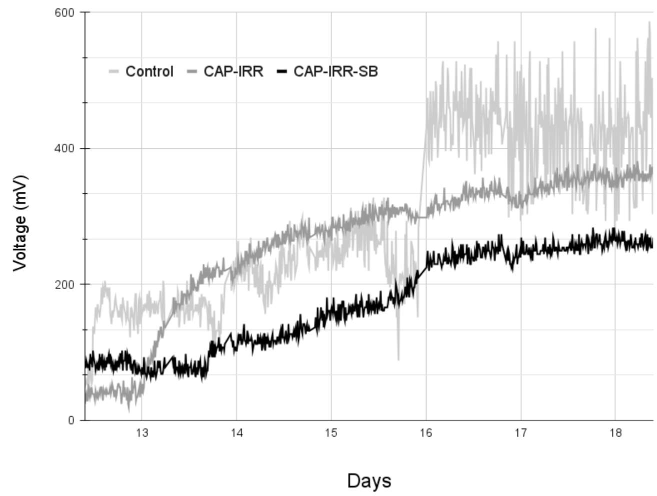

Figure 4. Open circuit voltage (OCV) observed during the P-MFC incubation stage between Day 12 and 18. OCV values plateaued after day 16 despite of some fluctuations, which suggested that bacteria were well incubated. Average OCVs between day 16 and 18 were 413 mV for Control, 359 mV for CAP-IRR, and 263 mV for CAP-IRR-SB.

OCV values of all three P-MFC units started to rise steadily. OCV values plateaued starting on day 16 for all three P-MFCs (**Figure 4**). The average OCV values between day 16 and 18 were 413 mV for Control, 359 mV for CAP-IRR, and 263 mV for CAP-IRR-SB. Therefore, the P-MFCs were successfully incubated and ready to deploy by adding an external load (resistors) to the circuit.

When external loads of 1 kOhm were added to circuits of the three systems on day 19, output voltages dropped in all three P-MFCs. Then voltages gradually increased between day 19 and day 48. The power density of CAP-IRR-SB remained the highest and the Control system the lowest. The soil moisture and power density increased for all systems when plants were watered on days 19, 28, and 39 (**Figure 5**). The relatively high moisture remained for less than 24 hours in all three systems since it quickly dropped to the level before irrigation. However, soil moisture was consistently higher in CAP-IRR and CAP-IRR-SB than in the Control, which can be attributed to the capillary sub-irrigation effect. After day 29, output power densities in all systems were generally plateaued, suggesting that P-MFCs were working consistently. The average power densities between day 29 and 48 were 0.110, 6.437, and 14.427 mW/m2 for the Control, CAP-IRR, and CAP-IRR-SB system, respectively.

The performance of an MFC is closely related to its internal resistance. We conducted polarization tests on days 11, 30, and 48 to evaluate the development and variation of the maximum power density and the internal resistance. Results of polarization tests were presented as power density and voltage curves as functions of the current density due to the variation of external load resistance (**Figure 6**). The peak value of a polarization curve and the corresponding external resistance represent the P-MFC's maximum power density and internal resistance, respectively. The maximum power density of the Control unit increased gradually over the experiment, but it remained low (less than 1 mW/m^2) compared to the CAP-IRR and CAP-IRR-SB. A notable boost

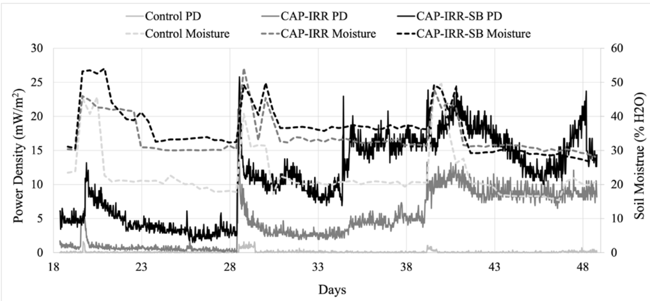

Figure 5. Power densities and soil moisture contents observed between day 19 and day 48. External load was kept constant at 1000 ohms. Sudden increases in soil moisture and power density on day 19, 28, and 39 were preceded by water irrigation. P-MFC output power plateaued between day 39 and 48, and their statistics (average ± standard deviation) were 0.110 ± 0.081 mW/m2 for the Control, 6.437 ± 2.979 mW/m2 for the CAP-IRR, and 14.427 ± 3.691 mW/m2 for the CAP-IRR-SB. Solid lines are P-MFC power densities, and dashed lines are soil moisture values.

