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Bioelectricity Generation in Established Cacao (*Theobroma cacao*), Oil Palm (*Elaeis guineensis*), and Peruvian Amazon Grass (*Axonopus compresus*) Crops: Insights from Amazonian Soils

Generación de bioelectricidad en cultivos establecidos de cacao (*Theobroma cacao*), palma aceitera (*Elaeis guineensis*) y grama amazónica peruana (*Axonopus compressus*): perspectivas desde suelos amazónicos

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ABSTRACT

As urban populations continue to grow, the global energy demand is expected to rise accordingly. Bioelectricity generation constitutes a promising and environmentally friendly alternative for sustainable energy production. This study evaluated the energy performance of biocells with galvanized graphite (GG) and copper-aluminum (CA) electrodes, which were installed in soils cultivated with three typical Amazonian crops: cacao (*Theobroma cacao*), oil palm (*Elaeis guineensis*), and Peruvian amazon grass (*Axonopus compressus*). Voltage and current measurements were recorded twice a day over a seven-day period. According to the results, the cacao-cultivated soil with GG electrodes achieved the highest electricity generation, with a voltage of 537 mV, a current of 0.17 mA, and power density of 26.2 mW/m^2. In comparison, the oil palm soil with GG electrodes reached a maximum voltage of 444 mV and a power density of 10.8 mW/m^2. CA electrodes showed lower energy yields across all crop types, reinforcing the importance of electrode material selection. By demonstrating significant bioelectricity generation in Amazonian agro-industrial crops and ornamental grass, this research highlights the potential of agricultural soils as renewable energy sources. As the first study to assess electricity generation in established Amazonian soils, our work provides novel insights into soil-based bioelectricity, an underexplored avenue for sustainable energy production. These findings pave the way for further research on optimizing bioelectricity generation in tropical soils, offering an innovative perspective on integrating renewable energy solutions into agricultural landscapes.

Keywords: biocells, bioenergy, electrodes

RESUMEN

A medida que las poblaciones urbanas continúan creciendo, se espera que la demanda global de energía aumente proporcionalmente. La generación de bioelectricidad constituye una alternativa prometedora y respetuosa con el medio ambiente para la producción de energía sostenible. Este estudio evaluó el rendimiento energético de bioceldas con electrodos de grafito galvanizado (GG) y cobre-aluminio (CA) instaladas en suelos cultivados con tres cultivos típicos de la Amazonía: cacao (*Theobroma cacao*), palma aceitera (*Elaeis guineensis*) y pasto amazónico peruano (*Axonopus compressus*). Se realizaron mediciones de voltaje y corriente dos veces al día durante un período de siete días. Según muestran los resultados, el suelo cultivado con cacao y electrodos GG logró la mayor generación de electricidad, con un voltaje de 537 mV, una corriente de 0.17 mA y una densidad de potencia de 26.2 mW/m^2. En comparación, el suelo de palma aceitera con electrodos GG alcanzó un voltaje máximo de 444 mV y una densidad de potencia de 10.8 mW/m^2. Los electrodos CA mostraron menores rendimientos energéticos en todos los tipos de cultivo, reforzando la importancia de la selección del material del electrodo. Al demostrar una generación significativa de bioelectricidad en cultivos agroindustriales amazónicos y césped ornamental, esta investigación destaca el potencial de los suelos agrícolas como fuentes de energía renovable. Como el primer estudio en evaluar la generación de electricidad en suelos amazónicos establecidos, nuestro trabajo proporciona conocimientos novedosos sobre la bioelectricidad basada en suelos, un campo poco explorado en la producción de energía sostenible. Estos hallazgos abren el camino para futuras investigaciones orientadas a optimizar la generación de bioelectricidad en suelos tropicales, ofreciendo una perspectiva innovadora para la integración de soluciones energéticas renovables en los paisajes agrícolas.

Palabras clave: bioceldas, bioenergía, electrodos

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Introduction

According to the United Nations, the global urban population was approximately 4.5 billion in 2022 and is projected to reach 6.6 billion by 2050 [1]. This increase is expected to escalate product consumption and energy demand. Currently, the primary energy sources are non-renewable, which significantly contributes to environmental pollution through greenhouse gas emissions [2]. The looming threat of climate change, the dependence on energy imports, and the finite nature of fossil fuels have raised widespread concern regarding energy security and the environmental impacts associated with energy production and consumption. Consequently, the United Nations have urged governments to implement strategies geared towards sustainable growth and development [3].

In response, numerous countries are increasing investments in renewable energy. A novel form of renewable energy that has attracted attention in recent years is bioelectricity generated by soil-dwelling microorganisms and plant root exudates. This growing interest arises from the global trend towards sustainable energy production and the capability of bioelectrochemical systems to degrade organic matter and perform bioremediation [4]. Biocells, *i.e.*, devices that utilize microorganisms to convert the chemical energy of substrates into electricity, represent an emerging technology with significant potential to mitigate the energy crisis [5]. During photosynthesis, plants produce compounds they do not fully utilize and release them through their roots. When these exudates interact with microorganisms in the rhizosphere that are capable of oxidizing carbohydrates under anoxic conditions, electrons are produced in the soil, facilitating organic matter degradation [6]. The potential of biocells is considerable, and previous studies have demonstrated their effectiveness [7], [8]. For instance, a study conducted by [9] using microbial fuel cells with ornamental plants in wetlands achieved outputs of 750 mV, and [10] investigated electric power generation in house-grown potted plants, reaching maximum voltages of 340 mV.

