IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received October 4, 2021, accepted November 5, 2021, date of publication November 23, 2021,
date of current version December 7, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3129717

Analyzing the Capabilities of Electric Field Energy Harvesting Using Natural Leaves

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This work was supported in part by the Advanced Center for Electrical and Electronic Engineering AC3E under Grant ANID/FB0008 and Grant ANID-PFCHA/DoctoradoNacional/2020-21200684, and in part by Dirección General de Investigación, Innovación y Emprendimiento (DGIIE)-Universidad Técnica Federico Santa María (UTFSM) Chile.

ABSTRACT Electric field energy harvesters (EFEHs) are reliable and sustainable power sources that may be used to power wireless sensor nodes (WSNs) in urban Internet of Things (IoT) networks, replacing traditional batteries. Despite the technology's effectiveness, large-scale deployments raise severe environmental concerns about fabrication material degradation and recycling. In this context, this work analyzes the performance of the natural green leaves as a replacement for standard electrodes in EFEH developments. To this end, different 10×3 cm^2 EFEHs were assembled with raw leaves from the following species Magnolia Obovata, Ravenala Madagascariensis, Acanthus Mollis, and Agapanthus Africanus. Each harvester was evaluated at different drying steps, concluding that natural leaves may collect electrostatic charges related to the urban electric field, which might power ultra-low-energy devices. Experimental results reveal that Agapanthus Africanus electrodes perform best, with an open-circuit voltage (VOC) of 111.88 V and a short-circuit current (ISC) of 229.09 nA. On the other hand, the VOC of Magnolia Obavata leaves achieved 76.76 V, and the ISC was 135.30 nA (the worst case). Although the performance for Ravenala Madagascariensis samples is less than Agapanthus Africanus ones, the size leaf is another critical parameter to design functional devices. Therefore, the experimental section also includes the conceptualization, design, and experimental testing of a functional EFEH prototype called Leaf-EFEH, which is assembled with Ravenala Madagascariensis leaves. Finally, numerous experiments have shown that the proposed Leaf-EFEH can power ultra-low-power devices.

INDEX TERMS Energy harvesting, electromagnetic induction, electromagnetic coupling, capacitance transducers, home area network.

I. INTRODUCTION

The Internet of Things (IoT) is a communication paradigm that connects and exchanges data between objects and systems in an intelligent environment using thousands of low-power computer devices known as wireless sensor nodes (WSNs) [1]. Each WSN consists of a microcontroller and a transceiver, which are both powered by ordinary batteries [2]. Although the batteries are reliable and efficient energy sources, the cost of replacement, pollution, and limited lifetime hinder the development of large-scale deployments of WSNs. In this context, energy harvesting (EH) technologies emerge as promising sustainable energy sources for WSNs [3], [4].

An electric field energy harvester (EFEH) is a capacitive conduction mechanism that exploits the electric induction phenomenon in electrified environments. Each harvester comprises metal electrodes placed within an alternating electric field (EF) and driving circuits to supply appropriate voltage and current levels to low-power loads [3]. In general, electric grid characteristics and harvesting plate design factors influence the performance of EFEHs [5]–[7]. Because of the strong electric field surrounding high-voltage power systems in all directions, self-powered sensors based on EFEHs appear as cost-effective technologies to monitor and control power system equipment [3], [8]–[16].

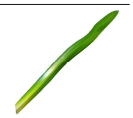
The associate editor coordinating the review of this manuscript and approving it for publication was Md. Abdur Razzaque.

The *University* of Strathclyde introduced the initial prototype of a potential harvester, which consisted of two parallel circle aluminum electrodes separated at a fixed distance (5 cm and 10 cm) [17]. The harvesting mechanism was tested in a continuous 200 kV m^{-1} EF, disclosing that the harvester can provide up to 200 mW of constant power. In addition, the authors showed that EFEHs are broadly inefficient due to their high capacitive impedance. As a solution to this issue, a switching stage was added in [18]. The proposed protocol entails an on/off function of the load by a microelectromechanical system (MEMS), whose power consumption is less than 100 μJ. Zangl *et al.* set out a harvester model that adjusts to the cylindrical distribution of the power lines [9]. The harvester can provide up to 370 mW of power by a 55×30 cm^2 cylindrical copper electrode was mounted on a 150 kV power line. More detailed analyses of cylindrical and parallel plates topologies were presented in [19] and [20], respectively.

The wide range of electromagnetic sources, such as domestic appliances, internal wiring, electric car engines, welding instruments, and industrial equipment, encourage the introduction of EFEHs in our living environment [5]. However, large-size harvesters or multi-harvesters are currently required to accomplish practical applications in all prototypes [5]–[7]. In addition, the modification of electric grid parameters is not practical because power utilities set them [21]. Several authors have proposed a discontinuous connection model between the harvester and the load [5], [6], [22]–[24]. First, the harvester stores energy in a capacitor up to achieve the operational requirements of the WSN. Then, the pulsing operation mode connects the load for a brief time to measure the variables and transmit the data. Another alternative to increase the output power of EFEHs is related to the development of high-efficient management circuits [5], [21], [25], [26].

On the other hand, the massification of EFEHs may cause adverse effects on the environment because the electrodes of EFEHs are made of non-degradable and non-recyclable materials [5], [22], [27], [28]. Electrodes of EFEHs are made of various metals, including aluminum, copper, silver, gold, gallium, and indium tin oxide [3], [29]. Nowadays, biodegradable, organic electrodes are considered emerging substitutes of traditional electrodes to reduce the environmental impact and environmental pollution associated with the mass application of harvesting technologies [30]–[32]. Since natural leaves, vegetables, and certain varieties of acidic fruits are composed of high-electrolyte solutions, bio-electrodes can also be used as a conductive liquid to collect electrostatic charges [32]. To this end, a comprehensive analysis of the natural leaf assembled triboelectric nanogenerator (TENG) was proposed in [30]. Experimental results disclosed that the power density of an 8×8 cm^2 TENG was approximately 45 mW m^{-2} using a loading resistance of 1×10^7 Ω. With the same aim, a natural lotus leaf based-TENG was designed, assembled, and tested in [33]. The proposed nanogenerator (NG) showed a robust electrical output performance to challenging environmental conditions. The success of bio-electrodes has inspired the development of artificial trees based on Leaf-TENGs, which exploit different ambient mechanical stimuli associated with the wind, vibration, and falling raindrop energy [31], [34]. In addition, the high water level in leafy green vegetables such as lettuce, cabbage, and leaf mustard, makes possible the development of a fully biodegradable TENG [35].