in output power was observed for both CAP-IRR and CAP-IRR-SB units from days 30 to 48.

We applied quadratic polynomial curve fitting to the measured polarization curve to estimate the maximum power density and the internal resistance. As a result of the polarization tests, variations of maximum power density, internal resistance, and OCV from day 11 to 48 were evaluated (**Figure 7**). The OCV of all three systems grew gradually during the experiments, and there were no substantial differences among them. At the end of the experiment (day 48), the maximum power densities of CAP-IRR (10.71 mW/m^2) and CAP-IRR-SB (25.97 mW/m^2) were substantially higher than the Control (0.56 mW/m^2). The internal resistance of CAP-IRR (1,518 Ohm) and CAP-IRR-SB (496 Ohm) were much lower than the Control (11,709 Ohm).

DISCUSSION

Data in this study showed that the sedum P-MFC's power density has a positive correlation with soil moisture. Capillary irrigation, particularly with the salt bridge configuration, effectively increased the soil moisture level and promoted proton exchange between the anode and cathode, thus significantly reducing the P-MFC's internal resistance. During the 48-day experiment, no substantial differences in OCV values were observed among the three systems. This suggested an equally favorable environment in the soil for electrogenic bacteria to grow and to attach the anode in the three systems, thus generating similar electrical potentials. Therefore, higher power densities in CAP-IRR and CAP-IRR-SB were largely due to their lower internal resistance values. For sedum P-MFCs in this study, the maximum power density of the Control system without capillary irrigation was about 0.56 mW/m^{2}at the end of the experiment. The power density of our Control system is much greater than that reported by another sedum P-MFC study (0.015–0.092 mW/m^2) but still much lower than a typical P-MFC system with flooded plants (13). With capillary irrigation and the salt bridge configuration in CAP-IRR-SB, the optimal power density was improved to about mW/m^2. A recent review article summarized P-MFC power densities reported in the literature, which are between 5.9 and 240 mW/m^2 for systems designed for wetlands or with

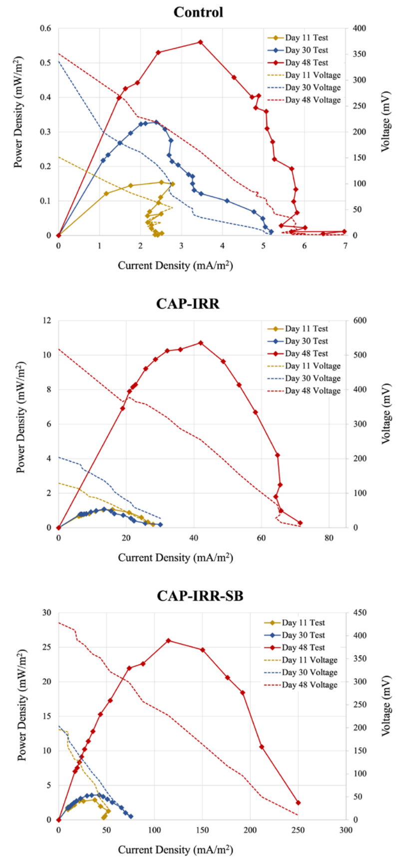

Figure 6. Polarization curves of P-MFCs. Day 11 (red), Day 30 (green), and Day 48 (blue). Dashed lines represent the change of voltage and solid lines represent the change of power density as the external load varies.

a liquid medium (14). Therefore, the performance of the sedum P-MFC system presented in this study was comparable to a typical P-MFC system with flooded plants.