Reflecting on the progress of field-based bioelectricity generation research, significant advances have been made in harnessing the electrical potential of plant-microbial ecosystems. [11] demonstrated the utility of plant-microbial fuel cells in diverse agricultural settings. These findings highlight the practicality of integrating bioelectrochemical systems into existing agricultural infrastructures to simultaneously enhance crop yield and renewable energy production. [12] further explored the deployment of these systems in field conditions, identifying key factors such as plant species selection and the optimization of reactor components that significantly influence bioelectricity generation efficiency. These insights are particularly relevant for this study, as they provide a foundation for evaluating the bioelectric potential of Amazonian soils and the performance of different electrode materials in an agro-industrial context.

Carbon-based materials and metal electrodes have recently been employed in biocell systems. These materials are promising candidates due to their cost-effectiveness, high electrical conductivity, large specific surface area, significant pore volume, and stability [13]. Galvanized graphite (GG) as an anode material is particularly suitable for soil-based microbial fuel cells because of its high conductivity and compatibility with microbial life, which is crucial for maximizing energy capture from soil microbial activity. Copper and aluminum (CA) electrodes are also promising; their exceptional conductivity may further enhance bioelectric potential in microbial fuel cells. Notably, copper supports the formation of highly active biofilms essential for bioenergy production [14]. Moreover, [15] suggest that coating metal electrodes with biocompatible materials could improve their performance, an approach that is beneficial for the CA electrodes used in our study.

Although these findings are encouraging, a noticeable research gap remains. To date, only a limited number of studies has evaluated electricity generation in soils with established crops. Consequently, this study seeks to estimate the potential for electricity generation in soils cultivated with two agro-industrial crops and one ornamental grass. The goal is to quantify the energy derived from the metabolic activity of microorganisms in soils planted with cacao (*Theobroma cacao*), oil palm (*Elaeis guineensis*), and Torourco grass (*Axonopus compressus*). Additionally, we aim to assess the performance of two electrode types (GG and CA) and understand the influence of environmental and soil conditions on voltage and current production. Significantly, this research offers a novel contribution to the field of bioelectricity, as it constitutes the first investigation into electricity generation in Amazonian soils cultivated with agro-industrial crops and ornamental grass. Thus, it provides a new perspective on the renewable energy potential inherent in these under-researched soils, marking a critical step forward in this innovative field and offering valuable insights despite its relatively short duration.

Materials and methods

To provide a clear and concise overview of the research methodology, a flowchart is included below. This flowchart outlines the key phases of the study, covering the experimental design and the materials and methods used. All this, with the purpose of guaranteeing clarity and facilitating replication by other researchers (Fig. 1).

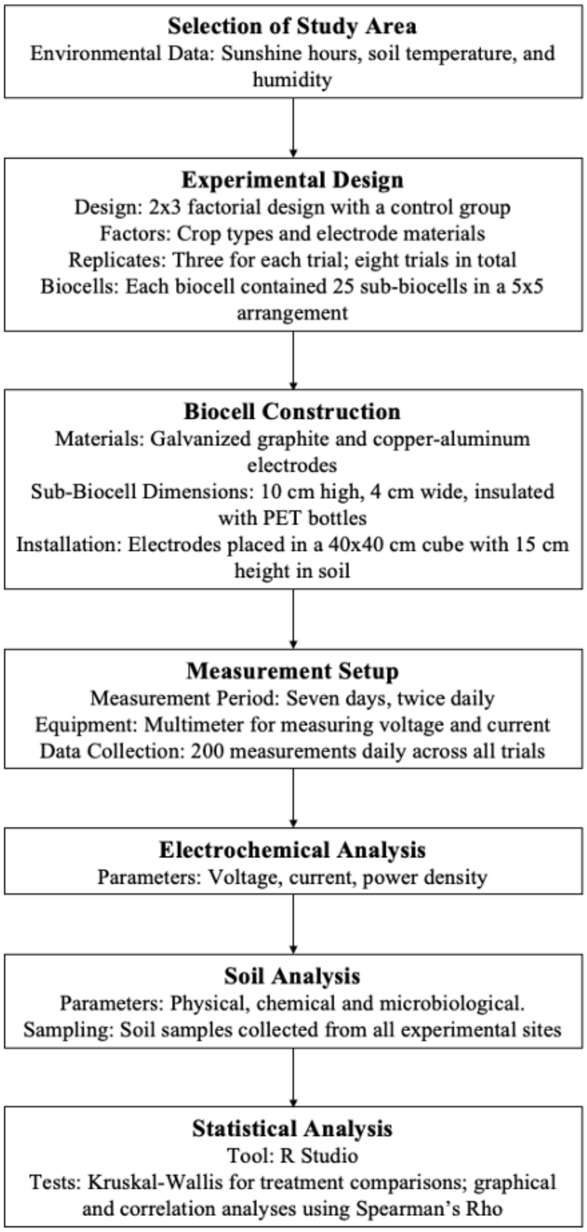


Figure 1. Flowchart of the experimental design and methodology **Source:** Authors