TABLE 1. Characteristic of analyzed natural leaves.

Leaves species	Magnolia Obavata	Ravenala Madagascariensis	Acanthus Mollis	Agapanthus Africanus
Picture				
Samples	10	10	10	10
Long (cm)	18-22	60-80	30-32	50-70
Broad (cm)	8-10	30-45	12-20	~5
Venation	Pinnate Brachidodrome	Pinnate	Pinnate Soft flexible	Parallel Leathery

The works mentioned above focus on developing TENGs, which is another displacement current-based harvesting technique [4]. Using the close link between TENGs and EFEHs, this work investigates the capabilities and performance of EFEHs constructed with natural leaves. For the remainder of this work, we will refer to the harvester as Leaf-EFEH. For more information, see [3], [4]. Unlike metal electrode harvesters, Leaf-EFEH is assembled with bio-electrodes made up of natural leaves. The primary outcome of Leaf-EFEH is the replacement of metal electrodes for bio-electrodes in EFEHs. According to [5], increasing the number of EFEHs improves the power density. Thus, we investigate the possibility of increasing power density by the development of several units. The output performance of Leaf-EFEH is tested according to water content, size, venation, and foliage shape that are the main parameters analyzed in Leaf-TENGs [30], [31]. A functional prototype based on the natural leaf whose electrical performance is the highest is also proposed. Finally, several practical applications are presented. The remainder of this work is organized as follows. Section II reviews the characteristics of Leaf-EFEH. Section III evaluates the performance of the low voltage prototype and presents several applications. Finally, section IV shows the conclusions of this work.

II. SYSTEM ARCHITECTURE

This section addresses the phenomenon of electric field induction in natural green leaves. To this end, several EFEHs made from raw leaves have been conceived, constructed, and tested. This section also contains the materials and methods required to duplicate experimental testing.

A. DESIGN OF LEAF-EFEH

During the winter season, from 09/01/2021 to 09/08/2021, large, leathery, and bright natural leaves were collected from wild tree species in the Valparaíso area of Chile. The weather conditions were ideal for harvesting, with temperatures ranging from 12 to 14 °C, a medium relative humidity of 57.5 percent, and no precipitation. Among the analyzed leaves are Magnolia Obovata, Ravenala Madagascariensis, Acanthus Mollis, and Agapanthus Africanus. Each leaf set consists of 10 samples collected from various sections of the harvested trees. Table 1 highlights the main characteristics of the collected leaves based on their morphological properties. After harvesting, all leaves were washed with deionized water to eliminate impurities and completely dried at 20 °C for 1 hour. Then, the green leaves are cut into pieces of 10×3 cm^2 to standardize the size of the constructed bio-electrodes. The dimensions of the harvesting plate were established by optimizing the electrode surface based on the length of Magnolia Obavata leaves (smaller area species) and the breadth of Agapanthus Africanus leaves (smaller width species). Each bio-electrode was kept in a plastic bag to preserve the freshness and quality of leaves over time, as recommended in [36].

Because home wiring is the primary EF source in residential settings, the performance of Leaf-EFEHs is evaluated in this context. To this end, a spiral base made of a 220 V, 50 Hz three-wire cable was designed to enhance contact between cable and electrodes, as shown Fig. 1. Unlike metal electrodes, the bio-electrodes use the mixture of water and electrolytes as conductive liquid to collect electrostatic charges. Since Leaf-EFEH was placed directly on the jacket of the spiral structure, Leaf-EFEH is characterized as a voltage capacitive divider network [5]. The value of each parasitic capacitor may be considered to be the same [20], and the open voltage is around 103 V according to [22].

On the other hand, EFEHs may not deliver continuous power to traditional electronics because of the poor power density of the harvesters in low-voltage scenarios [5], [6]. Therefore, EFEHs are used in low-duty-cycle sensing applications. In this regard, the suggested Leaf-EFEH requires steps of rectifying and storing. Rectifier circuits constructed using passive elements are the best alternative due to the few components and minimal switching losses [22], [37]. The rectifier stage in this application consists of a DB107 full-bridge rectifier that is directly linked to the harvesting plate and the grounded electrode through metal electrodes (alligator clips). The bridge rectifier has a reverse voltage of 1000 V, a voltage drop of 1.1 V, and a junction capacitance of 25 pF. The storage unit is a 2.2 μF metalized polypropylene film capacitor, which reduces the charging time and increases the gathered energy regarding traffic rate in data transmission and the power consumption of the WSN [2]. According to the manufacturer, the leakage current is approximately 22 nA for a voltage of 103 V.

B. DATA PROCESSING

The Leaf-EFEH consists of a 10×3 cm^2 bio-electrode, a grounded copper electrode, a DB107 full bridge rectifier, and a 2.2 μF storage capacitor. In this section, a methodology to evaluate the ability of each constructed harvester to gather electrostatic charges associated with electric field induction is provided. Figure 1 depicts the suggested harvester's architecture. Each stage in Fig. 1 is explained as follows:

1) The mass of the bio-electrodes was measured using a 0.1 mg resolution Kern PFB 120-3 precision balance after the leaves were chopped into pieces. In addition, we document each leaf sample by taking a full-HD color image with a 16-megapixel monocular camera and labeling it with the two initials of the complete name plus a validated digit ranging from 0 to 9 (Magnolia Obovata MO, Ravenala Madagascariensis RM, Acanthus Mollis AM, and Agapanthus Africanus AA).
2) The Leaf-EFEH is mounted on the jacket of the prefabricated base. A Keithley 6514 electrometer monitors the open-circuit voltage VOC) and the short-circuit current (ISC) of the harvester using computer measuring software written MATLAB 2020b. Since model 6514 is optimized for the 20 ms to 200 ms reading rate, the measurements are obtained via the DC-link. During the acquisition, the storage capacitor is disconnected. The data acquisition period is 30 seconds, and the baud rate is 57600 bps. The values of VOC and ISC are computed as the average of acquired data.
3) After VOC and ISC values acquisition, a storage capacitor was attached to full-bridge rectifier outputs. The Keithley 6514 electrometer recorded the charging profile of the capacitor for 30 minutes. We set this charging time because the maximum frequency for reporting the status of smart-city assets is 30 minutes, as shown in [2], [6]. Because there is not to acquire data with high sampling time, the baud rate is 9600 bps.
4) The bio-electrodes were placed in a Blank dehydrator at 65 °C for 6 hours. This selected temperature avoids potential damages to the leaf structure. In addition, the green electrode is introduced in the dehydrator with the plastic bag to reduce possible leaf deformations, as recommended in [38]. Each drying step requires documentation of the shape, weight, and electrical characteristics of each bio-electrode. Figure 2 shows pictures of each drying stage for each leaf analyzed species. To evaluate the water content of each bio-electrode, we use the equivalent water thickness (EWT) parameter, described in [39]. We repeat this process four times.

