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Electrochemical Energy Generation by Reusing Domestic Gray Water

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ABSTRACT

This study explores the potential of converting domestic graywater into electrochemical energy as a sustainable energy solution amidst growing environmental concerns. Employing a custom-designed galvanic cell prototype, the research aims to transform the chemical energy in graywater into electrical energy through redox reactions, quantifying the electrical potential generated. Results demonstrate the prototype's success in generating an average no-load voltage of 5.1907 volts, effectively powering low-power devices like LEDs and validating the viability of greywater as an alternative energy source. However, the study acknowledges limitations such as the prototype's small scale and the potential impact of varied graywater compositions on energy efficiency, suggesting cautious application at larger scales. Future research directions include enhancing prototype efficiency and scalability, understanding the effects of different graywater compositions, and conducting long-term performance assessments. The study contributes to sustainable energy research by offering a novel approach to wastewater energy recovery, promoting environmental sustainability and efficient energy utilization.

1. INTRODUCTION

The world is facing major challenges and dangers, such as the depletion of non-renewable energy resources, limited availability of fresh water, and insufficient food supply. As the world's population increases, so do the needs for freshwater, energy, and food [1]. The exposed hazards are related to food constraints, freshwater scarcity, and the depletion of nonrenewable energy sources, and innovative alternatives such as greywater reuse are required to address these urgent problems and provide a practical solution [2, 3].

The increase in population, together with the increase in agricultural and industrial activity, generated the sustained growth in demand for resources such as freshwater and energy, generating all this depletion of supply sources in an accelerated manner that, together with the global crisis of water and energy resources makes it a pressing challenge that adds to climate change that is also generating an adverse effect on the availability of freshwater and the consistency of energy sources [4].

According to the World Health Organization (WHO) [5], greywater constitutes between 50% and 80% of the total domestic wastewater volume, which shows that it is an underutilized resource. Therefore, reusing this water reduces the demand for freshwater resources, decreases the pressure on water treatment infrastructures, and provides an opportunity for innovation in energy generation [6].

Grey wastewater, typically sourced from sinks, showers, washing machines, and other non-toilet fixtures, contains several components or substances that can potentially be harnessed for energy production. Understanding the elements found in grey wastewater and their potential for energy generation requires a multifaceted approach, often focusing on biodegradable organic matter [7, 8].

The key components in grey wastewater relevant for energy generation are the organic matter such as fats, oils, greases (mostly from kitchen wastewater), and other carbon-rich compounds that are primary contributors to energy generation; these materials can be broken down anaerobically (without oxygen) to produce biogas, primarily methane, which is a valuable energy source, other components are the surfactants and biochemicals from detergents and soaps can also undergo degradation and contribute to the production of methane and other gases during the anaerobic digestion process. Nutrients such as nitrogen and phosphorus, while not directly linked to energy production, play significant roles in the biological processes that facilitate the degradation of organic waste in treatment systems [9, 10].

Diverse techniques exist for generating energy from gray effluent, including anaerobic digestion, which produces biogas through the bacterial decomposition of organic matter without oxygen; the biogas can subsequently be collected and utilized as an energy source [11, 12].

Microbial fuel cells (MFCs) convert effluents into a form of energy by harnessing the power of bacteria through the decomposition of organic substances that manifests itself through the displacement of electrons in the outer shell of atoms present on the surface of a conductive material, this phenomenon being intrinsically related to matter and life. Bacteria perform chemical changes that occur in a cell of organic compounds; these changes produce energy and materials that cells and organisms need to grow, reproduce, maintain themselves, and eliminate toxic substances, thus transferring electrons to an anode and generating an electric current that flows to a cathode. Biochemical production, such as fermentation, converts the organic carbon present in gray effluents into biochemical substances, and this alternative method can be used for biofuel production [13].

This background motivates the investigation of how to produce or generate energy with graywater treatment. Reusable and sustainable solutions are needed to reduce dependence on non-renewable energy sources, which requires facing challenges related to water and energy scarcity [3, 8]. Integrating this approach is not only environmentally friendly but also has the potential to generate economic benefits and raise the standard of living in diverse communities globally [3].