Selection of the study area

The experiments were conducted at Universidad Nacional de Ucayali (UNU), located in the Callería district, Coronel Portillo province, in the Ucayali region of Peru (Fig. 2). For the experiment, we selected three distinct sites within the university: the cacao botanical garden, the meteorological station where Torourco grass is cultivated, and the oil palm plantation. Additionally, a crop-less soil area was chosen to serve as the control. Data on sunshine hours, soil temperature, and environmental humidity were collected from the UNU weather station.

Figure 2. Location of the study area in a) America and b) the UNU campus. Specific location of biocells installed in soils with different vegetation, *i.e.*, c) cacao, d) grass, e) oil palm, and f) non-cultivated soil **Source:** Authors (images retrieved from Google Earth)

Oil palm, cacao, and grass were selected because they represent different vegetation strata – high, medium, and low elevation, respectively. Additionally, cacao and oil palm were chosen due to their agricultural significance in the study area and the extensive land area they occupy, which indicates their potential as energy sources beyond traditional agriculture. Torourco grass, widely cultivated in the study area for recreational centers, parks, and central berms, was selected due to the potential of using soil-generated electricity for public lighting purposes.

Care was taken to ensure that the experimental substrates were not affected by other experiments. Throughout the study period, the experimental sites remained free from any interference, ongoing work, or additional experiments conducted nearby. Moreover, no alternate uses of the area were permitted, thus preserving the integrity of the experimental conditions.

The experiments were intentionally conducted under natural field conditions, in order to accurately represent real-world scenarios involving bioelectricity generation systems. The frequency of voltage and current measurements, taken twice every day, was dictated by the study's objectives, specifically targeting the immediate response of the bioelectrochemical system to natural daily variations.

Despite the relatively short duration of our experiments (seven days), the standard deviation of the voltage measurements indicated stability (below 0.113 mV on most days), which was deemed sufficient for the preliminary scope of this work. The seven-day measurement period was strategically selected to balance the detailed observation of microbial consortia dynamics with logistical feasibility. Extending the duration of the study would have required significant additional resources, potentially complicating field logistics. Although a longer study could yield more comprehensive insights into external factors influencing energy generation, this preliminary research captures the immediate response under natural field conditions and sets a foundation for future extended studies.

Experimental design

A 2 x 3 factorial design, complemented with a control group, was employed to evaluate the influence of crop type and electrode material on the energy efficiency of the biocells, with a total of eight trials (Table I). The structure of the biocell is illustrated in Fig. 3. The control group consisted of uncultivated soil. As previously mentioned, the evaluated factors were crop type (Torourco grass, cacao, and oil palm) and electrode type (GG and CA). Each trial was conducted in triplicate. At each experimental site, two biocells were installed, each containing 25 sub-biocells with one electrode type, arranged in a 5 x 5 configuration.

Table I. Experiment design and coding

Electrode	Plant species			Control
	Cacao	Grass	Palm	Soil
Galvanized graphite	CGG	GGG	PGG	SGG
Copper and aluminum	CCA	GCA	PCA	SCA

Source: Authors

Figure 3. Biocell structure
Source: Authors

Biocell construction

The electron capture system was designed based on the fundamental principles of microbial galvanic cells [16]. Two types of electrodes were prepared: GG electrodes, which were constructed using galvanized steel (BCC Zincopro) (Fig. 4a) and graphite extracted from Panasonic AA batteries (Fig. 4b); and CA electrodes made from copper wire (Indeco) (Fig. 4c) and bare aluminum wires (Indeco) (Fig. 4d). After extracting the required materials, anodes and cathodes were fashioned to a length of 4.7 cm. The electrodes were soldered using 22-gauge tin wire and insulated with hot silicone to prevent oxidation and wire sulfation. Each electrode was placed within a sub-biocell structure measuring 10 cm high, 4 cm long, and 4 cm wide. A 650 mL PET water bottle, cut to a height of 10 cm, served as an insulator for each sub-biocell (Fig. 4e). Each biocell comprised 25 sub-biocells containing either GG or CA electrodes in a 5 x 5 array (Fig. 4f). The complete experimental set up is depicted in Fig. 4.

To install the biocells, a cube measuring 40 cm per side and 15 cm deep was excavated in the soil. Some of the removed soil was poured into the PET bottles before installing the electrodes. Each biocell was covered with a felt cloth layer and topped with an additional 5 cm of soil, leaving 5 cm of wire exposed at the soil surface for voltage and current measurements (Fig. 4g). To allow for sufficient root growth around the biocells, measurements began three months after installation.

