Design and Implementation of Smart Gardens for Bio-Photovoltaic Energy Generation as a Sustainable Alternative in Pucapuquio - Peru

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Abstract

This paper presents the design, implementation, and evaluation of a hybrid energy generation system that integrates bio-photovoltaic and conventional solar components within smart garden prototypes, intended for rural communities with limited access to electricity. The project is centered in Pucapuquio, Peru, and explores the use of native plants and soil microorganisms to generate bioelectricity via electrodes embedded in a controlled garden system. The prototype incorporates copper and aluminum electrodes, humidity and temperature sensors, and a microcontroller-based regulation unit to manage energy capture and storage in lithium battery banks. A supplementary 12V photovoltaic panel enhances energy availability. Experimental results with Sansevieria trifasciata showed voltage generation ranging from 0.39V to 0.82V during daylight hours. A second prototype, featuring six plants and a modular CAD-based design, is currently under construction to evaluate scalability. The system is modeled using both black-box and white-box diagrams to visualize energy and data flow, offering an educational and replicable framework. This work demonstrates the potential of bio-photovoltaic systems as a clean, low-cost, and decentralized energy alternative for remote regions, contributing to the global transition toward sustainable energy solutions.

1 Introduction

In recent decades, the global energy sector has witnessed a substantial transformation driven by increasing awareness of environmental sustainability, the urgency to mitigate climate change, and the critical need for energy access equity. Renewable energy technologies, characterized by minimal environmental impact and sustainable resource use, have emerged as indispensable alternatives to traditional fossil fuels [1]. According to the International Renewable Energy Agency [2] (IRENA), renewable energy accounted for approximately 30% of global electricity generation in 2022, highlighting its increasing global significance. Among these technologies, bio-photovoltaics (BPV) stands out as an innovative and promising approach, leveraging biological processes in living organisms, particularly plants and soil microbes, to generate electricity directly through photosynthetic and metabolic processes [3].

Bio-photovoltaic technology exploits the natural interactions between plants, microorganisms, and electrodes to harness electricity produced during photosynthesis and metabolic decomposition. This biological-electrochemical synergy presents significant advantages, such as low environmental impact, minimal operational costs, and the potential for decentralized applications [4], particularly beneficial for rural areas lacking conventional electricity infrastructure. According to a study by the World Bank, approximately 759 million people worldwide still lack access to electricity, primarily concentrated in rural areas of sub-Saharan Africa and South Asia [5].

Concurrently, the concept of smart gardens has evolved, integrating sensor technology, automated control systems, and data-driven management practices to optimize plant growth, resource use, and energy efficiency. Smart gardens employ advanced sensors to monitor environmental parameters, including humidity, temperature, soil moisture, and luminosity, facilitating precise, automated responses that enhance plant health, productivity, and energy generation efficiency [6].

The intersection of bio-photovoltaic systems and smart garden technology presents a novel opportunity for sustainable rural electrification [7]. Rural communities often face significant challenges due to limited or absent access to centralized power grids, affecting their economic development, educational opportunities, and overall quality of life. Renewable energy systems, particularly decentralized solutions, offer practical pathways to address these gaps effectively [8]. For instance, in Latin America, approximately 15 million people remain without access to reliable electricity, highlighting the regional urgency for decentralized renewable solutions [9].

Integrating BPV technology into smart gardens creates a synergistic system capable of sustainable energy production while simultaneously supporting agricultural productivity and ecological sustainability [10]. In particular, such integration is especially suited to remote and underserved regions, allowing communities to leverage locally available biological resources native plants, soil microorganisms, and abundant sunlight to produce clean, renewable electricity [11].

The project implemented in Pucapuquio, Peru, illustrates this integrative approach, employing local plant species and microbial populations in a carefully engineered garden environment equipped with bioelectric electrodes, solar panels, and smart sensor technology. Peru, a country with significant disparities in rural energy access, provides an ideal setting for such innovative solutions. According to the National Institute of Statistics and Informatics (INEI), around 7.8% of Peruvian households lacked access to electricity in 2022 [12], primarily affecting rural and remote communities. Additionally, Peru's renewable energy potential remains largely untapped, with significant opportunities in solar, wind, and bioenergy resources. This project aims to address the approximately 500,000 rural residents still without reliable electricity access, developing a self-sustaining, low-cost, replicable model for rural energy autonomy, promoting not only electricity generation but also environmental education, community resilience, and socio-economic development.