III. EXPERIMENTAL RESULTS

This section studies the performance of Leaf-EFEH by analyzing four species of endemic leaves (Magnolia Obovata, Ravenala Madagascariensis, Acanthus Mollis, and Agapanthus Africanus). Finally, a functional prototype is developed based on the leaf behavior, and several applications are proposed.

A. PERFORMANCE EVALUATION

The Leaf-EFEH performance is determined following the methodology described in Sction II. Experimental results

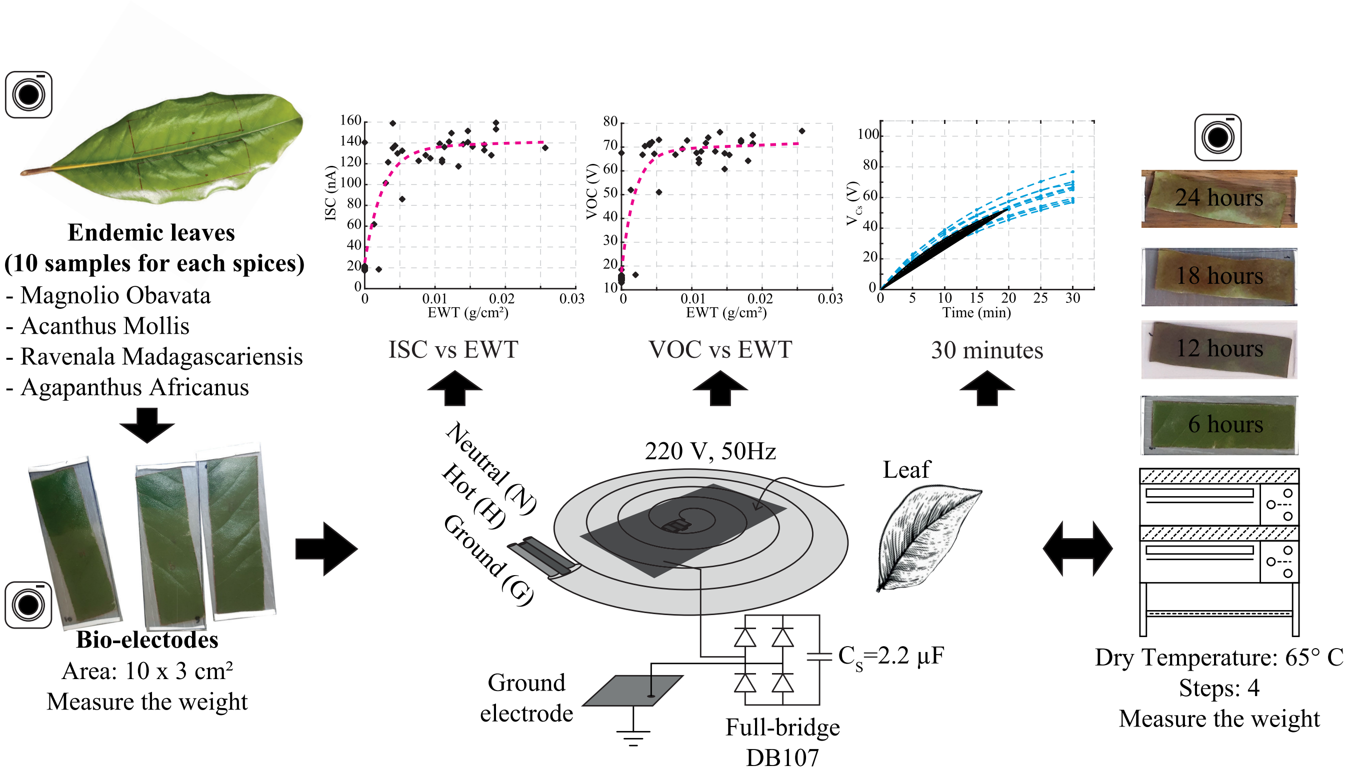


FIGURE 1. The general structure of Leaf-EFEH using different natural green leaves.

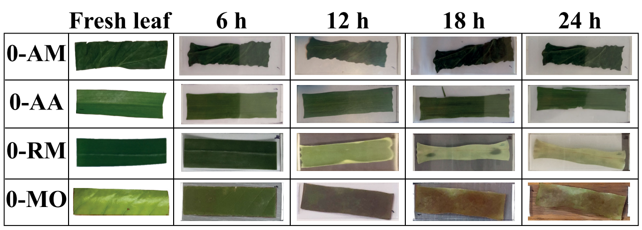


FIGURE 2. Pictures of different bio-electrodes at different drying stages.

disclose that the electrical performance of the bio-electrode assembled with Agapanthus Africanus samples is higher than the other species. The maximum VOC is 111.88 V with an ISC of 229.09 nA. In other words, the quantity of power per unit area that a harvester can supply utilizing bio-electrodes constructed from Agapanthus Africanus samples is substantially higher than the other ones. Of the 40 samples taken, it is possible to note that the electrical parameters drop for all analyzed species when the EWT index is reduced. Therefore, there exists a dependence between the electrical performance of the Leaf-EFEH and the quantity of water contained in the leaf, but it is not a linear relationship. Figures 3a and 3e show this phenomenon through charging patterns of the storage capacitor recorded for Magnolia Obavata leaves samples. The dash blue lines represent the voltage profiles of an external storage capacitor charging with each designed bio-electrode. The solid black line is the fit line obtained with the Curve Fitting Toolbox in MATLAB 2020b [40]. For fresh leaves, it is possible to see that the gathered energy fluctuates between 3.6 mJ (76.80 V) and 6.5 mJ (56.86 V) when the storage capacitor is charged for 30 minutes. However, the collected energy decreases to 641 μJ (24.14 V) in the same charging time for dried bio-electrodes. Table 2 summarizes the VOC, the ISC, and EWT of each analyzed Leaf-EFEH.