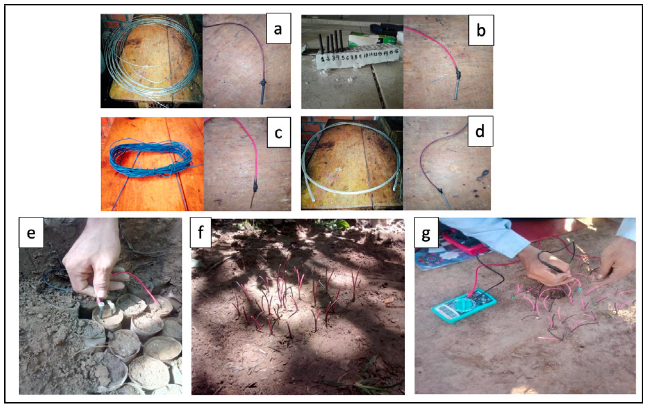


Figure 4. Experimental setup: a) galvanized steel cathode, b) AA battery graphite anode, c) copper wire anode, d) aluminum wire cathode, e) sub-biocell with anode and cathode, f) biocell composed of 25 sub-biocells, and g) voltage and current measurement setup
Source: Authors

Electrochemical analysis

Voltage and current were measured using a multimeter over seven days, twice every day, from 7 am to 12 pm and again from 2 pm to 5 pm. In each turn, 25 current and 25 voltage measurements were recorded for each of the two electrode types. Consequently, a total of 100 measurements per electrode (50 for current and 50 for voltage) were collected daily, amounting to 200 daily measurements for both electrodes.

The energy performance of each biocell was evaluated based on voltage, current, and power density. Voltage and current readings were obtained directly from the multimeter, while the power was calculated by multiplying the voltage (in mV) by the current (in mA). Subsequently, the power density (mW/ m^2) was calculated by dividing the power by the biocell's surface area.

The seven-day measurement period was chosen based on the specific objectives and logistical constraints of the study. This duration was considered sufficient to capture the immediate responses and initial patterns of bioelectricity generation under the given environmental conditions. While extending the measurement period could potentially yield more comprehensive data, seven days provided a preliminary exploration sufficient to observe notable trends within a feasible timeframe. It should also be noted that all measurements were conducted during September.

Soil analysis

Soil samples were collected from each of the four experimental sites in order to analyze their physicochemical and microbiological parameters by means of established methodologies. The physical properties assessed included sand, clay, and silt percentages, determined via the hydrometer method; as well as the wilting point, which was evaluated using the gravimetric method. The bulk density and field capacity were measured using the measuring cylinder method. The chemical analyses included electrical conductivity (measured using a conductometer in an aqueous extract), pH (determined with a potentiometer using a water-soil ratio of 1:1), and the organic matter content (assessed using the Walkley and Black method). The total nitrogen was measured using the Micro Kjeldahl method, while the available phosphorus was determined via the modified Olsen method ($NHCO_3$ 0.5M extract at pH 8.5). The available potassium was extracted using ammonium acetate (1N) at pH 7, and cadmium levels were analyzed through Tessier sequential extraction. The cation exchange capacity was measured using ammonium acetate (1N) at pH 7, while the effective cation exchange capacity and exchangeable acids were determined via displacement with KCl 1N (for soils at pH<5.6). The calcium, magnesium, potassium, and sodium concentrations were measured using an atomic absorption spectrophotometer, and the aluminum and hydrogen contents were analyzed using the Yuan method.

For the microbiological analysis, aerobic heterotrophic bacteria were quantified using the standard plate count method with nutrient agar, while anaerobic heterotrophic bacteria were counted using the most probable number (MPN) method on anaerobic agar. Actinomycetes were assessed via the spread plate method using actinomycete isolation agar, and fungi (mold and yeast) were identified through the dilution plate method on potato dextrose agar. Lactobacillus enumeration was conducted using the de Man, Rogosa, and Sharpe (MRS) agar plate count method, and the presence of mycorrhizae was evaluated through root staining and microscopic observation.

Statistical analysis

The statistical analysis was performed using R. The differences between the treatments and the control were assessed via the Kruskal-Wallis test. All treatments showed significant differences at an alpha level of 0.01. The variations in daily and hourly averages were examined through graphical representations, and the correlation between voltage and current was evaluated using Spearman's Rho.

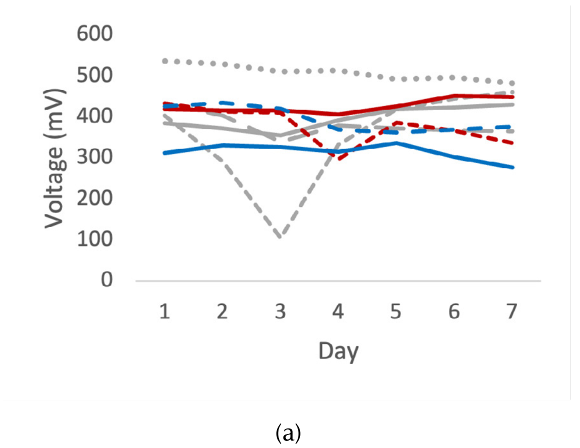
Results and discussions

Under uncontrolled field conditions, the daily variability in energy generation was analyzed and found to be stable. The data, collected twice in a day throughout the experiments, exhibited minimal fluctuations, with modest standard deviations for the voltage measurements on most days. The standard deviations ranged from 0.052 to 0.113 mV on all but one day, indicating a negligible impact of external climatic and solar variations on bioelectricity generation. These observations support the validity of the measurement approach and highlight the resilience of the bioelectric system under varying environmental conditions.