This paper aims to detail the design considerations, technological integration, and experimental validation of the proposed bio-photovoltaic smart garden system, underscoring its potential to significantly contribute to sustainable rural electrification and renewable energy proliferation in similar contexts worldwide.

2. Methodology

The project follows the methodological guidelines proposed by the VDI 2206 framework, specifically designed for systematic development and integration in complex interdisciplinary projects. The V-model from VDI 2206 emphasizes a structured, iterative process that moves from conceptual requirements to detailed implementation, followed by systematic integration, verification, and validation of the final product.

Initially, comprehensive requirements were gathered based on community surveys and field observations in Pucapuquio. Specific considerations included environmental sustainability, availability of local biological resources, ease of maintenance, scalability, cost-effectiveness, and technological accessibility for rural inhabitants.

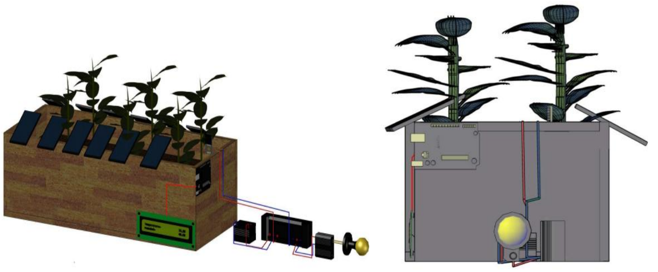
Following the VDI model, detailed domain-specific designs were developed, incorporating multidisciplinary expertise:

- Mechanical Engineering: Design of physical structures including the garden beds and protective casings using locally sourced, sustainable materials such as wood and insulating foam (technopor).
- Electrical Engineering: Selection and configuration of electrodes (aluminum as anode and copper as cathode), solar panels (12 V), lithium polymer battery storage systems, and DC-AC inverters.
- Information Technology: Implementation of IoT (Internet of Things) sensors (humidity, temperature, and luminosity) and Arduino-based microcontrollers to automate and optimize the energy harvesting and monitoring processes.
- Natural Sciences: Selection of appropriate plant species (Sansevieria trifasciata) and microbial communities compatible with local climate and soil conditions to maximize bioelectric generation efficiency.

Figure 1 and 2 shows the Computer-Aided Design (CAD) and flowchart that were developed to visualize the physical layout of the smart gardens. Furthermore, functional system modeling was carried out using both black-box and white-box approaches to clearly define energy flows, control logic, and component interactions within the bio-photovoltaic system.

In Figure 1, the CAD representation provides a tangible overview of the system layout, making it easier to identify the connection between the biological components (plants and soil) and the technological elements (sensors, cables, and converters). It also facilitates planning the spatial layout for actual implementation.

In Figure 2, the diagrams illustrate both the functional dynamics and procedural framework of the bio-photovoltaic system. The left diagram outlines the pathway of bioelectrical energy, beginning at the root-soil interface and progressing through various components until it becomes usable power. Meanwhile, the right diagram provides a sequential breakdown of the system's development stages, including design, assembly, and testing procedures.



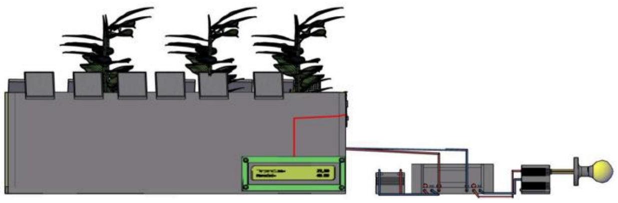
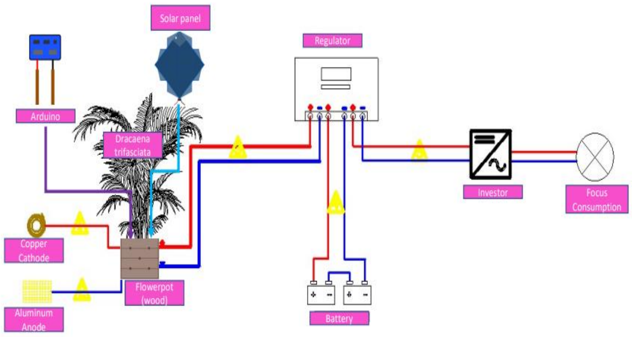


