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Conference Paper

Electronic Design of a DC-DC Boost Converter for Powering a Lo-Ra Communication Board with Bioelectricity by "Plantas Andinas"

Diseño electrónico de un Convertidor DC-DC Boost para alimentar una tarjeta de comunicación Lo-Ra con bioelectricidad de "Plantas Andinas"

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IX CONGRESO INTERNACIONAL DE INVESTIGACIÓN DE LA RED ECUATORIANA DE UNIVERSIDADES Y ESCUELAS POLITÉCNICAS Y IX CONGRESO INTERNACIONAL DE CIENCIA TECNOLOGÍA EMPRENDIMIENTO E INNOVACIÓN SECTEI-ESPOCH 2022

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Abstract

The use of bioelectricity in various areas of science has made it indispensable to resort to new technologies to take full advantage of this natural resource. Plants are living beings, and through their biochemical processes produce a small amount of electricity derived from oxidation-reduction processes. For this reason, it is proposed to use electronic and power techniques to increase the flow of electrons produced by plants of Andean characteristics, and consequently feed a Lo-Ra type communication card, meeting the needs of long-distance data transmission, used in the collection of field information, either in areas where access or availability of power lines is complex. This proposal motivates us to continue working on sustainable energy and the exploitation of natural resources. This document details the theory, practice, and methods used to meet the objective of supplying power to a wireless communication system over a long distance. First, a description of the most important issues to be addressed is developed, and then special focus is given to the design for development of the power electronics circuit, specifically an elevator type DC-DC converter. Finally, the results obtained through the implementation used in this case are documented.

Keywords: *bioelectricity, MFC, boost-converter, Andean plants, totora, Lo-Ra TTGO.*

Resumen

El uso de bioelectricidad en diversas áreas de la ciencia ha hecho indispensable recurrir a nuevas tecnologías para aprovechar al máximo este recurso natural. Las plantas, como seres vivos, producen una pequeña cantidad de electricidad a través de sus procesos bioquímicos, derivada de procesos de oxidación-reducción. Por esta razón, se propone utilizar técnicas electrónicas y de potencia para aumentar el flujo de electrones producidos por plantas de características andinas, y alimentar así una tarjeta de comunicación de tipo Lo-Ra, satisfaciendo las necesidades de transmisión de datos a larga distancia, utilizadas en la recolección de información de campo, ya sea en áreas donde el acceso o la disponibilidad de líneas eléctricas es compleja.

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Esta propuesta motiva a continuar trabajando en energía sostenible y en la explotación de recursos naturales. Este documento detalla la teoría, práctica y los métodos utilizados para cumplir con el objetivo de suministrar energía a un sistema de comunicación inalámbrico a larga distancia. En primer lugar, se desarrolla una descripción de los temas más importantes a abordar, y luego se presta especial atención al desarrollo del diseño del circuito de electrónica de potencia, específicamente un convertidor DC-DC tipo elevador; y finalmente, se documentan los resultados obtenidos a través de la implementación utilizada en este caso.

Palabras Clave: *bioelectricidad, CCM, convertidor-elevador, plantas andinas, totora, TTGO Lo-Ra.*

1. Introduction

Autonomous power supply for electrical and electronic systems is one of the most valued characteristics in the field of engineering, which opens the field of multiprofessional development and research directed towards tasks that do not require full dedication but rather ingenuity. This initial ingenuity is sufficient to make rapid progress while not neglecting simpler tasks but rather automating them. This initiation of operations allows for multi-sectoral work in different scenarios under suitable conditions. However, these conditions are not always optimal for humans but rather for other types of operations. A clear example is nature, which has dominated every corner of the planet, thriving in even the most remote environments. Where humans cannot enter, we can ally ourselves with powerful instruments that make our lives easier. One of the clear examples is bacterial processes in certain microenvironments, through which it is possible to obtain large quantities of usable combustible gases as a source of renewable energy. Consequently, highlighting the importance of anaerobic bacteria in biogeochemical processes, their adaptability and survival capabilities, as well as their role in the preservation of life itself, forming communities of life and sustainable life cycles. [1]

It is faced the need to find better surveillance methods, for example, in highlands and plains. Everything leads to the consumption of human and material resources, and it is in optimizing certain operations where the objective of this research lies. By utilizing a natural source of clean energy based on microbial fuel cells (MFCs), a deployable and robust energy system can be achieved, which could provide power to the data collection system, allowing it to operate continuously by powering low-power electrical loads. This would be accomplished with a voltage generation ranging from 110 to 135 mV, employing different types of flora. [2]. The demand for renewable energy has increased due to its clean nature, coming from unlimited resources, and its contribution to the fight against climate change. Furthermore, the development of microbial fuel cells (MFCs) is highlighted to harness energy from the physical and chemical processes of various plant species on the planet. [3].

