Bioenergy production of fuel cells using *Aloe barbadensis* influenced by calcium and associated with lithium batteries for residential use

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Abstract*– The Plant Microbial Fuel Cell system is observed as a very effective alternative, having an obvious advantage over the application of conventional electrodes. However, only 16.7% of the authors propose as an innovative alternative to explore the implementation of charcoal-based electrodes for greater efficiency. Likewise, 25% of studies agree that the use of plants in plant microbial fuel cells whose climatic conditions by nature involve semi-arid climates have greater resistance to adverse physical and chemical variations. While those of tropical origin have an advantage in generating greater bioenergy due to their physical characteristics. The objective of the study is to analyze and measure the influence of the calcium micronutrient on the Aloe barbadensis species, in the production of electrical energy of a CCM-V, additionally implement a lithium battery system in the residential location and evaluate its performance. To fulfill this purpose, the appropriate organism must be selected, suggesting the implementation of CAM plants. Additionally, an increase in efficiency of 29.1% of bioelectricity production is guaranteed by controlling factors such as nutrients, pH, conductivity, temperature, salinity, COD, radiation and C/N ratio. In this way, high productivity rates will be obtained in the CCM-V. In addition, managing to improve the system proposal by monitoring calcium levels to increase efficiency in the development of the energy activity proposed by the study organization.

Keywords: Bioenergy, micronutrient calcium, Aloe barbadensis, lithium battery.

I. Introduction

According to the United Nations, globally about 800 million people do not have electricity [1]. This entails social, economic and environmental gaps. It worsens in the Southern Hemisphere, standing out with the highest rate of energy poverty: Africa and Latin America. Furthermore, the Economic Commission for Latin America and the Caribbean (ECLAC) established that around 28.6% of the population of Central America did not have access to electricity While in South America, Peru stands out with an index of 18% [2].

Also, energy instability is a cause for concern in countries such as Peru and Chile, which have the longest duration of supply outages between 3 to 6 hours per month, especially in rural areas [3].

The electrification gap in Peru has decreased. According to the National Institute of Statistics and Informatics, homes suffer from constant electricity outages [4]. Likewise, around 34.2% suffer from electrical interruptions in public lighting [5].

On the other hand, the Disaster Risk Prevention and Reduction Plan (PPRRD) of the district Municipality: 3.15% of homes do not have lighting and according to surveys, 76% suffer from outages. Among the most vulnerable areas to electrical suspensions is Pamplona Alta, San Juan de Miraflores [6].

The area is subdivided into 3 sectors: Pamplona Alta, La Rinconada and La Nueva Rinconada. The latter stands out for its high level of danger from urban fires. It should be noted that this problem intensifies in high-risk and poverty areas, such as human settlements. A specific case deals with A.H. José Olaya located in Sector A of Nueva Rinconada. Homes have access to electricity but public lighting is insufficient. In detail, the topography is characterized as an area with a moderate slope between 15 to 35°. Its climate is desert type so the average temperature ranges from 17°C to 19°C. Although it is made up of 2 blocks, 75 people live there. They have poor basic services such as drainage and energy. Indeed, electrical connections increase the risk of fires [7].

On the other hand, in 2015, the Paris Agreement was adopted during the United Nations Climate Change Conference, establishing a global framework to reduce greenhouse gas emissions and driving the transition of the global energy matrix towards affordable, renewable energy sources and accessible [8].

That is why, given this national problem, the external factors that influence the application of bioenergy have to be evaluated to guarantee its effectiveness and to prevent violations of Ley N° 28832, law to ensure efficient development during electricity generation [9].

In Peru, the Ministry of Energy and Mines (MINEM) continued with the rural electrification program in 2023 to guarantee full access to electrical energy in the peripheries, achieving 85.8% coverage in these areas [10].

In this regard, the System Economic Operation Committee (COES) estimates an investment to expand the electricity supply in Peru of more than 1.13 million dollars between 2023 and 2032 [11].