Our study supported the hypotheses that capillary irrigation and salt bridge configuration can improve sedum P-MFC's performance significantly. Therefore, it is viable to convert a conventional sedum-based extensive green roof module into a renewable energy generator.

Our project presents a preliminary study of a sedum-based green roof P-MFC design. Our conclusions were limited to the specific experimental design presented in this study, which included only one replicate unit for each system. Additional experiments would optimize the design and performance by experimenting with different sizes and distribution of capillary wicks and testing the system without a PEM while relying on the capillary wick as the only cation transport channel.

There are already commercial green roof modules that include an additional water storage layer and capillary sub-irrigation (e.g., the Hydropack™ system made by the company Vegetal i.D. They are usually designed to increase the capacity of stormwater retention without adding the thickness of soil media. Such systems can be easily modified to integrate the P-MFC function, following the design of the CAP-IRR-SB unit in this study. With the currently designed prototype, up to 26 W of power could be generated on 1,000 square meters of a roof covered with sedum P-MFCs.

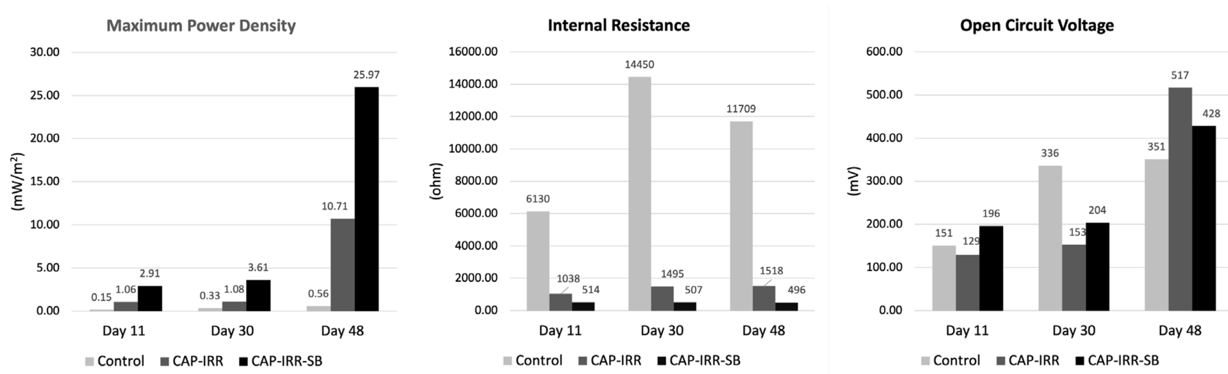

Figure 7. Change in P-MFC's maximum power density, internal resistance, and open circuit voltage. (a) maximum power density; **(b)** P-MFC internal resistance, and **(c)** open circuit voltage between days 11 and 48, according to the polarization test.

This system could continuously power sensors and small electronic devices. The energy could also be stored to power lights at night or other small appliances. Moreover, electricity generation enables many advanced treatment options to remove contaminants in stormwater runoff that cannot be easily removed by filtration, such as disinfecting stormwater effluent with an electrochemical oxidation process (15) or removing heavy metals and organic contaminants through electrolysis processes (16).

There is ample space for future improvement. Ultimately, the power density of a P-MFC is limited by the amount of solar radiation. It was estimated that the theoretically maximum P-MFC power can reach 3–4 W/m^2, considering a typical solar radiation density of 150~190 W/m^2 in mid-latitude regions and solar conversion efficiency of about 2.1% through photosynthesis (5%), rhizodeposition (70%), and MFC energy recovery (60%) (12). Future research and experiments will focus on increasing P-MFC's power density and reducing the cost of materials and production. For example, low-cost materials such as cheesecloth and terracotta clay, may serve as alternative PEMs to replace the expensive Nafion membranes used in this study (17). The power density could potentially be greater if experiments were conducted outdoors with higher solar radiation. It is necessary to conduct long-term tests to evaluate the P-MFC's performance in different seasons and outdoor environments.