The only exception occurred on day 2, for which a higher voltage fluctuation was observed, possibly due to specific environmental events. This outlier underscores the importance of careful data interpretation and the consideration of unquantified variables, which are inherent in field-based studies. Nonetheless, the overall stability of voltage measurements throughout the experiment suggests that the chosen measurement frequency was sufficient to capture variations in bioelectricity generation under field conditions.

Efficiency of the biocells

The area of non-cultivated soil exhibits voltage emissions comparable to those from soils with crops (Figs. 5a, 5b). This could be explained by cattle frequently passing through and depositing manure, thereby promoting the growth of pioneer grasses. The roots of these grasses, along with the organic matter content from manure, could contribute to voltage generation. This hypothesis was supported by the soil characterization results (Table III), according to which the soil without cultivated crops had similar levels of organic matter, nutrients, and microorganisms, albeit slightly lower than those in the cropped soils.



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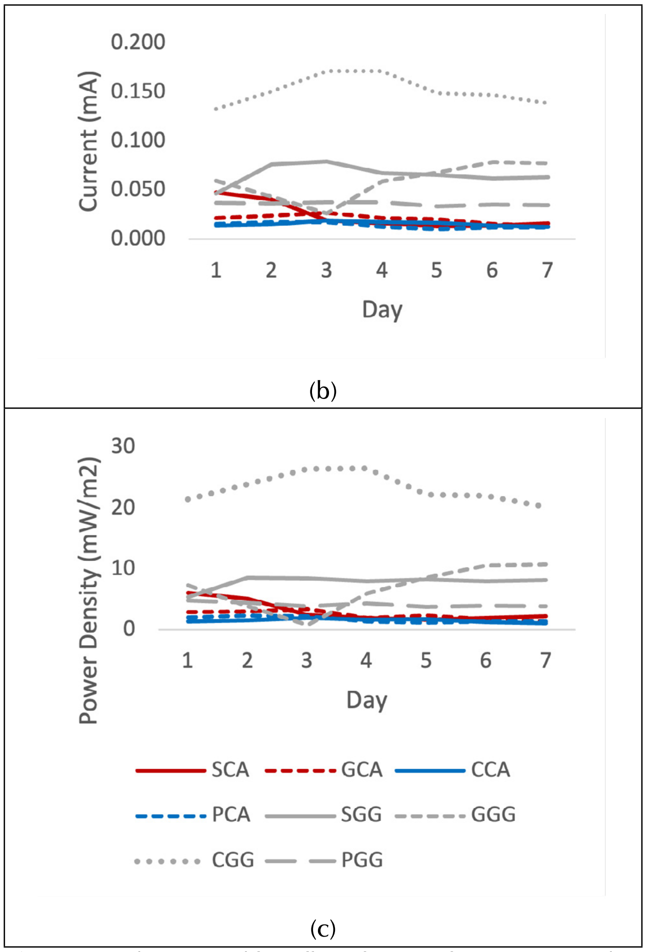


Figure 5. Performance of biocells with CA and GG in terms of a) voltage, b) current density, and c) power density
Source: Authors

Energy generation measurements began after root colonization had occurred, resulting in initial recorded voltage values of 355-434 mV. Throughout the seven-day period, no significant fluctuations in voltage, current, or power density were observed across the experiments, except for a slight dip in voltage on the third day of the GGG trial. All other trials maintained consistent voltage levels throughout the measurement period. This stability may relate to the acclimatization period before electrode installation. The generated energy is associated with the characteristics of microbial communities in the rhizosphere around the electrodes.

Generally, the microbial growth cycle comprises four phases: dormancy, exponential growth, stationary, and death. The experimental conditions and results suggest that electrical current measurements were taken during the stationary phase [17], with the dormancy and exponential growth likely occurring during the initial three-month period prior to measurement. Therefore, our measurements remained relatively stable during the seven-day experiment. A steady voltage output is associated with the maturity of the biofilms formed on electrodes [18], indicating that, by the time measurements commenced, plant roots had already colonized the biocells and had begun releasing the enzymes necessary for electron transfer [19].

However, electricity generation is not expected to remain unchanged indefinitely. The voltage showed a slight downward trend on day 7, while current and power density peaked between days 3 and 4. In these systems, fluctuations in daily power generation measurements are common and can be attributed to microbial consumption and the subsequent depletion of the available organic matter around the electrodes [20].