However, the geographical location on a slope, the absence of approved urban planning plans and/or possession certificates limit them. According to the Municipality of San Juan de Miraflores, Nueva Rinconada is a recent invasion, poor and difficult to access. Family income is between 264 and 1200 soles. So that 38% of

households are of low-medium socioeconomic level and 9% are low [12].

Indeed, in 2021 OSINERGMIN states that energy expenditure is 100 soles for 113 kWh per month, which determines the accessibility of the service. In the technological field, worldwide the electricity generation matrix comes 61% from fossils [13].

Moreover, electrical energy is distributed to users by Luz del Sur, ENEL and Electro Dunas. In San Juan de Miraflores, only Luz del Sur is a distributor. However, due to the low quality of the service, alternatives such as energy through photosynthesis are being explored [14].

Otherwise environmental impact includes greenhouse gas (GHG) emissions from the conventional energy sector, fossil fuels. ECLAC mentions that GHGs of the energy sector represented around 3,064.6 Mt CO2eq in 2020 [2].

Also, according to Vinyl Council Australia, common PVC cables in electrical installations can cause fires without proper maintenance [15]. This releases emissions that negatively impact air quality and the environment. In Peru, 37,584.04 GgCO2eq were emitted: 71.08% CO2, 28.46% CH4 and 0.46% N2O of the Ministry of the Environment [16].

For this reason, at peruvian territory there is a National Electric Code named CNE, it covers rules and regulations for generation, transmission, distribution and commercialization [6].

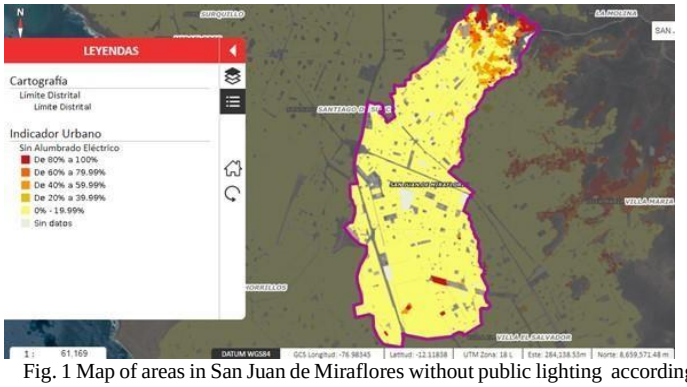

Fig. 1 Map of areas in San Juan de Miraflores without public lighting according to their percentage. Taken from the National Georeferenced Data Platform by Geo Perú, 2024.

Energy security

It corresponds to the capacity of a territory to satisfy demand continuously without interruptions. This entails the conservation of the integrity of the electrical infrastructure [17]. It also includes guaranteeing equitable access to electrical services in quantity and quality [18]. Consequently, energy security allows social and economic development. However, according to Echegaray, in Peru this is only considered an indirect threat to national security. In fact, energy insecurity leads to poverty. An example of this is shown in one type of need: lighting [19] Without it, society cannot satisfy its basic needs. Therefore, energy security is essential to offer resilient services where minimum standards and guarantee of a constant supply are met [18].

Energy transition

Model based on reducing dependence on the consumption of fossil fuels for electricity generation and increasing zero carbon sources. Likewise, it is considered as a tool to mitigate CO2 emissions in the energy sector [19]. Indeed, it seeks to sustain the energy demand of industries using clean energy that promotes economic growth [20].

Bioenergy

It deals with solar energy stored in plant products from chemical reactions. It guarantees energy security and reduces the emission of greenhouse gases. Therefore, it is a sustainable alternative and captures C [21]. There are two types of use: traditional and modern. The first refers to the combustion of biomass. Secondly, there are technologies based on plants or organic waste. In both cases, bioenergy produces low carbon emissions [20].

Microbial-Vegetable Fuel Cell (CCM-V)

As Patel mentioned, the fuel cell consists of static generation converters. In this way, they transform chemical energy into electrical energy. They generally represent an efficiency of 80 to 85%. Its composition consists of an anode, cathode and an electrolyte. In more detail, the electrolyte transmits the hydrogen ions and electrons from the chemical reaction. These reactions arise from photosynthesis [22].