Driven by solar power, fueled essentially by CO_2 in the atmosphere, and catalyzed through the excess stormwater, a green roof P-MFC is truly a sustainable stormwater-energy-nexus solution. It is self-sustaining as long as bacteria replicate themselves continuously. The generated electricity can provide advanced treatment options to clean the stormwater before it is discharged into receiving water bodies, thus protecting natural aquatic ecosystems. The P-MFC technology developed in this project can also be applied to other green infrastructures such as rain gardens and bioswales. As technology advances in the future, the solar efficiency of green roof P-MFCs may increase to more than 2%. Although it does not match the efficiency of a solar panel which can exceed 20%, electricity generated by scaled-up green roof P-MFCs can potentially be stored in batteries to power outdoor lighting for buildings and streets. This helps to offset installation costs and provides critical incentives to residential and business owners to adopt green roofs, which benefit them as well as the entire society, by reducing stormwater floods and sewer overflows, improving water quality, and capturing more CO_2 from the atmosphere.

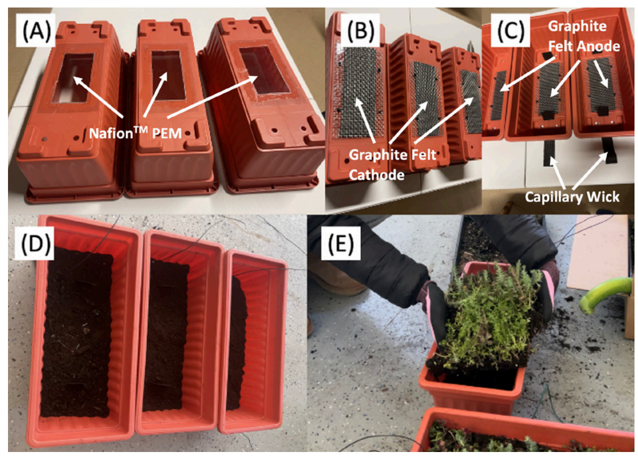

Figure 8. The creation process of green roof P-MFC prototypes. (A) Bottom of P-MFC planters with PEMs covering the proton exchange window; **(B)** Graphite felt air cathodes with stainless wire mesh reinforcement; **(C)** Graphite felt anodes and stainless wire mesh reinforcement inside planters, and capillary wicks in CAP-IRR and CAP-IRR-SB units **(D)** Garden soil mixed with graphite powder covering the anode; **(E)** Sedum mat planted on the top of the soil.

MATERIALS AND METHODS

Three green roof prototypes were created with one replicate representing each of the three systems (**Figure 2**), which are the Control, CAP-IRR (capillary irrigation), and CAP-IRR-SB (capillary irrigation with salt bridge configuration). All prototypes were made with rectangular plastic planters (20×40×15 cm). The bottom of the planter was cut open and a NafionTM Proton Exchange Membrane (Fumasep, cat# FKB-PK-130) was glued to cover the open window (4×9 cm) (**Figure 8A**), which separated anodes and cathodes. Graphite felt (4×10×0.6 cm, AvCarb, cat# G150) was selected as the material for both anodes and cathodes. Both electrodes were reinforced with stainless wire mesh. The stainless wire mesh also served as the electron collector to which copper wires were connected. Capillary wicks (2×15×0.4 cm) made of polyester fabric were inserted into the CAP-IRR and CAP-IRR-SB units with 4 cm of length inside each planter to contact with soil (**Figure 8B-C**).