1.1. Start point

The point of convergence in all ecological alignment focuses on the sun, as the initiator of energy transformations. It imparts the necessary force to trigger a sequential chain of processes that culminate in the complex actions of living beings, such as synthetic, electrical, or mechanical work. The entire outcome of life is attributed to the generation of energy, its accumulation, and its direction from thereon. Energy synthesis takes place at the base of the food chain. As a standalone aspect, we can mention the functioning of plants as the first link in the context of this study. They harness energy from the sun, combining this light energy with a carbon source (CO2) and water from the soil to obtain complex molecules that store energy during the dark phase of their metabolism. Meanwhile, during the light phase, they generate chemical energy (ATP and NADPH). [4].

Going into detail, solar radiation energy is converted into chemical energy through plant metabolism, with the Calvin cycle playing a key instrumental role. This cycle is preceded by non-cyclic photophosphorylation, which is responsible for the breakdown of water, the production of ATP from ADP (cyclic electron transport), and the energization of coenzyme NADPH to sustain the synthesis of biological molecules that serve as energy stores. Firstly, photons that reach the leaves are captured by the light-sensitive pigments in plants. Simultaneously, they are captured by the antenna complex (a network of pigments grouped in chloroplasts, which in turn are organized in thylakoids) and then transferred to photosystem I. Here, the two high-energy electrons are coupled to the first electron acceptor, ferredoxin, and then to the second acceptor, plastoquinone, which transports them to a cytochrome complex. All of this forms an energetic proton gradient that can be utilized in the conversion of ADP to ATP. Finally, the electrons return to the reaction center to complete the cycle.

This entire process captures energy that will be used in the non-cyclic electron transport, which charges the coenzymes responsible for carbohydrate production, such as sugar. On the other hand, cyclic electron transport maintains the flow to conserve and produce immediately available energy. Chemically, oxidation is defined as the removal of electrons, while reduction is the gain of electrons, as in the conversion of ferrous ions to ferric ions. When organic matter is gradually oxidized, either by microorganisms or not, energy is sporadically released into the environment, where natural electron acceptors, such as oxygen, couple to maintain an environmental energy flow. Oxidation reactions are accompanied by the release of energy as the reacting chemical system transitions from a higher energy level to a lower one. Often, this energy is released in the form of heat and is found in a chemical medium that can be directly utilized in electrical transformation. The acquisition of energy in biological systems is achieved through the coupling of reactions. [5].

Therefore, oxidation is always accompanied by the reduction of an electron acceptor. In this case, the acceptance of electrons is directed towards a suitable cathode that directly conducts electric current to a circuit or receiving system that harnesses this potential to utilize the obtained energy. This forms the foundation for the functioning of microbial fuel cells. One of the challenges is the need to control water quality, temperature, pH, among others, and transmit this data to the receivers. Typically, these systems rely on batteries, which presents an inconvenience due to their limited lifespan and the need for recharging or replacement. A solution for environmental monitoring is the use of plant microbial fuel cells (P-MFCs), which have emerged as a renewable, cost-effective, clean, and sustainable source of energy capable of producing bioelectricity. This makes them an attractive source of bioenergy. [6–8].

The unique climatic conditions of the Andean region make it a mega-diversity hotspot for flora and fauna. The Andes are categorized as the most biodiverse mountain range in the world, comprising a complex array of ecosystems ranging from tropical forests to alpine habitats, each providing different conditions to support the life of both plants and animals. In this region, there are at least 28,691 distinct georeferenced and documented species of Andean flora to date. The mid-altitude cloud forests are the most species-rich Andean ecosystems, containing around 10% of the world's vascular diversity while occupying only 0.6% of the land surface. [9].

The totora *(S. californicus*), also referred to as *Scirpus californicus*, is an aquatic macrophyte, bulrush, or reed plant found not only along the Andes in Ecuador but also across various species from Florida to Argentina, in Hawaii, Easter Island, and the Austral Islands, and naturalized in New Zealand. Within the Andean region of South America, it has been used as a raw material in the manufacturing and construction of boats, huts, as fuel, among other purposes. [10, 11]. It mainly grows in this sector above 2000 meters above sea level, where the temperature ranges from 12-16 °C and the annual precipitation is 400-1200 mm. [12, 13]. Additionally, within the same ecosystem, in Ecuador, it has been used as an artificial wetland for wastewater treatment, serving as an environmentally friendly and non-polluting technology. [14], and it has even been studied for its use in the bioremediation of aquatic ecosystems, surface waters, and the removal of contaminants in wastewater. [15]. The generation of bioelectricity through MFCs (Microbial Fuel Cells) and its integration with constructed wetland systems significantly improves the performance of wastewater treatment. [16], However, they have also demonstrated that the use of S. californicus flora increases electricity generation by 2.2 to 3.5 times, providing an improvement in P-MFC systems.

This latest type of technology derived from MFCs converts solar energy into bio-electricity through the interrelation between the plant and the microbe in the plant's rhizosphere region. [17].