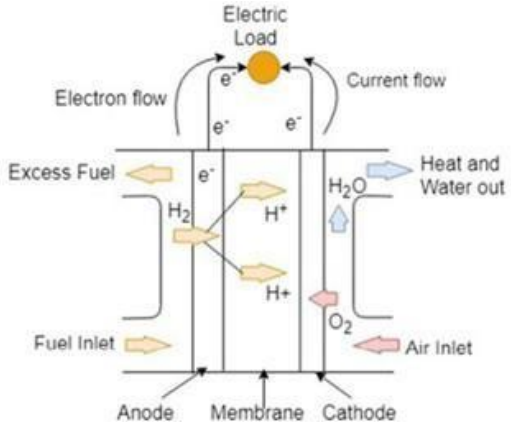

Fig. 2 Basic structure of a fuel cell. Retrieved from Intelligent Systems Reference Library by Patel et al., 2020, Springer.

This bioreactor takes advantage of the metabolic activity of the rhizodeposition process of organic matter from photosynthesis. In fact, the root system excretes compounds.

Microorganisms then use them as a substrate for metabolization. Consequently, they release CO2, protons and electrons [23]

In greater detail, according to Gupta for the generation of electric current, the biofilm catabolizes the substrates in the absence of oxygen and the electrons are captured in the anode. Finally, the electrons reduce the molecular oxygen at the cathode [24].

On the other hand, there are two types of CCM-V configurations. In the first instance, the tubular design contains an anode that surrounds the cell covered by a membrane. The cathode is located in this structure. However, this arrangement presents high resistance so there are more losses. Secondly, the flat plate consists of an anode and cathode where the distance is minimal. Only an ionic membrane separates them [23].

So, there are various cell modeling. One of them deals with a single population and a cell where the transfer of electrons can be direct or indirect. On the other hand, cells with two populations and one cell evaluate more parameters. This highlights the control of microorganisms and the degree of water absorption. Finally, the two-cell, one-population mechanism oxidizes the substrates at the anode and generates protons [22].

Electrode

Surfaces where semi-reduction or oxidation reactions originate. If they do not have any reaction, they are considered inert [25]

Cathode

That electrode in which reduction occurs when electrons are gained. The material is a significant factor that decides the performance of the system in an open circuit potential voltage. For this reason, it is suggested in the case of cells to use electron sectors such as hydrogen as phosphate, oxygen and magnesium. In fact, it must have high conductivity and resistance [22].

Anode

Electrode that produces oxidation when electrons are lost. In particular, the bacteria in this cell generate protons that are transferred to the external circuit to allow the flow of electrons. Additionally, in CCM-Vs, the anodes must transfer the material, so they must be highly conductive and non- corrosive like graphite [22].

Photosynthesis

Physicochemical biological process where plants use solar energy to synthesize organic compounds naturally. In other words, there is a transformation of solar energy into chemical energy to store it [26]. This phenomenon originates from chloroplasts, whose role is to capture light using their pigment called chlorophyll [27]. In detail, photosynthesis is made up of two stages: Light Phase and Dark Phase.

Light phase

Sunlight hits the chloroplasts, where chlorophylls transform energy into chemicals. Then, the H2O molecule breaks down to release O2. This way, around 4H+ are used. Where they will finally originate the ATP molecule that stores energy. It should be noted that when a molecule absorbs the photon, it also loses an electron. It is transported through the electron transport chain where it produces NADPH and ATP. Finally, chlorophyll recovers the electron and breaks the bond of the water molecule resulting in an oxygen molecule [28].

Dark phase

Energy from the light phase is used to synthesize glucose from H2O and CO2. In this case, the incidence of sunlight is not needed, so the rubisco enzyme captures CO2 during the Calvin cycle and uses NADPH and ATP. Thus, it releases three-carbon sugars that can result in the formation of glucose [28].