Fig. 1 CAD design, frontal and lateral view



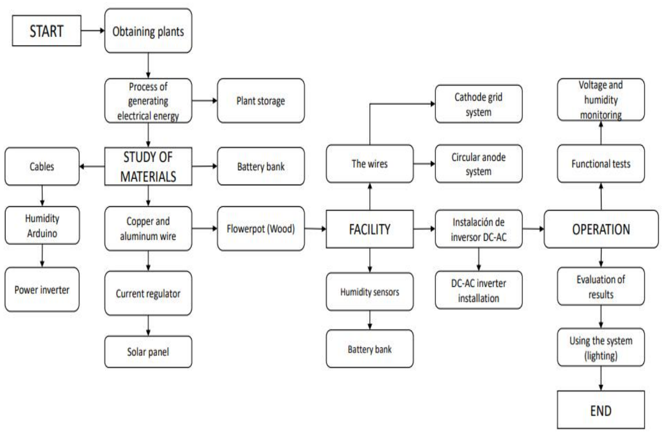


Fig. 2 Flowcharts

3 Results

3.1 Implementation and prototyping

A first-stage prototype was constructed using a single unit of Sansevieria trifasciata. Electrodes were placed strategically within the soil substrate, integrating solar panels and sensor arrays connected via Arduino microcontrollers. This prototype provided initial performance data and established a baseline for scaling. Following the V-model approach, integration of individual components mechanical structures, electrical systems, IoT sensors was systematically conducted. Performance testing and monitoring included hourly voltage measurements from 7:00 a.m. to 4:00 p.m., validating system functionality with a single unit of Sansevieria trifasciata, achieving a peak voltage of 0.82 V. For reference, a common alkaline battery, such as AA or AAA, has a nominal voltage of 1.5 V. Extrapolating from these initial results, a hypothetical garden comprising 30 similar plant units could potentially achieve a peak cumulative voltage of approximately 24.6 V (0.82 V × 30), significantly surpassing the nominal voltage of typical alkaline batteries and illustrating the considerable scalability and practical potential of bio-photovoltaic systems for rural electrification, see figure 3 and table 1.

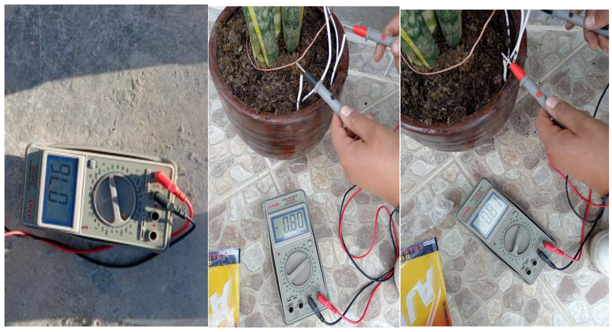


Fig. 3 Voltage measurement 12:00 pm, 13:00 pm and 14:00 pm

Table 1 Voltage measurements at different times

Hour	20V	mV
7:00 am	0.39	390
8:00 am	0.43	430
9:00 am	0.49	490
10:00 am	0.52	520
11:00 am	0.66	660
12:00 pm	0.76	760
13:00 pm	0.80	800
14:00 pm	0.81	810
15:00 pm	0.82	820
16:00 pm	0.76	760
17:00 pm	0.77	770

Considering the experimental conditions where each bio-photovoltaic smart garden of approximately 2 m² generates a peak voltage of around 24.6 V (30 plants × 0.82 V each), scaling this technology to one hectare (10,000 m²) could potentially generate around 123,000 V. Furthermore, Pucapuquio covers an area of 110,490 hectares, with nearly 60% (66,294 hectares) dedicated to agriculture. If even a small fraction of this agricultural land were integrated with bio-photovoltaic smart garden systems, the region could achieve substantial decentralized electricity generation, greatly enhancing rural electrification, sustainability, and environmental conservation efforts.

This scenario underscores the remarkable scalability and potential impact of bio-photovoltaic technology within agricultural communities such as Pucapuquio. see figure 4.

Furthermore, considering the practical application, as the deployment area increases, so does the number of energyproducing units (plants and microbial interactions), allowing for greater voltage accumulation. This relationship indicates that energy availability is scalable and adaptable to the spatial resources of each community, making it suitable for both small- and large-scale applications.