Throughout the biocells' operation, both the voltage and power density values remained relatively stable but displayed distinct trends. For instance, the CGG trial achieved the highest power density: 26.2 W/m^2, with a maximum voltage of 537 mV. Meanwhile, the GGG trial reached a maximum voltage of 444 mV and a peak power density of 10.8 W/m^2. These differing outcomes can be explained by several hypotheses [21]: (i) biocells undergo complex variations under natural conditions; (ii) plant species influence microbial communities, altering the root exudate composition; and (iii) root exudates, primarily products of photosynthesis, nourish the rhizosphere microorganisms. Several studies have demonstrated that the composition and quality of microbial communities in the rhizosphere vary according to plant type, genotype, and photosynthesis strategy [22]. Although exudate production generally reflects photosynthetic activity, numerous factors influence its composition, which can vary even within different root zones of the same plant [23].

A comparison between the maximum power density values obtained in this study and those reported in previous research (Table II) indicates that plant species tested under field conditions generate electricity at levels comparable to those of laboratory studies. Furthermore, identifying electroactive microorganisms responsible for electrical activity could allow their introduction into crops in order to enhance electricity generation.

Table II. Maximum power density values in biocell experiments

Plant species	Maximum power density (mW/m^2)	Reference
Chlorophytum inornatum with copper plate electrodes	10	[24]
Pipremnum aureum with carbon fiber electrodes	15.38	[25]
Agapanthis africanus with carbon fiber electrodes	15.55	[26]
Chlorophytum with graphite electrodes	18	[21]
Rice with carbon felt anode	41.41	[27]
Eichhornia crassipes with graphite and zinc electrodes	100.2	[17]
Theobroma cacao with graphite and galvanized electrodes	26.6	This study

Source: Authors

The duration of the measurements (seven days) was selected as a practical compromise to achieve meaningful data collection within the feasibility constraints of this preliminary study. Recognizing the limitations of a shorter observation period, this timeframe was sufficient to observe initial trends and variations in bioelectricity generation under natural environmental conditions. Despite its limited duration, the study successfully identified key trends and patterns, providing foundational insights into bioelectrochemical systems in natural settings. Although extended measurement periods could offer more comprehensive insights, the selected seven-day window effectively captured the system's immediate response to environmental fluctuations, establishing groundwork for future extended studies.

Biocell performance and atmospheric parameters

The atmospheric conditions recorded over the seven-day study period are shown in Fig. 6. We monitored environmental and soil temperatures, which are considered to be among the most influential abiotic factors affecting photosynthesis [28], [29]. Despite this, Spearman's Rho correlation analysis indicated a very weak relation between electrical parameters (current and voltage) and atmospheric conditions. It is generally expected that increased temperatures enhance photosynthesis, thus promoting plant growth and rhizosphere biomass. However, the anticipated temperature-voltage relationship was not evident during our experiment, nor was there a clear association between environmental humidity and biocell efficiency. This suggests that environmental moisture might not significantly influence plant growth, and that, consequently, it has a limited impact on microbial activity within the rhizosphere. Nonetheless, it is possible that an extended observation period could reveal more pronounced correlation between these parameters [21].

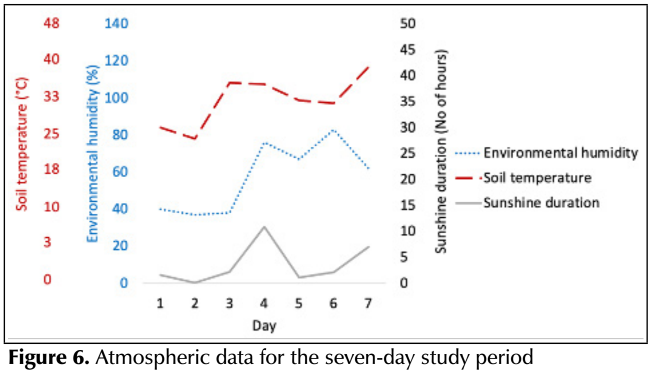


Figure 6. Atmospheric data for the seven-day study period
Source: Authors

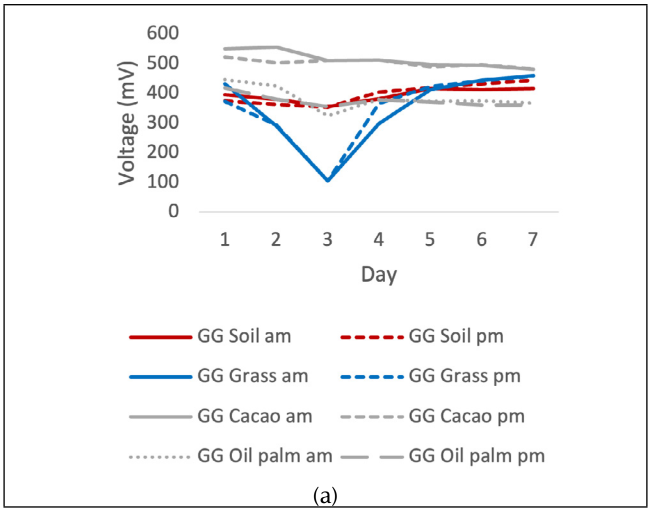
Effect of electrode type

In our experiments, the GG electrodes outperformed the CA ones, particularly in cacao soils. Throughout the experiment, the CGG trial consistently achieved the highest voltage (527 mV), current (0.17 mA), and power density (26.2 mW/m^2). This trial exhibited superior performance from the outset, beginning with a notable power density of 21.5 W/m^2, while other trials started with values ranging between 1.3 and 7.3 W/m^2. The trials using CA electrodes maintained stable power densities between 1 and 3 W/m^2, and they even recorded lower values than the control during the first three days (Fig. 5c).