CAM plants

They are plants that fix carbon dioxide during the night. In more detail, this substance is fixed in the form of organic or malic acid. During the day the plants absorb light but the stomach remains closed. Therefore, the acids leave the vacuoles and supply CO2 to the chloroplasts to start the Calvin cycle. Their main characteristic is that they lose less water through their stomata [29].

In fact, aloe vera is considered a CAM or Crassulacean Acid Metabolism plant that prevents water loss through transpiration. The species presents this characteristic due to its ability to adapt to biotic and abiotic stress [30].

Aloe Vera - *Aloe barbadensis*

A succulent plant whose size ranges from 80 to 100 cm in height when it matures after 6 years. It is estimated that the lifespan is almost 50 years. Likewise, due to its conditions as a CAM plant, it can survive extreme temperatures. For this reason, it has the characteristic of having turgid, rosette- shaped leaves. In fact, its composition is 55% polysaccharides, 17% sugars, 16% minerals, 7% proteins and 4% lipids [31].

Coulumbic efficiency

According to Ramos Pérez Egaña, the degree of energy efficiency is determined within a plant microbial fuel cell. In this sense, the greatest quantity of those electrons that are recovered as electric current by rhizodeposition is called coulumbic efficiency. This is how, the higher the index, the greater the production of electricity. Therefore, the

percentage of electrons that are effective on the substrate, that is, that passed through the electrode, determine the index [32].

Calcium micronutrients

The growth and productivity of plants lies in adequate mineral nutrition. This requires a healthy soil with an adequate pH and availability of nutrients. In this way, it manages to absorb them through the root system. In particular, calcium is essential to strengthen the individual and protect it during its growth. In fact, these ions activate protein kinases so chemical reactions increase. Otherwise, its deficiency can cause cell death since water transport is obstructed [33].

Lithium ion battery

Storage systems that accumulate and discharge energy are essential for energy security. Indeed, there are various species with a wide variety of efficiencies. According to Huang those composed of lithium metal can reach a Coulomb efficiency of up to 99.7%. Consequently, it is classified as high energy density equipment. Another benefit is its durability that reaches 700 cycles [34].

Therefore, the objective of the study is to analyze and measure the influence of the calcium micronutrient on the *Aloe barbadensis* species, in the production of electrical energy of a CCM-V, additionally implement a lithium battery system in the residential location and evaluate its performance.

II. Methodology and Results

Study population

According to the Municipality of San Juan de Miraflores, the A.A.H.H. José Olaya, located in Pamplona Alta, has a total of 75 inhabitants [7].

Sample Size

To determine the representative sample size, the following equation was used as Hernandez-Sampieri [35].

$$n = \frac{N \cdot Z^2 \cdot p \cdot q}{(d^2 \cdot (N-1) + Z^2 \cdot p \cdot q)} \rightarrow (1)$$

$$n = 62.89$$

n = sample size
N = population size = 75
Z = confidence level = 95% = 1.96
p = probability of succes = 50%
q = probability of failure = 50%
d = margin of error de 5%

Surveyed population

With the objective of verifying the existence of the energy vulnerability problem in the town of Pamplona Alta, in San Juan de Miraflores, a field visit was carried out. It was decided to collect data through surveys, in which clear and simple questions were used, related to key aspects of the study variables. The objective was to know the perception of the inhabitants of the area, regarding the quality and stability of the electrical system, as well as the obstacles they face in relation to it.

The variables considered in the questionnaires were: access to electricity, frequency of power outages, electricity rate per month, replacement material for electric light, presence of fires.

TABLE I
ACCESS TO ELECTRICITY QUESTIONARY

Variable	Options	N° Population
Access to electrical energy	yes	55
	not	8
Frequency of power outages per month	1 to 3	48
	4 to 6	15
	6 to 9	0
Electricity rate per month	1 to 50	20
	50 to 100	26
	100 to 150	17
Replacement material for electric light	charcoal	19
	wood	30
	candle	14
Have you seen fires in the area?	yes	43
	not	20

Regarding the results obtained from the surveyed population, it is recorded that 87% of the total has access to energy service, while 13% lacks it. On the other hand, 76% of the inhabitants surveyed claim to suffer from power outages with a frequency of 1 to 3 times a month, and 24% 4 to 6 times. Regarding the monthly electricity rate, most of the respondents, that is, 41%, consume an average of 50 to 100 soles, likewise, 32% have a consumption of 1 to 50 soles, while 27%, Pay between 100 to 150 soles. Now, referring to the most used material for replacing electric lights, it can be seen that 48% of residents surveyed use firewood as fuel, while 30% prefer to use candles, and only 22% use coal. Finally, regarding the variable presence of fires, 68% of respondents claim to have witnessed fires, while 32% indicate they have not witnessed any.