The motivation for this research encompasses several aspects, from addressing the global crisis of freshwater scarcity that has put a strain on water sources worldwide and projecting its scarcity in the coming decades [1]; another factor is graywater reuse, which is presented as a viable solution to alleviate the pressure on freshwater sources, considering that society still relies on fossil fuels that over time generate the depletion of non-renewable resources [4], therefore using graywater as a means to generate electricity through electrochemical technologies, with microbial fuel cells (MFC) and galvanic cells, offers a sustainable and environmentally friendly alternative [14].

Greenhouse gas emissions and carbon footprint are other important motivations since wastewater treatment plants contribute to the emission of greenhouse gas emissions due to anaerobic processes in waste assimilation. Considering the development of new electrochemical technologies for water treatment and energy generation, the implementation and optimization of these require the specific adjustment of the greywater electrolyte and the combination of electrode materials; it is possible to lead to significant advances, following the principles of cellular economy involving greywater reuse [15].

The alternative studied is MFCs, which are bioelectrochemical devices that possess a remarkable ability to directly convert by converting chemical energy to electrical energy via microorganisms functioning as catalysts [16]; this process has demonstrated energy recovery through the use of MFCs, which makes the use of wastewater converts it into a source of energy to generate electricity [17], this reuse of greywater is evident in addressing these pressing problems and providing a practical solution [18]

The proposal presents a novel approach integrating greywater treatment technologies with power generation through galvanic cells and MFCs [19]. It focuses on optimizing the electrodes and electrolytes using graywater, significantly improving system efficiency [20]. This implies the application of electrochemical technologies is little investigated in the graywater reuse process. Testing with different electrode materials and modifications in electrolyte composition projects better performance. Therefore, by combining treatment and power generation technologies, this field of knowledge presents a practical and adaptable solution that can be implemented in different situations to boost sustainability [21].

Graywater reuse is essential as the challenges of water and energy resource shortages increase, and moving towards its more efficient and sustainable use becomes an ongoing task. The efficient strategy is the reuse of domestic wastewater as an alternative to conserve the limited availability of potable water [22]; this whole process involves the reuse and treatment of domestic water intended for irrigation, cleaning, and flushing toilets but not for consumption by the population. The CBM can convert the organic matter of wastewater into electricity, which implies that this process is efficient and makes possible with this technology the recovery and use of energy [23]. Harnessing the energy contained in graywater offers a renewable and sustainable alternative to meet growing energy demand while promoting energy autonomy and reducing greenhouse gas emissions [22]. An increase has been observed in the quantity of research studies focusing on the prevailing methods of greywater utilization in the recycling industry. In addition, the simultaneous utilization of greywater for greywater recycling and energy recovery systems has become increasingly popular [24].

Research gaps identified in the literature reviewed are in the limitation of comprehensive studies combining graywater treatment and energy generation, which needs to be addressed to develop practical and efficient solutions [25]; there is also a need to further investigate the best materials and compositions to maximize the efficiency of electrochemical systems [26], another identified gap is the limited studies related to large-scale scalability and feasibility and economic cost-benefit analysis in the implementation of greywater reuse and energy generation systems [24], another important gap to consider is the scarcity of studies that sufficiently address the variability of greywater quality and the effect on system performance which is essential for realistic implementation of these greywater harnessing technologies [25].

According to the study conducted by Chafloque et al. [26], greywater is the most sustainable solution to cope with the increasing demand for freshwater. It provides an avenue for applying economical and environmentally responsible technology in greywater treatment, thus promoting sustainable wastewater management.