As observed in the Agapanthus Africanus study, several bio-electrodes have a high water content after 24 hours of drying. This phenomenon occurs due to numerous leaf species resisting a water shortage by closing their stomata to conserve water. Figure 3h discloses that a Leaf-EFEH assembled with Agapanthus Africanus leaves can harvest up to 5.06 mJ of energy in 30 minutes with bio-electrodes dried at 65 °C for 24 hours. In this context, bio-electrodes based on Agapanthus Africanus leaves can be exploited to develop harvesters with an extended lifetime due to the high resistance to the temperature. In addition, it is necessary to dry the bio-electrodes for 24 extra hours to determine the dried mass, which is an important parameter to specify the EWT index. It is possible to see that the electrical outputs of Leaf-EFEHs produced from Acanthus Mollis leaves are high (second-best performance). The highest VOC is 108.90 V with an ISC of 218.96 nA. However, these leaves tend to lose their water content rapidly. Experimental findings showed that the bio-electrodes are thoroughly dried in approximately 12 hours when the drying temperature is 65 °C.

TABLE 2. Comparison of the Leaf-EFEH assembled with different natural leaves, according to the open-circuit voltage (VOC), the short-circuit current (ISC), and equivalent water thickness (EWT).

Leaf	0 h			6 h			12 h			18 h			24 h		
ID	VOC (V)	ISC (nA)	EWT (g/cm^2) $\times 10^{-3}$	VOC (V)	ISC (nA)	EWT (g/cm^2) $\times 10^{-3}$	VOC (V)	ISC (nA)	EWT (g/cm^2) $\times 10^{-3}$	VOC (V)	ISC (nA)	EWT (g/cm^2) $\times 10^{-3}$	VOC (V)	ISC (nA)	EWT (g/cm^2) $\times 10^{-3}$
0-MO	60.77	140.70	14.67	72.78	125.21	9.93	51.97	61.85	1.33	18.46	20.56	0.00	16.22	18.45	0.00
1-MO	75.01	153.15	18.67	68.18	117.49	13.33	51.04	86.00	5.33	16.31	18.52	2.00	15.36	18.48	0.00
2-MO	72.12	138.25	17.00	64.92	123.80	11.00	71.50	158.83	4.00	14.94	18.62	0.00	13.24	20.02	0.00
3-MO	71.57	**159.33**	18.67	68.18	136.07	11.33	73.05	132.49	5.33	15.69	21.82	0.00	12.94	20.80	0.00
4-MO	72.86	133.04	17.00	63.33	121.63	11.00	70.87	135.09	4.00	14.19	19.82	0.00	13.94	20.49	0.00
5-MO	**76.76**	135.30	25.67	64.23	128.19	18.00	71.70	141.19	12.00	14.21	19.42	0.00	14.69	18.12	0.00
6-MO	67.38	151.48	14.67	67.56	139.23	10.67	72.06	137.43	4.33	15.85	20.23	0.00	14.32	19.30	0.00
7-MO	66.70	136.49	15.33	69.23	128.24	8.67	70.42	121.46	3.33	15.05	19.55	0.00	16.09	18.74	0.00
8-MO	73.97	149.44	12.33	67.16	129.95	4.67	67.52	140.49	0.00	15.21	18.57	0.00	14.13	20.18	0.00
9-MO	76.27	138.81	14.00	66.82	122.76	7.67	66.77	101.53	3.00	14.88	17.27	0.00	13.84	20.24	0.00
0-AA	111.88	196.58	31.33	86.00	163.31	10.67	90.97	160.93	7.33	26.71	40.22	2.33	19.95	30.41	0.67
1-AA	**111.88**	229.09	46.33	93.10	179.27	20.00	98.14	177.30	11.67	66.54	109.60	4.00	35.29	55.00	0.67
2-AA	97.54	196.71	66.00	98.58	189.95	44.67	92.93	165.10	37.33	89.37	165.92	20.33	77.35	136.21	7.00
3-AA	102.66	216.17	40.00	105.85	219.65	27.67	101.91	190.12	24.33	92.59	168.26	9.67	81.71	139.25	6.00
4-AA	101.41	208.20	24.33	97.58	193.14	14.33	85.10	152.27	12.00	65.34	109.92	2.00	16.79	26.51	0.33
5-AA	111.21	230.28	30.00	85.81	160.04	7.00	30.67	46.31	3.00	23.75	38.22	0.00	16.79	28.41	0.00
6-AA	93.59	183.64	48.67	87.30	157.69	16.00	60.95	101.84	6.00	47.80	77.36	3.33	17.35	27.36	1.00
7-AA	118.08	200.60	32.33	91.14	163.88	17.00	81.61	143.40	7.00	75.71	130.79	3.33	32.20	49.78	0.33
8-AA	118.08	**252.41**	49.33	107.40	211.16	34.67	90.80	169.43	28.00	87.13	157.99	10.33	68.65	118.27	6.67
9-AA	88.88	176.85	50.33	91.54	172.99	35.67	90.69	165.97	29.33	84.84	152.63	20.67	75.16	129.08	14.33
0-AM	102.27	207.08	15.33	81.23	137.89	1.33	18.33	27.26	0.00	22.52	33.92	0.00	22.50	29.05	0.00
1-AM	106.28	211.50	19.67	79.43	130.24	2.67	18.03	27.01	0.33	21.83	33.37	0.00	19.52	27.79	0.00
2-AM	102.31	198.67	20.33	86.73	155.23	7.00	20.46	31.29	2.00	21.30	31.98	0.00	21.30	27.45	0.00
3-AM	102.59	209.23	23.00	102.36	188.82	5.67	74.60	126.55	1.67	27.05	40.85	0.00	27.05	32.39	0.00
4-AM	101.01	195.08	25.00	81.55	136.83	7.00	18.27	27.40	2.33	18.74	27.55	0.00	18.74	28.05	0.00
5-AM	92.09	170.08	16.33	89.47	159.34	7.33	18.06	27.20	1.00	18.74	28.67	0.00	18.74	30.69	0.00
6-AM	107.72	202.46	25.67	51.32	81.25	3.33	17.67	26.44	0.67	22.43	36.71	0.67	22.43	26.93	0.00
7-AM	102.91	207.19	20.67	50.57	77.53	1.33	19.04	28.26	1.33	17.83	27.89	0.00	17.83	35.75	0.00
8-AM	**108.90**	**218.96**	19.67	86.59	152.05	7.00	78.65	128.45	1.67	44.90	69.51	1.33	21.90	25.74	0.00
9-AM	104.22	212.79	21.00	100.63	183.76	11.00	73.58	121.98	3.67	44.90	29.93	1.00	24.16	30.00	0.00
0-RM	**80.91**	165.59	29.00	61.67	156.23	13.67	39.06	129.48	3.00	23.45	35.40	0.00	17.10	30.81	0.00
1-RM	76.49	**174.61**	27.00	60.53	139.76	11.67	60.30	89.39	5.33	22.11	46.01	0.00	16.46	30.30	0.00
2-RM	73.87	117.53	26.67	64.35	110.89	12.33	62.98	123.64	4.67	22.07	35.02	0.00	13.93	30.18	0.00
3-RM	76.09	121.68	24.67	64.53	146.53	14.33	66.11	125.11	8.33	24.94	69.70	0.00	26.30	29.62	0.00
4-RM	69.14	112.47	31.33	64.25	150.65	14.67	31.45	111.73	3.67	22.92	37.40	0.33	25.19	31.69	0.00
5-RM	66.98	118.28	22.33	54.14	142.68	11.00	45.44	102.26	4.33	29.85	42.63	0.00	19.46	30.01	0.00
6-RM	59.37	158.86	27.33	61.21	143.13	18.00	67.12	117.27	11.33	60.72	33.94	2.00	18.73	30.39	0.00
7-RM	64.31	154.12	25.33	58.84	139.88	16.67	69.24	80.80	9.67	66.30	34.85	2.67	21.47	36.29	0.00
8-RM	57.61	118.14	29.33	59.79	134.18	20.33	65.24	91.68	11.00	32.19	47.99	0.00	18.65	33.64	0.00
9-RM	62.71	121.08	25.33	67.92	112.94	14.00	62.10	74.95	6.33	28.60	31.14	0.33	19.17	28.12	0.00