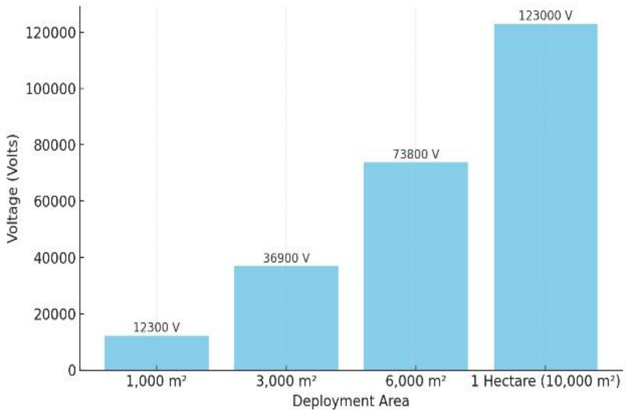


Fig. 4 Bio-Photovoltaic Voltage Potential By Deployment Area

The selection of electrode materials for the anode and cathode is a critical design decision that affects the efficiency, sustainability, and durability of bio-photovoltaic systems. Figure 5 presents a flowchart comparing the suitability of copper and aluminum based on electrical, environmental, and mechanical criteria. Copper is recognized for its superior electrical conductivity and is generally preferred for efficient energy capture in low-voltage bioelectrochemical systems. However, the environmental impact of copper mining and processing—namely, the emission of toxic waste and greenhouse gases—raises concerns regarding long-term sustainability. The chart also notes that while alternative materials like zinc could be used, they adversely affect soil quality, making them unsuitable for agricultural-integrated systems. On the other hand, aluminum, although offering only 64% of copper's conductivity, presents notable advantages in corrosion resistance due to its natural oxide layer. This makes it a durable choice for outdoor installations in varying climatic conditions. However, its performance deteriorates at high temperatures, which can lead to component failures if not properly managed. The flowchart supports a dual-material strategy: copper is favored for performance, while aluminum is leveraged for structural stability and environmental resilience. This hybrid approach balances energy efficiency with material longevity, aligning with the goals of decentralized, sustainable energy deployment in rural environments like Pucapuquio.

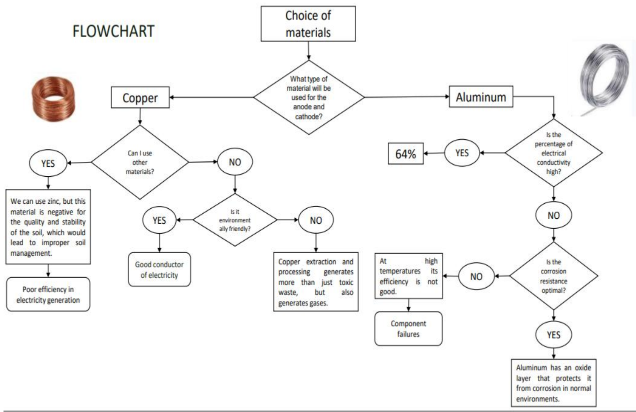


Fig. 5 Electrode materials

4 Conclusion

This study demonstrated the design, implementation, and performance evaluation of a hybrid smart garden system that integrates bio-photovoltaic and conventional solar technologies for decentralized energy generation in rural areas. By combining biological and electronic subsystems—specifically, copper and aluminum electrodes, native plant species (Sansevieria trifasciata), and IoT-enabled environmental sensors—the project successfully validated a low-cost and sustainable alternative for electricity production in off-grid settings like Pucapuquio, Peru.

Experimental results confirmed that a single plant can generate up to 0.82 V under optimal daylight conditions, with projections suggesting that a 30-plant garden could yield approximately 24.6 V. Moreover, scaling this model to one hectare could theoretically produce up to 123,000 V, indicating significant potential for broader rural electrification. Given that nearly 60% of Pucapuquio's 110,490 hectares are agricultural, even partial deployment of such systems could yield transformative outcomes in clean energy access, sustainability, and community resilience.

Additionally, the project highlighted the importance of electrode material selection, balancing performance and environmental impact. The dual use of copper (for conductivity) and aluminum (for durability and environmental compatibility) reflects an effective, scalable design strategy.

Overall, this work contributes a replicable, interdisciplinary framework that merges renewable energy, agroecology, and digital automation, offering a novel solution to the global challenge of sustainable energy access in remote and underserved communities. Future work will focus on long-term field testing, economic modeling, and integration with agricultural productivity metrics to further validate the model's practicality and scalability.

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