It utilizes the plant roots to directly feed soil microbes at the anode through the excretion of rhizodeposits to produce electrons, which are then transferred through an external load to the cathode, thus generating bioelectricity. Its configuration involves a buried anode in sediments (planted), allowing for the (microbial) oxidation of reduced compounds, and a cathode in the overlying water. P-MFC is influenced by various conditions such as plant type, climate, lighting, temperature, humidity, and soil nutrient conditions, which cause variations in process performance. Therefore, the first step is to establish the system that would provide an initial energy: the microbial electrochemical system (MES) based on plant-mediated power (P-MFC) complemented with microbial oxidation to convert chemical energy into electrical energy through human intervention. [18], Given the first step, it is necessary to establish the foundations of electrochemical operation and its energy utilization source. Then, we can proceed with the study of energy generation from the selected plant species, the junco or totora (*S. californicus*), to observe the voltage values that this type of plant can generate. These data will serve as a basis for the subsequent design of an electronic voltage boosting system, capable of supplying power to a TTGO Lo-Ra T-beam communication board for long-distance data transmission.

2. Materials y Methods

2.1. Construction and Configuration of the P-CCMs

The simplest construction of a P-CCM consists of using non-catalyzed carbon materials for both the anode and cathode, while avoiding the use of expensive proton exchange membranes. There are several considerations to consider when building a P-CCM, such as the location of the anode, the distance between the anode and cathode, and the dimensions of the electrodes. In this research, a tubular model was employed, using polyethylene plastic containers with two lateral perforations and respective rubber stoppers to expose the electrodes. Both the anode and cathode are made of carbon fiber and are connected by a mesh (membrane) and stainless-steel wire to establish a connection between them. The monitoring of electricity generation was carried out by connecting the cables to a data acquisition device (DAQ), which is connected to a computer. Finally, the data is visualized through a front panel VI using National Instruments' LabVIEW software. The following illustration (Figure **1**) visually depicts the configuration used for each P-CCM. From the top, the totora plant can be seen in its natural ecosystem, down to the gravel substrate. The different dimensions employed in the P-CCM prototype are also shown.

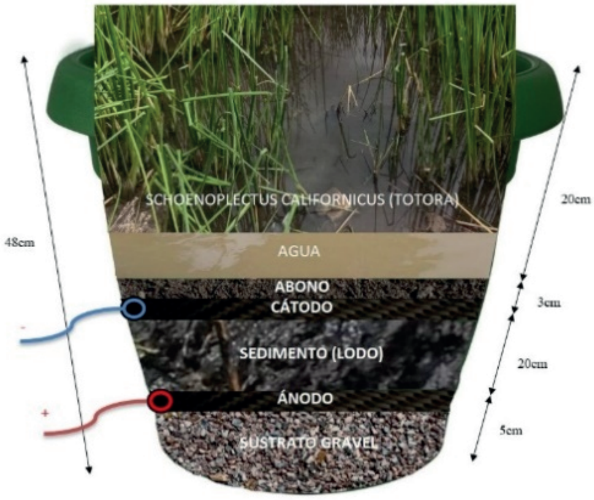

Figura 1

Configuration of a microbial fuel cell, using the plant species s. californicus.

1. The composition of each P-CCM is detailed as follows:
2. 1 kg of stones as gravel substrate, cut to an appropriate size to allow better porosity and plant stability.
3. 11 kg of mud or sediment obtained from its natural ecosystem, Laguna San Antonio, Riobamba (-1.650° S, -78.638° E), and the anode was placed.
4. 21 kg of sediment mixed with 1.5 kg of compost and placed on top of the plants (the reeds), and the cathode was placed around the plant.
5. The water section was filled with 8 liters of liquid extracted from the same lagoon.

2.2. Matrix Model of P-CCM Connection

It is necessary to combine the operation of each P-CCM into a plant system, based on the principle that they are variable voltage sources dispersed in a working area. Thus, a matrix of plants can be modeled, where each point represents a plant with a certain voltage and current output that, when combined, provides system stability for the required final load, which is 1.8 - 3.7V and a minimum current of 10 - 14 mA, as specified in the datasheet of the Lo-Ra TTGO T-beam module, a bidirectional long-range data communication module useful for various data logging applications incorporating IoT features into their working environment. Therefore, data collection of voltage generation was performed based on the configuration (Figure **2**), using the same configuration for a collection period of 30 days to observe the behavior of each P-CCM. The system (Figure **2**, left) shows the connection scheme of the 4 P-MMCs, including the data acquisition system, NI USB-6002 DAQ, and its visual interface designed through a front panel in LabVIEW.

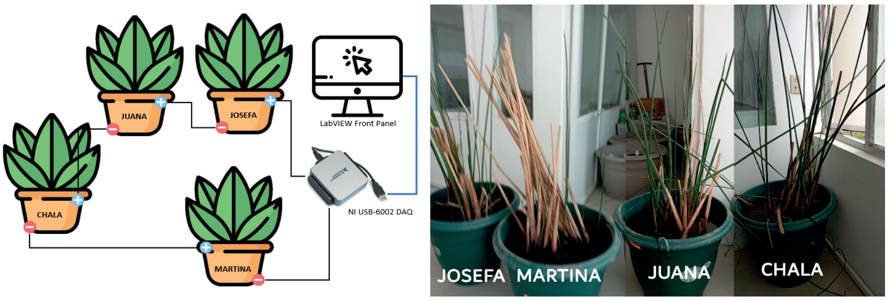

Figura 2

(Left) Matrix Connection Scheme of the P-CCM set. (Right) Actual connection of the plants in their simulated natural conditions environment.