Figures 3c and 3g show the charging curves of an external capacitor powered by Leaf-EFEHs made from Acanthus Mollis leaves. Note that the collected energy drops from an average of 7.04 mJ (80 V) to 842 μJ (27.67 V).

B. LEAF-EFEH PROTOTYPE

The selection of the type of the bio-electrode is based on six essential criteria that are summarized in Fig. 4a. Although harvesters made from Agapanthus Africanus leaves have the best electrostatic charge collecting capability, as demonstrated in Section III-A, Ravenala Madagascariensis leaves have the best overall behavior. In general, Ravenala Madagascariensis leaves present high elasticity and size, with sufficient power density. However, note that the following analysis can be generalized to other leaves. As seen in Fig. 4b, larger electrodes collect more charges for the same time when the electrode is in contact with the spiral bed. It is possible to see that a 17.5×17.5 cm^2 Leaf-EFEH might accumulate about 15.84 mJ in a 2.2 μF storage capacitor in 30 minutes. However, the energy reduce when several parts of the leaf are not mounted on spiral constructed bed. It is worth noting that the gathered energy reduces to 11 mJ when a 20×20 cm^2 Leaf-EFEH was used. On the other hand, note that the harvester's performance is independent of the electrode rotation as shown in 4c; however, it depends on the distance between the electric field source and the harvesting plate, as Fig. 4d presents. It is possible to see that a 17.5×17.5 cm^2 Leaf-EFEH located at the limit of the electrical cable collects 90% fewer charges than the other one centered in the base. We studied the repeatability of the harvester by analyzing e performance of the harvester for seven days. The data was taken once a day at 11 a.m. In addition, this test was developed by fixing laboratory temperature to normal temperature level (National Institute of Standards and Technology uses 20 °C). Experimental results disclosed high repeatability for tested samples, as Fig. 4e shows.

Figure 4f depicts a comparison of the Leaf-EFEH equipped with a voltage doubler against the Leaf-EFEH supplied with a full-bridge rectifier. Both circuits were built with 1n4007 diodes. According to the manufacturer, the voltage drop of