Garden soil mixed with graphite powder (Fasco Epoxies,

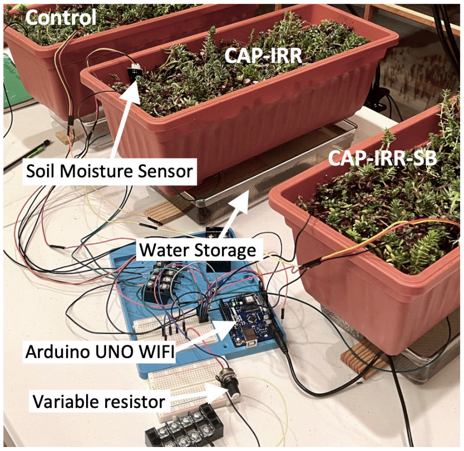

Figure 9. Green roof P-MFC prototypes and electronic components. An Arduino Uno microcontroller with WIFI module was applied to measure and record P-MFC voltages every 30 minutes. The microcontroller also read and recorded soil moisture sensor measurements twice daily. Polarization tests were conducted with a 0-5 kOhm variable resistor.

cat# 0819794021036) with a 30:1 ratio was filled in the planter with a 4 cm thickness to cover the anode felt (**Figure 8D**). Adding graphite powder to a soil MFC could reduce its internal resistance and increase electric power (18). Sedum plants and soil media were added to the planter with a total soil thickness of 14 cm (**Figure 8E**).

Experiments were carried out in an indoor environment with room temperatures ranging between 18 to 22°C. All three modules were placed above a transparent and rectangular plastic tray (31 x 15 x 5 cm), simulating a water storage layer that retains water drained from the roof module and provides water for sub-irrigation for CAP-IRR and CAP-IRR-SB modules. To demonstrate the effect of capillary irrigation, water was filled in the containers to 4 cm depth at the beginning of the experiment. The prototypes were placed on a table next to a window facing south so sedum plants could receive partial solar radiation. The plants were not fertilized during the experiments, although the plant soil used contained some organic matter for plant growth. During the 48-day experiment, the green roof modules were watered about once every 10 days by sprinkling 400 mL of water into each planter, simulating a precipitation event with 0.5 cm of rainfall depth.

Electric potentials (voltage) between anodes and the cathodes were measured continuously with an Arduino Uno microcontroller (Arduino, cat# ABX00021). Three capacitive soil moisture sensors (Songhe, cat# B07SYBSHGX) were inserted in each prototype, and sensor analog output signals were recorded through the Analog Input (AI) ports of the Arduino Uno (**Figure 9**). Voltage signals of moisture sensors were converted into moisture (% H2O) with the manufacturer's calibration function. The Arduino Uno microcontroller was programmed to measure P-MFC voltage once every 30 minutes and data were saved to the cloud in real-time through its embedded WiFi module function. P-MFC voltage was also measured with a multimeter daily to validate the Arduino measurements. Since capacitive soil moisture sensors used in this study may interfere with P-MFC voltage readings, sensors were turned on for soil moisture measurements only twice daily. P-MFC output power was calculated following Ohm's law using the measured voltage and the known external load resistance. The power density (PD) is defined as the power per unit area of the anode surface:

$$PD = \frac{V^2}{RA}$$

where V is the measured voltage, R is the load resistance, and A is the anode surface area (0.004 m^2).

Polarization tests were applied to estimate P-MFC's internal resistance and the optimal power output, which is the maximum power density with the optimal load resistance. In the polarization test, a 0-5 kOhm variable resistor (ALAMSCN, cat# B07SYBSHGX) was used, and the change of voltage with varying resistance was measured. A polarization curve, which shows the relation between power density and current density, was then plotted to estimate the maximum power density.

The MFC's internal resistance (R_i) equals to the external load resistance (R_o) when the output power is at its maximum. This can be proved as the following: the current (I) in the circuit is related to the open circuit voltage (E) as:

$$I = \frac{E}{R_i + R_0}$$

Therefore, the output power can be given as:

$$P = I^2 R_0 = \frac{E^2 R_0}{(R_i + R_0)^2}$$

When the power is at its maximum, it is expected that:

$$\frac{dP}{dR_0} = \frac{E^2(R_0 + R_i)[(R_0 + R_i) - 2R_0]}{(R_0 + R_i)^4} = 0$$

which suggests that $R_i = R_o$.

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