As shown (Figure **2**, right), the various P-MMCs tend to settle according to their new tubular configuration in the containers and depend on various external factors such as solar illumination, relative humidity, oxygenation, among others, which determine the settlement and growth of the plant in a new unknown environment. It can be observed that the Chala P-CCM, located closer to the laboratory windows, visually exhibits better growth and color, while the Martina P-CCM appears to wither. The following section will analyze the results of the electrical generation of each plant and the matrix model of the system.

The configuration that was made for voltage data acquisition using a virtual interface (VI) in LabVIEW consists of a block diagram and a front panel (Figure **3**), where it is possible to observe voltage graphs over time, as well as a record of all the data in a calculation file. In the main panel, a DAQ assistant was used, which was calibrated for analog data readings from 0 to 3. The acquisition mode is set to single-point sampling, with an RSE configuration terminal to obtain values in discrete time.

It is worth noting that the LabVIEW Data Acquisition (DAQ) card allows for the acquisition of very small values expressed in millivolts from biological power sources. These cards have an input/output (I/O) interface that can be used to connect different types of sensors and measurement devices to a computer. The operation of a DAQ card starts with configuring the inputs of the DAQ card. Once connected, the LabVIEW

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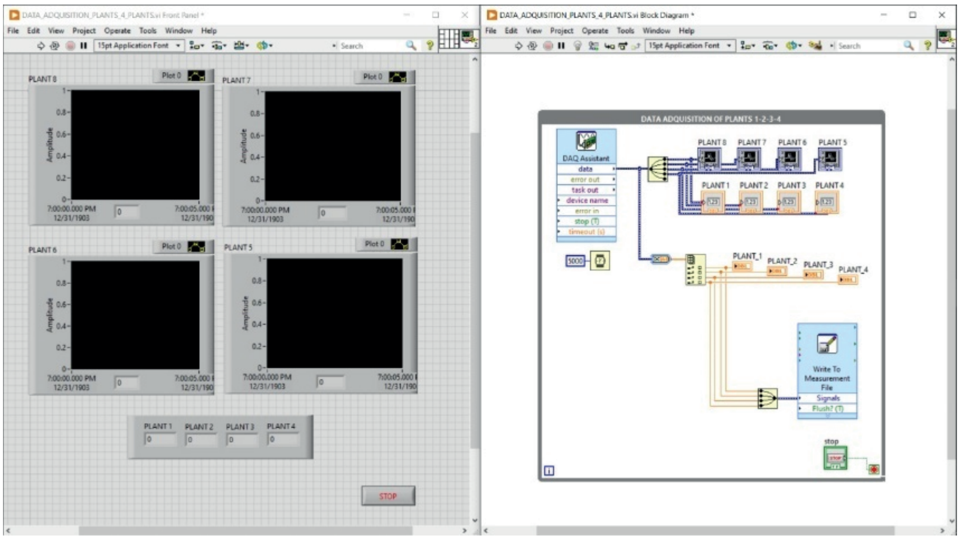

Figura 3

Front panel and block diagram of the virtual interface designed in LabVIEW for data acquisition and logging.

software recognizes the configured settings for data acquisition. The user can select the type of measurement to be performed, in this case, voltage and current measurement during sampling. It should be noted that the amount of information to be collected depends solely on the internal timing, as this control loop takes the value at a given moment x, which does not guarantee an accurate reading of the plant's state, as it tends to vary drastically due to its natural behavior. Therefore, the more voltage data available, the better the system, as it allows for a more thorough analysis of the plant's behavior and characterization of its electrical generation.

2.3. Design of the Boost-Type Converter

The Boost-type converter, also known as a step-up converter, is a powerful tool in power electronics that allows for achieving ideal voltage values according to the requirements. DC-DC converters with voltage boosting capabilities are widely used in a large number of power conversion applications, ranging from fractions of volts to tens of thousands of volts, and power levels from millivolts to megawatts. The fundamental elements for such circuits are inductors, capacitors, transformers, as well as switches and diodes.[19, 20].

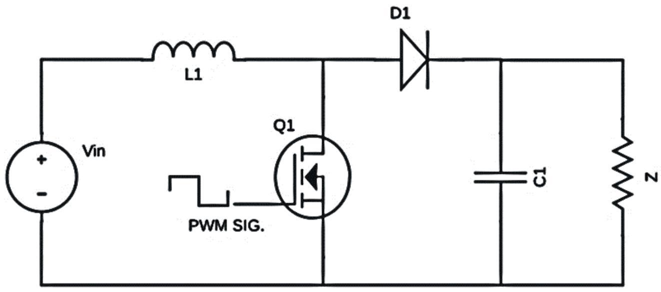

Figura 4

Basic diagram of a Boost-type DC-DC voltage converter.