Interview with expert

To enrich this research work, it was decided to seek an expert perspective, carrying out three interviews with Juan Carlos Barbaran, electrical engineer, Pedro Gamio Aita, lawyer, Master in public policy management and Former

Vice Minister of Energy of Peru, and with Aracelli Ramos Pérez- Egaña, environmental engineer, Expert in Technical Assistance to the Sustainable Business Program of the European Union in Peru. The meetings were developed after coordination of the availability of the expert, through the virtual platform Google Meet. Their valuable contribution has allowed us to deepen key aspects in relation to the specific objectives of the study, providing an encouraging overview of the relevance and validity of the work.

Scope Suitability Assessment

How relevant is this type of project in the chosen field?

After discussing with members of "Plantalámparas" project, developed in the department of Ucayali during his university years, at the University of Engineering and Technology (UTEC). The importance of these projects lies in their potential to contribute to the fight against energy poverty, while promoting a transition towards a more sustainable and accessible energy matrix. In the context of the research work, the town of Pamplona Alta presents an evident energy vulnerability, which is why the implementation of the project is justified, since it offers a sustainable solution to combat the problem.

Information Accessibility Assessment

What type of information will be required for a successful implementation?

In relation to technical information, it is necessary to obtain data on the plant species implemented, its characteristics and development in relation to the climate and availability of water in the study location, the optimal dosage of micronutrients selected for improve system performance. In this regard, engineer Aracelli Ramos mentions that one of the limitations of microbial plant fuel cells is that in Peru it is not a highly studied technology. However, abroad there are many successful studies where the cells have various applications for water and soil remediation, in addition to electricity generation. Likewise, lawyer Pedro Gamio suggests reviewing the regulatory framework for renewable energies and the General Environmental Law. Additionally, consult current regulations on hazardous solid waste, which includes disused batteries, to draw up an appropriate final disposal plan.

Information Feasibility Assessment

Is the implementation of a CCM-V feasible in the town of Pamplona Alta?

The implementation of a plant microbial fuel cell (CCM-V) in Pamplona Alta is feasible, since the background of the application of this technology is supported by current and proven information. So, by adapting the methodology and technical conditions to the specific study environment, the proposal will effectively contribute to solving the energy problem in the area. In addition to this, lawyer Pedro Gamio characterizes the town of Pamplona Alta as an area with high solar radiation seven months of the year, so there is potential to apply renewable technologies that require solar energy. However, the social factor is important. "People want to see not only that the project works but also that energy costs are reduced. One option for this is converting the system to hybrid with solar panels," he says. Finally, engineer Aracelli Ramos highlights the community as a place constantly exposed to energy insecurity, which is why research within the framework of renewable energies is feasible to address the problem.

III. Conclusions

Pamplona Alta is a potential area to implement technologies related to bioenergy. Specifically, the production of electricity with plant microbial fuel cells can reduce their electric vulnerability and promote a stable connection. Therefore, it is necessary to investigate the application of these technologies. Even more in developing countries, since the problem is highly notable. Also, they the disponibility of biomass is an advantage.

Finally, as Master Gamio and Engineer Ramos confirm, exploring alternatives to reduce the carbon footprint of the electric sector is necessary. Consequently, the implementation of our resources to produce energy is a tentative technology. Additionally, to guarantee the effectiveness of this resource the system may include batteries. At last, microbian activity when you add substrate can increase electricity production. So it is necessary to investigate and explore more about the application of this fuel cells.

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