These findings underscore the significant role that electrode materials play in electricity generation. The GG electrode conducted electricity more effectively than the CA one, likely due to factors such as standard reduction potential, electrical conductivity, and resistivity. The standard reduction potential of zinc (used to coat galvanized steel) ranges between -0.76 and -1.25 V at 25 °C, whereas those of copper and aluminum are 0.52 V and -1.66 V, respectively [30]. Metals with lower standard reduction potentials are generally harder to reduce [31]. Consequently, although aluminum has a more favorable reduction potential compared to the zinc in galvanized steel, the GG electrodes demonstrated greater efficiency. Regarding electrical conductivity, zinc and copper provide values of 1.60×10^7 and 5.96×10^7 ds/M, respectively. In terms of resistivity, copper and aluminum exhibit lower values (1.72×10^{-8} and 2.74×10^{-8} $\Omega \bullet$m, respectively) than graphite (3.5×10^{-5} $\Omega \bullet$m) [32]. A lower electrical resistivity implies a lower resistance to electric current. Despite graphite's higher resistivity, the presence of graphite in the GG electrodes significantly improved energy performance, potentially even more so than the zinc coating itself.

Effect of light variation

As shown in Fig. 7, solar radiation appeared to influence the experiments. Voltage readings in the morning were slightly higher than those recorded in the afternoon. Peak light intensity hours coincide with higher temperatures, potentially facilitating the release of root exudates and enhancing the activity of soil microorganisms [21]. Nevertheless, plant-generated electricity is expected to persist into nighttime, since root exudate production from photosynthesis includes processes independent of immediate light availability. This characteristic allows biocells to function similarly to energy storage batteries [33]. Interestingly, during the GG electrode trials in this study, the afternoon's voltage generation occasionally exceeded morning values, a phenomenon previously observed in algal biocell studies [34].



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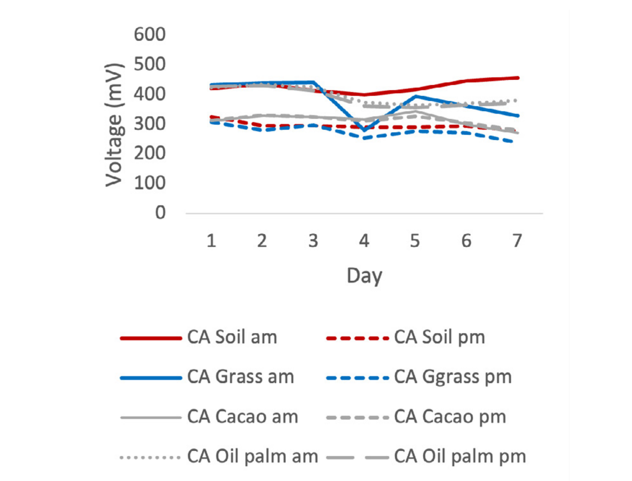

(b)

Figure 7. Variation during the seven-day experiment, illustrating the effects of morning and afternoon light phases on a) GG and b) CA electrodes
Source: Authors

Effect of soil type

Table III shows that physical soil parameters were fairly consistent across all four experimental sites. However, the chemical properties were notably superior in the soil cultivated with cacao, as evidenced by higher concentrations of organic matter, nutrients (N, P, K, Ca, Mg), and the percentage of exchangeable bases (associated with substrate fertility). The cacao-cultivated soil also had a higher concentration of heterotrophic microorganisms, fungi, and yeasts. These findings highlight a direct correlation between electricity generation and soil organic matter, nutrients, and microbial content. Specifically, the cacao crop trial with the GG electrodes produced the highest energy output (Fig. 5). It can therefore be inferred that cacao had better access to carbon sources and displayed increased microbial activity, both contributing to enhanced electricity generation. This pattern aligns with previous research studies that observed greater bioelectricity generation in soils richer in organic matter and nutrients [35]. Although this study did not explicitly measure the impact of fertilization on energy production, the observed trends suggest a hypothesis for future investigation: increased fertilization could correlate positively with enhanced bioelectricity generation.

Additionally, the robust electricity generation observed in cacao-soil biocells may be attributed to the unique interactions between the cacao crop's root system and the soil microbial community. Cacao plants, known for their dense and extensive root network [36], significantly influence the biological and chemical properties of the soil, creating favorable conditions for microbial electricity generation. As described by [37], plant roots provide substantial biomass, serving as substrates for cellulose-degrading microorganisms, which are often associated with electroactive anode-respiring bacteria. This interaction between cacao roots and soil microorganisms likely facilitates efficient electron transfer processes, resulting in higher electricity production. Furthermore, organic matter from dead plant roots and manure, as indicated by the soil characterization results, may stimulate microbial consortia involved in bioelectricity generation, thereby enhancing the overall biocell performance in cacao-cultivated soils.