2.3.1. Operating modes of the Boost converter.

The operation principle of this type of converter lies in its components, primarily in the ability of the inductor, L1, to store energy as a magnetic field. The purpose of the boost converter is to increase the voltage to a higher level than the input supply, and this depends on the duty cycle during the switching of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET).

Switched-On State: When the MOSFET switches to a closed state, the current flows from the power supply to the inductor, storing energy as a magnetic field. If the switching time is dT seconds, the change in current flow during the switched-on state follows the following equation, where Vin = input voltage [V], L = inductance [H], and i_L = inductor current. [A].

$$\frac{di_L}{dt} = \frac{V_{in}}{L} \quad (1)$$

Switched-Off State: When the switching opens, the current flow will be reduced as the impedance increases. The previously generated magnetic field will decrease, maintaining a current through the load Z, resulting in two voltage sources in series and causing an increase in the voltage across the load capacitor C1 through the forward-biased diode D1. When the open switching time is (1 - D)*T seconds, the variation in current flow during the switched-off state is given by the following equation, where Vo = converter output voltage [V] and D = duty cycle of the switching.

$$\frac{di_L}{dt} = \frac{V_{in} - V_o}{L} \quad (2)$$

Since the average voltage across an ideal inductor is zero, the following equation describes the voltage across the inductor during a complete cycle.

$$V_{L(prom)} = D * V_{in} + (1 - D) * (V_{in} - V_o) = 0 \quad (3)$$

Therefore, the output-to-input voltage ratio of the voltage boost DC-DC converter is given by the equation.

$$\frac{V_o}{V_{in}} = \frac{1}{1 - D} \quad (4)$$

Consequently, the duty cycle corresponds to the following expression, where t_{on} = ON switching time [ms] and T_s= total switching time [ms].

$$D = \frac{t_{on}}{T_s}, 0 \leq D \leq 1 \quad (5)$$

The duty cycle, or power cycle, is the fraction of a signal, commonly expressed as a percentage [%]. Furthermore, two important equations that allow us to approximate the value of the inductor and capacitor are explained below, where L_{min} = minimum inductor value [H], f = switching frequency [Hz], ΔV_o = expected variation in the output voltage [V], and C = capacitor value [F].

$$L_{min} = \frac{D(1 - D)^2 R}{2f} \quad (6)$$

$$C = \frac{D(V_o)}{Rf(\Delta V_o)} \quad (7)$$

2.4. Simulation of the boost converter in MATLAB using design values.

The design of the parameter/component values for the circuit shown earlier (Figure **4**) was performed using the described equations (Equations 1-7), along with the use of a simulation tool like MATLAB and specifically its virtual environment Simulink. The P-CCMs are connected in series (Figure **5**), and this voltage is fed into the simulated voltage boost circuit in Simulink, resulting in an output voltage with a time response.

2.5. General system diagram and Lo-Ra communication.

LoRaWAN is a low-power communication technology used for data transmission in low-power wide area networks (LPWAN). The communication takes place between end

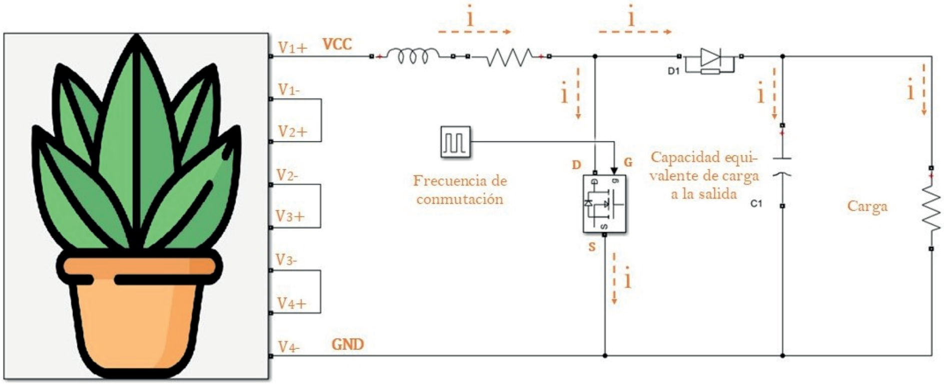

Figura 5

Simulation of the boost circuit, powered by 4 P-CCMs.

nodes and a gateway, where the end nodes are responsible for acquiring and transmitting data, while the gateway collects packets from the end nodes and communication link messages ACK. The architecture used to test the prototype in the laboratory consists of a sensor node and a gateway or base station. This architecture allows for more efficient data transmission and greater capacity for connecting IoT devices. Additionally, LoRaWAN technology offers longer battery life and greater coverage compared to other wireless communication technologies, making it an excellent choice for low-power IoT applications.

Based on the above premise, a test configuration was developed based on LoRa technology, which proposes a long-range communication system with low power consumption and sufficient data rate. The purpose is to demonstrate the practical utility of LoRa TTGO T-beam modules in practical environments such as remote monitoring, precision agriculture, meteorology, and others, which will be used for acquiring environmental data in conditions where direct electrical power availability is not present. In this case, the P-CCMs and the Boost converter will be responsible for supplying and storing the appropriate energy for stable and continuous self-sufficiency for the operation of the sensor node.