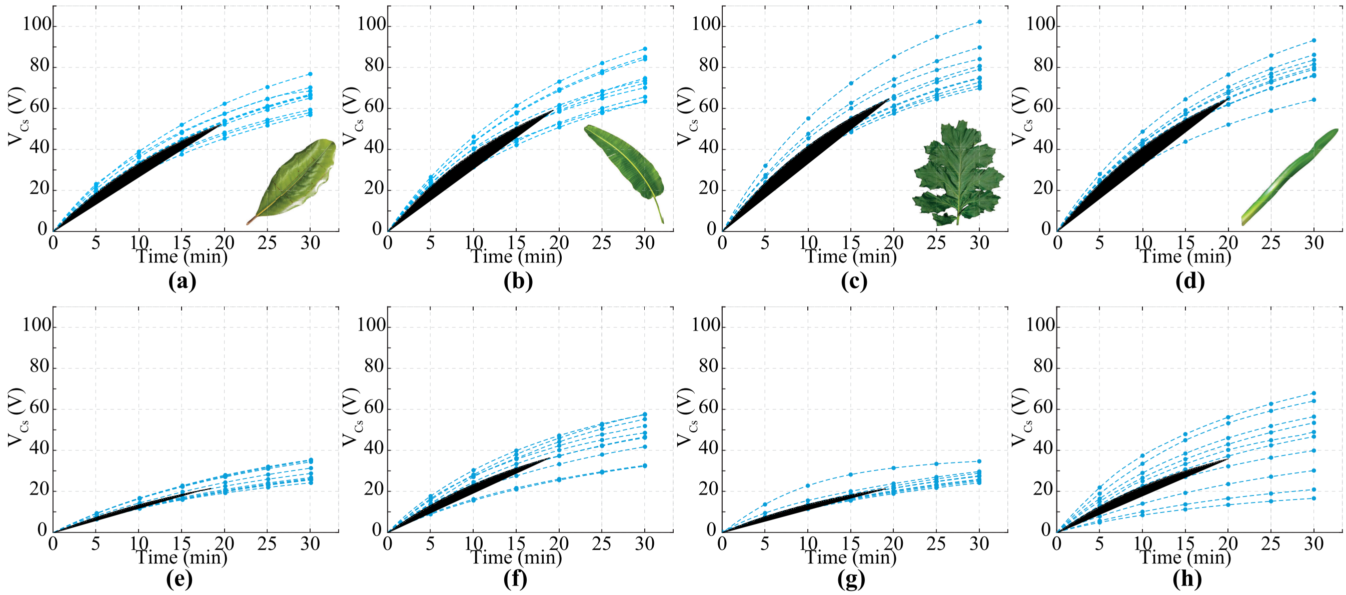


FIGURE 3. Voltage profiles of 2.2 μF capacitor charged by different Leaf-EFEHs assembled with various leaves, each analysis shows the corresponding leaf picture. The top row shows the performance of Leaf-EFEHs assembled with fresh leaves. The bottom row shows the performance of Leaf-EFEHs assembled with dehydrated leaves (65 °C for 24 hours). (a, e) Magnolia Obovata, (b, f) Ravenala Madagascariensis, (c, g) Acanthus Mollis, and (d, h) Agapanthus Africanus.

the selected diodes is 0.7 V, and the typical junction capacitance is between 2.5 pF and 30 pF. Full bridge rectifiers have two additional diodes that increase their power losses. However, the conduction in both semi-cycles compensates this detrimental effect, as shown Fig. 4f. In addition, full-bridge rectifiers provide an extra insulation between harvesting plates and the load. Finally, a DB107 integrated circuit is employed as the rectifier stage to reduce mobile parts. As Fig. 4g determines, it is possible to regulate the voltage and to increase the gathered energy by adjusting the value of the storage capacitor. It is possible to see a 17.5 × 17.5 cm^2 Leaf-EFEH equipped with a 10 μF can collect 16.76 mJ (57.90 V) of energy in 30 minutes. On the other hand, the same harvester fitted with a 2.2 μF reduces the gathered energy to 14.51 mJ while increasing the storage capacitor voltage to 114.85 V. Moreover, for the Leaf-EFEH, a long-term test under no-load conditions is carried out over eight hours. The device was located in a non-controlled environment (ambiental temperature and humidity). To ensure continuous charge of the storage capacitor, we used a 470 μF. Experimental results are present in Fig. 4h.

As Fig. 4i illustrates, the elastic structure of the Ravenala Madagascariensis leaves enables the direct integration of the Leaf-EFEH in the outer jacket of an electric cable, following the criteria proposed in [5]. The power density of the Leaf-EFEH increases with the sheath length, as shown in Fig. 4j. Note that a 25 cm long single layer Leaf-EFEH collects up to 15.84 mJ in 20 minutes. The robustness and repeatability of the Leaf-TENG were evaluated by connecting the harvester for ten hours in an external electrical cable located in an outdoor environment. Empirical results disclosed that harvesters exhibit a cyclical and homogeneous performance, as shown in Fig. 4k. As concluded in Section III-A, electrical outputs of bio-electrodes depend on the water content. The direct contact between the electrical cable and electrode improves the ability of charge collection. However, dried leaves suffer several breaks with loss of elasticity. Therefore, we analyze the performance of the Leaf-EFEH under temperature variations. To this end, different Leaf-EFEH assembled with Ravenala Madagascariensis leaves were dried at a temperature of 45 °C over periods of 30 minutes. As shown in Fig. 4l, the energy density of Leaf-EFEH is reduced in each drying step.

C. PRACTICAL APPLICATIONS

In this section, we will use UKL2A101MHD1TO electrolytic capacitors. According to the manufacturer, the leakage current is approximately 0.2 μA. As concluded in Section III-A, Leaf-EFEHs are durable, stable, and reliable devices that energize ultra-low-power devices. This section presents different applications using Leaf-EFEHs. Figures 5a and 5b show the activation circuit of a LED array parallel and serially connected, respectively, using a 17.5 × 17.5 cm^2 Leaf-EFEH assembled with Ravenala Madagascariensis leaves. The connection between LEDs and the bio-electrode is carried out by a DB3 Diac. With the aim to reduce charging time, we select a 0.33 μF capacitor as the storage unit. Figure 5c depicts the performance of Leaf-EFEH by substituting bio-electrodes with whole natural Magnolia Obovata leaves.

A 100 μW electronic load (Arithmetic Logic Unit plus LCD) was powered by a 17.5 × 17.5 cm^2 Leaf-EFEH