Table III. Physical, chemical and microbiological soil parameters

Parameters	**Soil**	**Grass**	**Cacao**	**Oil palm**
Physical				
Texture	Loam	Loam	Loam	Loam
Bulk density (g/mc^{3})	1.4	1.4	1.4	1.4
Field capacity (%)	25	24	22	23
Field capacity (%)	8	7.8	7.8	7.7
Soil temperature (°C)	32	28	32	28
Chemicals				
Electrical conductivity (mS/cm)	0.1	0.05	0.16	0.04
pH	4.1	5.11	5.33	4.64
Organic matter (%)	0.9	0.9	1.19	0.75
Nitrogen (%)	0.04	0.04	0.05	0.03
Phosphorus (ppm)	3.4	5.99	6.39	4.4
Potassium (ppm)	51.98	72.47	88.46	55.98
Calcium Cmol(+)/kg	1.78	2.29	2.99	1.83
Magnesium Cmol(+)/kg	0.8	0.87	1.16	0.81
Aluminum Cmol(+)/kg	5.7	0.69	0.4	1.3
Hydrogen Cmol(+)/kg	0.3	0.01	0.1	0.1
Cation exchange capacity (meq/100g)	8.58	3.85	4.65	4.04
Exchangeable bases (%)	30.04	81.83	89.24	65.33
Exchangeable acids (%)	69.96	18.17	10.76	36.67
Aluminum saturation (%)	65.47	17.91	8.61	32.19
Microbiological				
Aerobic heterotrophic bacteria counting (CFU/g)	56x10^{3}	48x10^{3}	63x10^{3}	8x10^{3}
Anaerobic heterotrophic bacteria counting (CFU/g)	31x10^{3}	25x10^{3}	88x10^{3}	10x10^{3}
Actinomycetes counting (CFU/g)	9x10^{3}	86x10^{3}	88x10^{3}	53x10^{3}
Fungi (Moha and yeasts) counting (CFU/g)	1x10^{3}	1x10^{3}	5x10^{3}	2x10^{3}
Enum. of Lactobacillus (mo/g)	Absence	Absence	Absence	Absence
Mycorrhizae	Presence	Presence	Presence	Presence

Note: CFU: Colony-forming unit, mo: micoorganisms
Source: Authors

Conclusions

Bioelectricity generation through interactions between the plant rhizosphere and soil microorganisms presents a promising pathway for renewable energy production. This study evaluated bioenergy performance in three soil types cultivated with cacao, oil palm, and Torourco grass. Biocells were installed in these soils and in a non-cultivated control, with voltage and current measurements taken over seven days, both in the morning and afternoon. Power density results demonstrated that the evaluated crops generate electricity at levels comparable with previous studies, suggesting potential for even higher energy outputs with increased fertilization. Notably, biocells with GG electrodes consistently outperformed those with CA electrodes. An analysis of the standard reduction potential, electrical conductivity, and resistivity values indicated that graphite likely played a crucial role in enhancing electricity generation.

Interestingly, variations in atmospheric parameters and daily light intensity had minimal impact on electricity production. The most effective setup involved cacao cultivation with a GG electrode, achieving peak voltage, current, and power density values of 537 mV, 0.17 mA, and 26.6 mW/m^2, respectively. The superior energy performance observed in cacao soils coincided with their enhanced chemical and microbiological properties, including higher organic matter, nutrient content, and microbial populations.

Despite its limited duration, this study successfully identified significant trends and patterns in bioelectricity generation, validating the utility of monitoring bioelectrochemical systems under natural field conditions. These results address a critical gap in the existing research by quantifying the energy potential in soils cultivated with agro-industrial crops and ornamental grass. The demonstrated potential for electricity generation in soils with established oil palm, cacao, and grass crops suggests these agricultural soils can serve as renewable energy sources.

As the first exploration of electricity generation in Amazonian soils cultivated with agro-industrial crops and ornamental grass, this research provides novel insights into the renewable energy potential of these under-researched soils. Consequently, this study represents a significant advancement in the field of bioelectricity, laying important groundwork for future research and sustainable energy applications while highlighting the potential of soil-based bioelectricity as an environmentally friendly energy source that can contribute to a sustainable future.

CRediT author statement

Edwar Edinson Rubina-Arana: conceptualization, methodology, writing – review & editing (original draft), supervision, funding acquisition. *Letty Leonor Sandoval-Mendoza and Glendy Sánchez-Sunción:* formal analysis, investigation. *Dalia Carbonel:* formal analysis, writing – review & editing (original draft), visualization. *Grober Panduro-Pisco:* investigation, supervision, resources and validation.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during and/or analyzed during this study are available from the corresponding author upon reasonable request.

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