Consequently, a sensor node prototype was implemented to demonstrate this function (Figure **6**). LoRa utilizes spread spectrum modulation to ensure long-distance data transmission and operates in the license-free ISM bands of 433 MHz, 868 MHz, and 915 MHz. The LoRa module has a maximum transmission current of 14 mA, a maximum power of 100 mW, and a range of 10 km to 30 km, making it suitable for acquiring data from remotely deployed sensors.

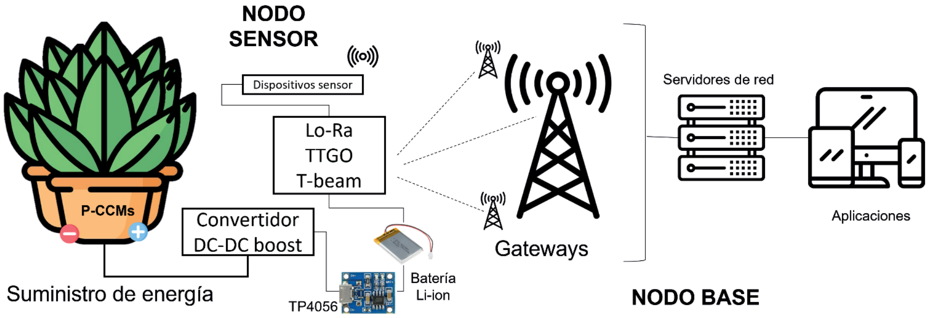

Figura 6

Diagram of the LoRa communication system powered by bioelectricity.

The first node is responsible for data acquisition and transmission, while the second node is responsible for collecting all packets from the end nodes as well as communication link messages ACK. The architecture used to test the prototype in the laboratory consists of a sensor node and a gateway or base station.

3. Results and Discussion

3.1. Voltage Generation of P-CCMs

The acquisition of voltage values produced by each of the P-MMCs during a 30-day period in the simulated natural conditions environment is summarized below (Table I).

Tabla 1

Voltage Values of Each Plant, in a 30-day Sampling, under the Same Laboratory Climatic Conditions.

Data/Plants	Chala [V]	Juana [V]	Martina [V]	Josefa [V]
Avergae	0.765	0.242	0.193	0.192
Maximum Value	0.88	0.286	0.421	0.728
Minimum Value	0.598	0.194	0.0715	0.056

From this collected and analyzed information, it can be deduced that the average sum of maximum voltages is 2.315 V and of minimum voltages is 0.9195 V, resulting in an average value of 1.62 V supplied by the laboratory plants. This value is the primary parameter for designing the boost circuit, as the minimum power requirement for the TP4056 module is 3.75 V ~ 4.25 V for battery charging to occur. It should be considered that the plants are in individual environments simulating their ecosystem, with time differences from the adaptation period to the new environment, which prevents them from achieving their full electrical potential as their photosynthesis process is interrupted due to adaptation to the new surroundings.

The behavior (Figure **7**) during the sampling time of approximately 2×10∧6 seconds shows how the voltage generation varies over time, indicating that CELL 1 (P-CCM Chala) generates the highest amount of voltage, followed by CELL 2 (P-CCM Juana), CELL 3 (P-CCM Martina), and finally CELL 4 (P-CCM Josefa), which shows an increase towards the end of the sampling period due to better adaptation to the simulated natural environment.

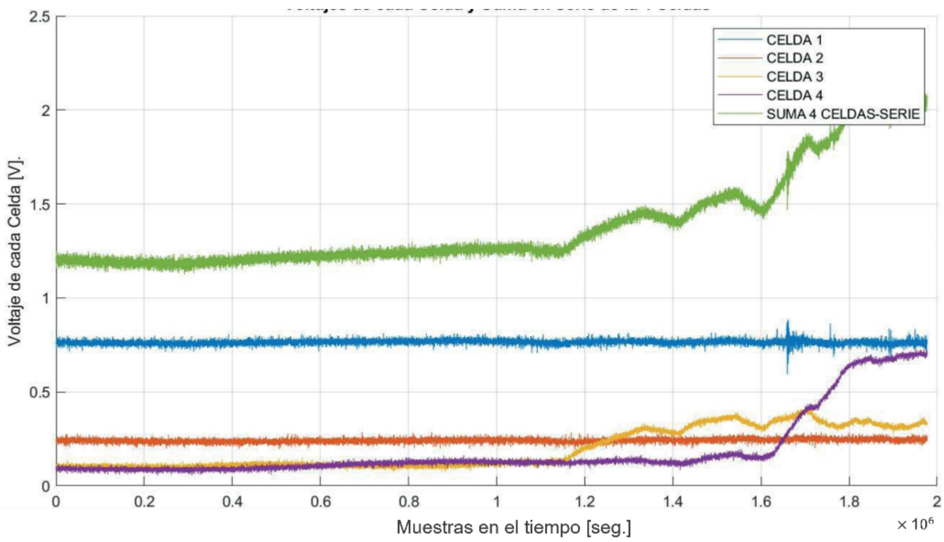

Figura 7

Voltages of each P-CCM and series sum of the 4 cells.