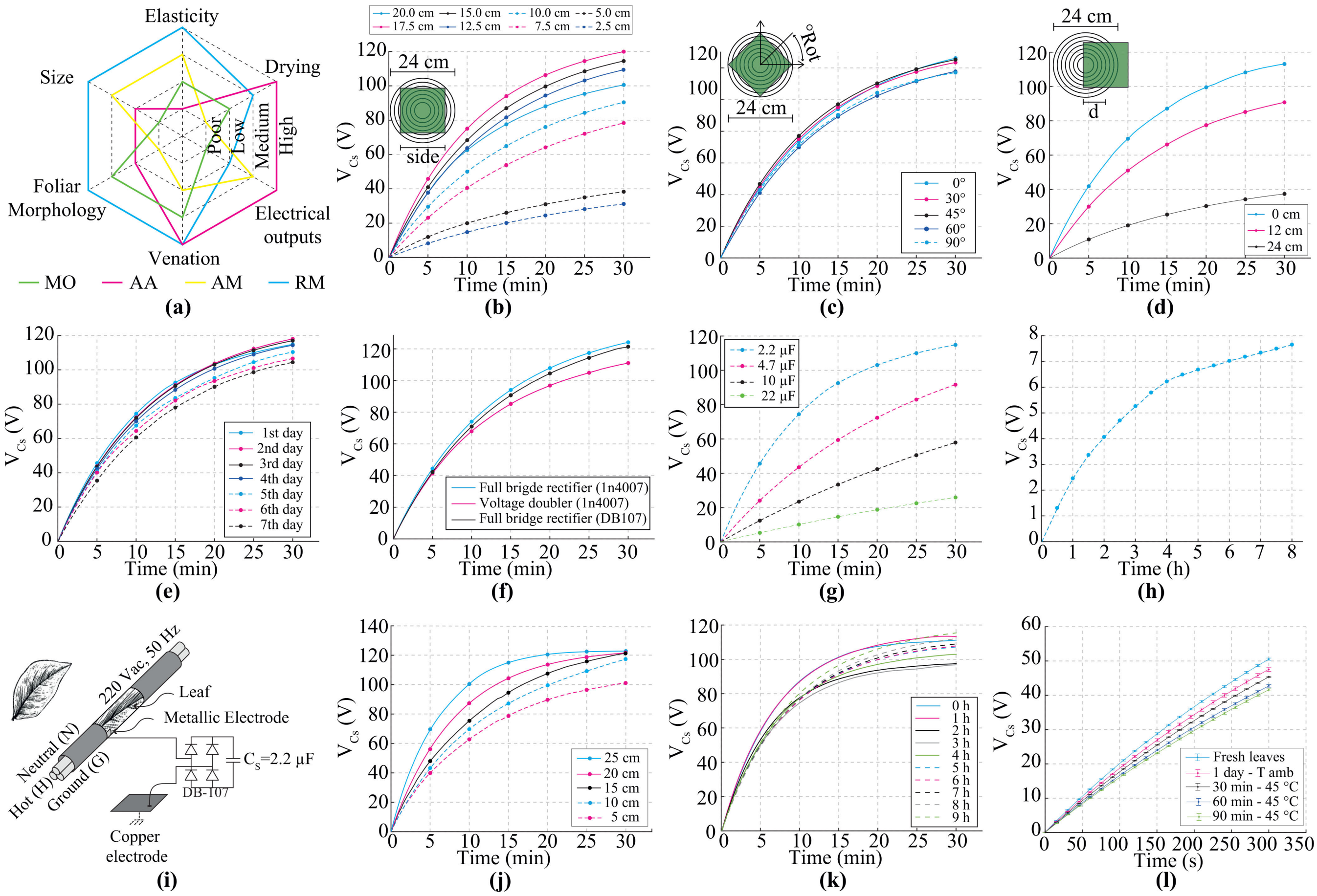


FIGURE 4. The output performance of as-designed Leaf-EFEH. (a) Qualitative evolution of the electrical performance of the different natural leaves analyzed. (b) Accumulated voltage in storage capacitor for varying harvesting plates sizes. (c) Accumulated voltage in storage capacitor for varying angles between harvesting plate and constructed base. (d) Accumulated voltage in storage capacitor for varying distances between harvesting plate and constructed base. (e) Accumulated voltage in storage capacitor for a 17.5 × 17.5 cm^2 Leaf-EFEH acquired in different days. (f) Comparison of the 17.5 × 17.5 cm^2 Leaf-EFEH equipped with different managing circuits. (g) Comparison of the 17.5 × 17.5 cm^2 Leaf-EFEH equipped with different storage capacitors. (h) The electrical performance of Leaf-EFEH as a function of time. (i) Schematic illustration of working principle of Leaf-EFEH (Cylindrical topology) (j) Accumulated voltage in storage capacitor for varying harvesting tube lengths (Cylindrical topology). (k) Accumulated voltage in storage capacitor for a 25 cm Leaf-EFEH acquired in different days (Cylindrical topology). (l) The relation between the Leaf-EFEH water content ant the electrical output (Cylindrical topology).

assembled with Ravenala Madagascariensis leaves, as shown in Fig. 5d. An external switch connects the Leaf-EFEH to the load when the voltage in the storage capacitor is 1.5 V. The gathered energy in a 100 μF capacitor provides a 14 seconds autonomous operation to the portable device. When the capacitor voltage is between 0.6 and 1 V, the electrical gadget goes into sleep mode. Once 3 minutes, the electrical circuit can be reconnected after the external button is turned off. In addition, the Leaf-EFEH is installed near a power strip that is connected to the 220 VAC, 50 Hz household grid, in no-load condition, as shown in Fig. 5e. Experimental findings show that harvester can run a 100 μW load every 17 minutes for 14 seconds. With the same aim, we developed two experiments replacing the bio-electrodes with natural green leaves (See Fig. 5f and 5g). Moreover, the Leaf-EFEH was replaced by a plant. The plant was placed over a spiral structure built with a three-wire cable (200 V, 50 Hz). Experimental findings disclosed that the harvester could power a 100 μW electronic load during 14 seconds, every two minutes, as Fig. 5h illustrates.

Figure 5i shows the picture of a 100 μW load powered by the Leaf-EFEH device (See Video 1, Supporting Information). An external switch is manually turned on when the capacitor has been charged up to 1.5V (Charging time of 8 minutes). The Leaf-EFEH device gives a 20 seconds autonomous operation to the portable device. Since the electronic device operates over the voltage range of 1 to 1.5 V, the external switch is manually off when the voltage is less than 1 V. The external load may be reconnected after 3-minutes. On the other hand, a three-wire cable is wrapped with a 25 cm bio-electrode (Ravenala Madagascariensis leaves), as shown in Fig. 5j. Empirical results show that the electricity generated by Leaf-EFEH can power up to serial-connected 38 commercial green LEDs (See Video 2, Supporting Information). In addition, the same green electrode can drive a blue LED array, as Fig. 5k discloses. LEDs are activated every 5 seconds