3.2. Boost Converter and Simulation Responses

There is a strong need to power loads that exceed the values obtainable from the original source. To achieve this, it is necessary to use electronic mechanisms that can increase the initial values by certain proportions. In this case, we used a ratio of approximately 1:3, which leads us to analyze the duty cycle of the PWM signal or square wave pulse (Figure **8**).

Considering the power consumption levels of the load, Lo-Ra TTGO T-beam module, a supply voltage between 1.8 - 3.7 V, a working current consumption between 10 - 14 mA, and a transmission current of 120 mA @ +2 dBm, we can obtain the values of the theoretical load by converting dBm to real power [W]. These calculations result in the design parameters (Table II), obtained using the described equations.

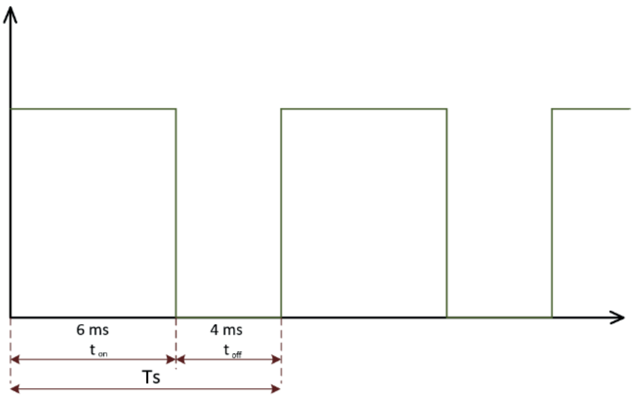

Figura 8

Duty cycle of the switching signal, with D = 60%.

These values were brought into the simulation environment, yielding the following results. For both graphs (Figure **9**), we have the system response represented by voltage and current, respectively. In both cases, we can observe system stabilization, suggesting an immediate response without the presence of disturbances that would cause the curve trajectory to enter areas that could damage the load module and shorten its lifespan. In the parameter and value list (Table II), there is a theoretical consumption of 4 to 7 ohms. To get a better view of the behavior, we proceed to capture the stabilization curve on the oscilloscope to determine its behavior in data transmission.

Tabla 2

Design parameters of the boost DC-DC converter for simulation purposes.

Parameter Value	Valor
Input voltage (Vin)	2 V.
Duty cycle (D)	0.6
Inductor (Lmin)	0.28 μH
Capacitor (C)	3.5 μF
Load resistance (R)	7 Ohms.
Switching frequency (fs.)	1.2 MHz

When using this type of voltage boost circuits, there is a risk of not being able to control the output voltage since it solely depends on the input voltage (Equation 3).

There is an underlying problem (Figure **9**) where it is clearly observed that there is no constant voltage since it varies according to the biochemical conditions present in the CCM reaction. Therefore, it is essential to have feedback on the input voltage to achieve stability in the system and maintain a constant value at the converter's output. The MT3608 module offers a feedback input on its third pin. The FB voltage is 0.6V. The MT3608 automatically switches to pulse frequency modulation mode with light

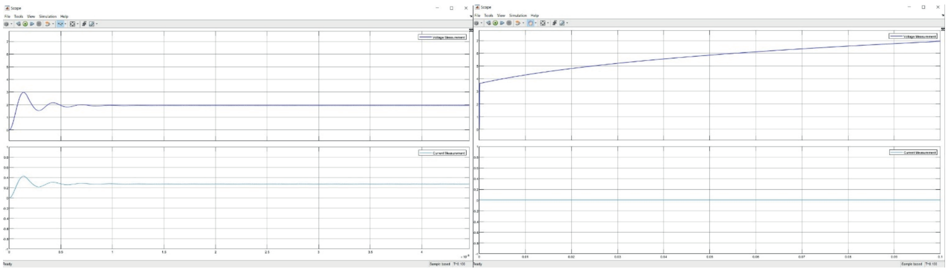

Figura 9

Current and voltage response in the simulation without load, ideal conditions, and maximum values (Right), simulation with load, ideal values, and maximum values with respect to the output graphs.

loads, including undervoltage lockout, current limiting, and thermal overload protection to prevent damage in case of output overload (Figure **10**).