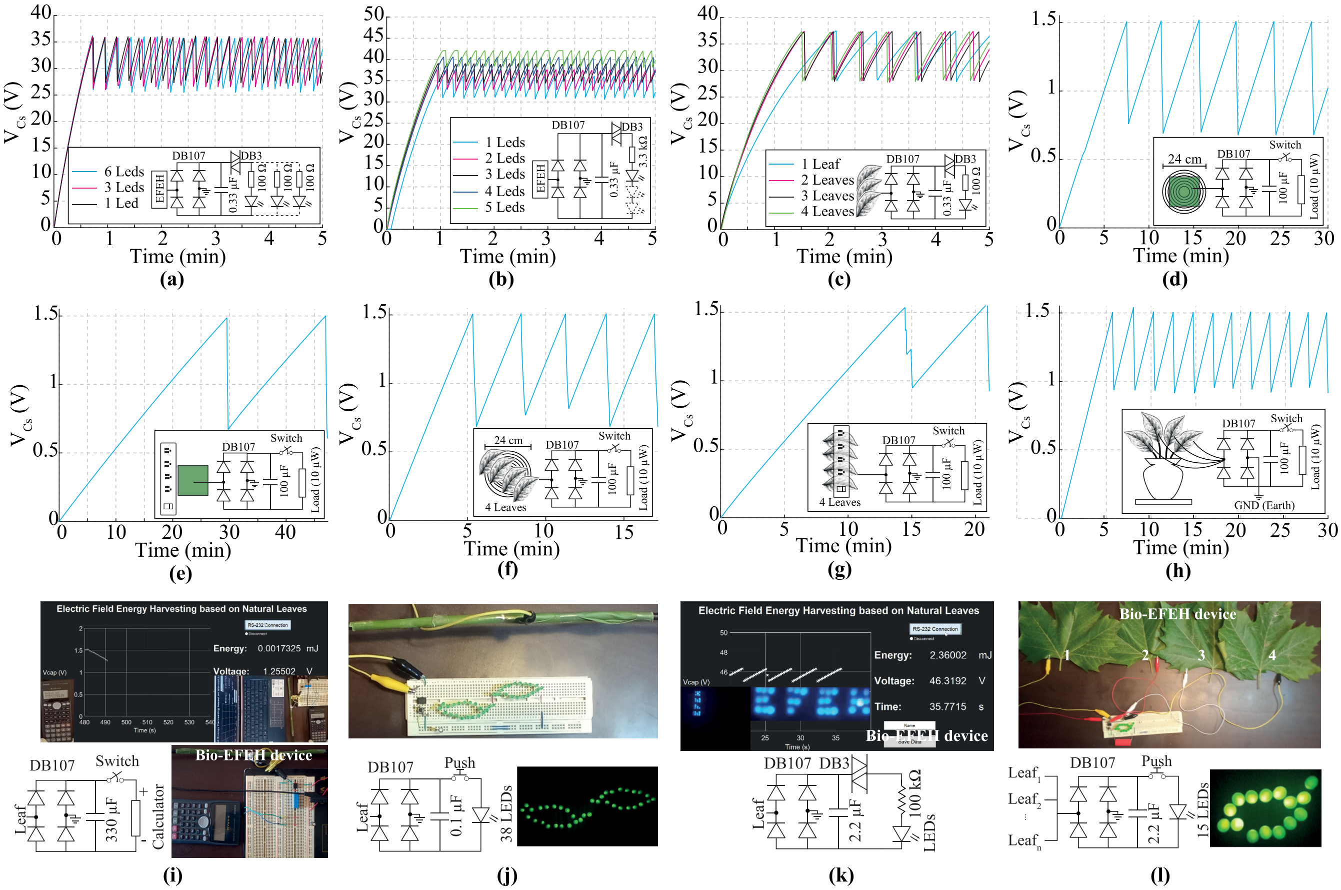


FIGURE 5. Real applications of Leaf-EFEHs for electric field energy harvesting. In each figure, the inset shows the equivalent circuit. (a) Voltage profile of a 0.33 μF capacitor charged by Leaf-EFEH. A parallel-connected LED array is connected to capacitor terminals. (b) Voltage profile of a 0.33 μF capacitor charged by Leaf-EFEH. A serial-connected LED array is connected to capacitor terminals. (c) Voltage profile of a 0.33 μF capacitor charged by natural entire leaves. A serial-connected LED array is connected to capacitor terminals. (d) Voltage profile of a 100 μF capacitor charged by Leaf-EFEH mounted on a spiral constructed base. A 100 μW load is connected to capacitor terminals. (e) Voltage profile of a 100 μF capacitor charged by Leaf-EFEH placed near a power strip. A 100 μW load is connected to capacitor terminals. (f) Voltage profile of a 100 μF capacitor charged by natural entire leaves mounted on the developed base. A 100 μW load is connected to capacitor terminals. (g) Voltage profile of a 100 μF capacitor charged by natural entire leaves placed near a power strip. A 100 μW load is connected to capacitor terminals. (h) Voltage profile of a 100 μF capacitor charged by a plant mounted on the built base. A 100 μW load is connected to capacitor terminals. (i) Picture showing a Leaf-EFEH powering a 100 μW load. (j) Picture showing Leaf-EFEH device (cylindrical topology) powering 38 green LEDs. (k) Picture showing Leaf-EFEH device (cylindrical topology) powering 29 blue LEDs. (l) Picture showing Leaf-EFEH device using Platanus Acerifolia leaves to power 15 green LEDs.

using a DB3 Diac as an external switch (See Video 3, Supporting Information). Figure 5l depicts a Leaf-EFEH device that operates in a parallel-electrode architecture. Four Platanus Acerifolia leaves with dimensions of 17-20 cm long, and 20-25 cm wide were mounted on the outer jacket of electrified wires. The collected energy can drive an array of commercial green LEDs with nominal voltages of 3.3 V every 20 seconds (See Video 4, Supporting Information).

IV. CONCLUSION

This work presented a comprehensive analysis of the natural leaves as potential replacements for conventional electrodes in EFEH advancements. Empirical results have demonstrated that fresh leaves have a solid performance in electrostatic charges' collection associated with the low-voltage electric field. Also, we have proved that the electrical performance of EFEH depends on the water content of natural leaves and their foliar morphology. Furthermore, the proposed harvesters, known as Leaf-EFEHs, are biodegradable and friendly environmental devices with steady and reliable functioning, which can power portable electronics, such as commercial LED arrays and WSNs. Experimental findings showed that a 17.5 × 17.5 cm^2 leaf-EFEH could store up to 15.75 mJ of energy in a 2.2 μF capacitor in 30 minutes. The collected energy was used to power up to 38 green LEDs and a 100 μW load for 14 seconds.

On the other hand, although the acquired data revealed that Leaf-EFEH directly depends on water content, a significant issue is to determine an effective form to measure electrical outputs (VOC and ISC). Thus, we suggest performing more experiments to determine a precise relation between both parameters. In general, this work might expand the development of green technologies for the proper and continuous monitoring of ambient variables (temperature, humidity, speed of the wind, etc.) in agriculture scenarios. In addition, different parameters associated with the leaf water content, such as Foliar Mixture Content (FMC) and Equivalent Water Thickness (EWT), could be determined by exploiting the relationship between the electrical outputs of the harvesters and the water content. Finally, we recommend connecting the alligator clips to different parts of the bio-electrodes if the drying is not uniform.

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