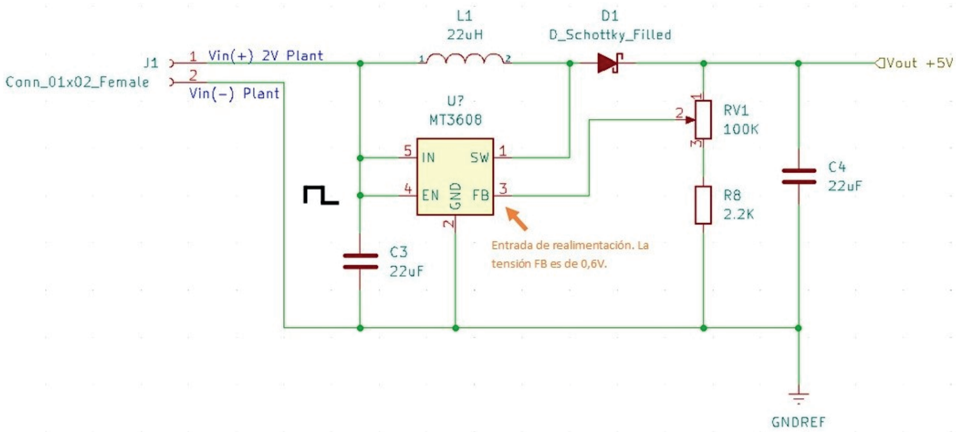

Figura 10

Schematic of the boost converter module with the MT3608 IC.

Obtaining the final design that includes the boost converter, the TP4056 battery charging module, the 3.7V and 1000 mA Li-ion battery, and the Lo-Ra TGO T-beam communication module (Figure **11**).

The LoRa TTGO T-beam module is a compact development platform that integrates multiple components, making it ideal for creating end nodes for IoT applications. The use of the ESP32 development board allowed for easy programming and seamless integration with other modules. Additionally, the Sx1278 radio frequency module enabled long-distance communication and low power consumption, which is crucial for applications requiring extended battery life.

The inclusion of the DS18B20 temperature sensor and GPS enabled the acquisition of precise real-time data on location and temperature, which is important for a wide

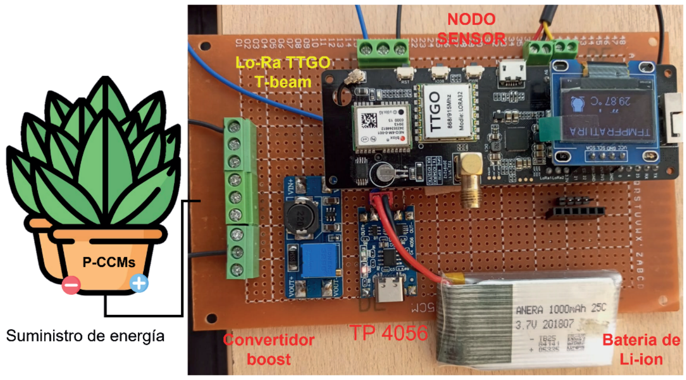

Figura 11

Final design of the power supply circuit and sensor node.

range of applications. The configuration of the end node was done using the Arduino Integrated Development Environment (IDE), which is a widely used open-source programming platform with a large community of developers. In conclusion, the utilization of this development platform and the inclusion of multiple components allowed for the creation of a highly functional end node for LoRaWAN application, which is crucial for the successful implementation of IoT projects.

4. Conclusions

This research investigated the behavior of microbial fuel cells (MFCs) using the *s. californicus* species as the flora, due to its high presence in the Andean paramo and the need to collect and store information and meteorological data in these locations efficiently and in a modern way. While MFCs represent an innovative and promising technology for electricity production, a larger number of P-MFCs is required to increase energy production. Current research in this field is focused on improving the efficiency and stability of MFCs, as well as optimizing operating conditions to maximize their performance. However, as advancements are made in these areas, it will be necessary to increase the number of MFCs in operation to obtain larger amounts of electricity. In summary, although MFC technology is very promising, further research and development are needed to harness its full potential and achieve significant energy production.

Additionally, the P-MFC system can be optimized in terms of volume and reactive capacity of bacteria to produce larger quantities of electrical energy with better prospects. The ratio between organic and dead matter can be improved through selective pruning to achieve the highest amount of root-based organic matter. Standardizing the applied microbiome in each container could include measures of biological control to ensure stable and healthy growth of the microscopic agents necessary for energy generation and microbiological processes. The anaerobic model approach could yield better results by specializing in facultative and extreme anaerobic species, potentially leading to a power upgrade in energy production. A broader and interdisciplinary study is needed that includes research on various external factors that influence both the healthy growth of the plant and subsequently a greater synthesis of electrical energy.

Therefore, the MFC system has great potential for generating electrical energy from organic matter. To maximize its efficiency, it is necessary to optimize the system in terms of volume and reactive capacity of bacteria, allowing for greater amounts of electrical energy production. Selective pruning and standardization of the microbiome in each container are key strategies to improve the proportion of organic matter and ensure healthy growth of microscopic agents. The specialization of facultative and extreme anaerobic species can further enhance energy production. The use of this energy in any low-power direct current consumer electronic system is highly beneficial, especially in situations where access to the electrical grid is limited or when significant financial investments are required for other unconventional energy alternatives. Therefore, this MFC-based bioelectricity generation system promises to be a power source for wireless data transmission devices with low-power consumption protocols.

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Conflicts of interest

We declare that there are no conflicts of interest that could influence the results of our research. We have not received any funding or compensation from any entity that may have a direct or indirect interest in the results obtained in this study. We also have no personal, professional, or financial relationships with any entity that may have an interest in the research results. Thus, we can guarantee the integrity of the data and results presented in our publication.

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