Present-day scholarly discourse places significant emphasis on novel methodologies that aim to optimize the recovery of wastewater resources, including energy [27]. Research studies offer valuable insights into the efficiency of different technologies [28]. There are studies that focus on the MFC for the conversion of chemical energy from biological material into electrical energy, finding that the performance and efficiency of the cells depend on factors such as the wastewater components, the microbial cultures used, and the cell design, however, the output power and maximum voltage of the MFC present variability with oscillations, using optimized gray wastewater when subjected to laboratory conditions, ranging from millivolts to hundreds of millivolts per cell, which requires scaling up the system to improve the output voltage or also applying the proposal to connect the cells in series to improve their practical applicability. Recent research endeavors, including those conducted by Chafloque et al. [26] and Jahin et al. [29], propose that gray wastewater pretreatment increases the concentration of biodegradable material and efficiency while also exploring the potential of genetically modified microorganisms to enhance output voltage and, consequently, energy recovery. Despite notable advancements in energy recovery from gray wastewater, the practical and pervasive implementation of these technologies continues to face obstacles. Consequently, ongoing innovation and research are essential for enhancing the systems' efficacy, scalability, and sustainability.

2. MATERIALS AND METHODS

In a galvanic cell, copper and galvanized iron can act as the cathode and anode, respectively. The iron is oxidized, releasing electrons that generate current. This electric current passes through the external circuit and reaches the copper cathode. The voltage of a galvanic cell can be roughly estimated using standard reduction potentials. The reaction of dissolution of zinc in galvanic iron (mainly zinc) possesses a standard capacity for -0.76 V, during the reduction of $Cu^{2}+$ to Cu has a standard capacity for +0.34 V. The difference in these potentials provides the maximum theoretical voltage of approximately 1.10 V.

During the reaction, organic contaminants in graywater can undergo electrochemical degradation processes. Energy generation is related to charge transfer which can also facilitate the degradation of these organic compounds, improving water quality. An electrochemical cell functions spontaneously if the sum of the reduction potentials of the half-reactions is positive. In the case of Cu and Zn, this is true.

The Zn anode in galvanized Fe undergoes oxidation $Zn \rightarrow Zn^{2+}+2e^{-}$, and the cathode (Cu) undergoes reduction $Cu^{2+}+2e^{-} \rightarrow Cu$. Electrons traverse the circuit that connects the anode to the cathode externally, generating current. Through the application of biological fuel cells, it is possible to generate energy and degradation of organic matter by using microorganisms responsible for transferring electrons from the oxidized organic materials to the anode, generating electric current; in this way, the microbes act as natural catalysts for Facilitating the movement of electrons from the organic matter. Spontaneous reactions are possible in the case of copper and galvanized iron electrodes. Cu and Zn generate spontaneous redox reactions in which Zn dissolves in solution, releasing electrons $Zn \rightarrow Zn^{2+}+2e^{-}$, which are captured by the Cu cathode.

Voltage generation and operation are given in "fuel cell mode"; for this, a relationship is given with galvanic half reactions where the cell voltage depends on the redox potentials of these half-reactions occurring at the electrodes with grey water containing impurities and contaminants that can influence the voltage produced.

To achieve stability and charge transfer stability in the experiment, select electrode materials that do not corrode quickly and offer good conductivity. However, it is possible that copper and galvanized iron may not be stable in the long term and may reduce the efficiency of the cell; for this reason, formal electrochemical studies were applied in the experimental techniques, considering methods such as measurements using chronoamperometry, electrochemical impedance spectroscopy, and cyclic voltammetry.

The phenomena involve electron transfer between the anode and cathode, ionic conduction through the electrolyte, and other influences such as internal resistance and overpotential potentials. Generating energy from graywater requires specific electrodes. At the cathode, Cu is reduced, while galvanized iron undergoes oxidation, with organic pollutants in the graywater possibly participating.

2.1 Prototype design

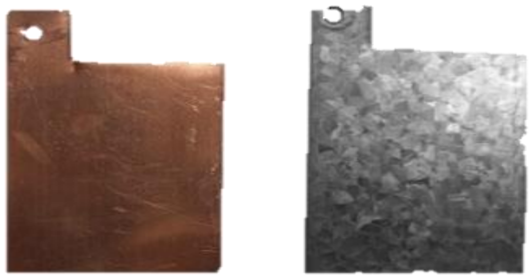
2.1.1 Galvanic cell prototype design

Each galvanic cell has a corrosion-resistant plastic compartment with two electrodes: one copper and one galvanized iron (zinc-coated) electrode. The electrical energy generated in the galvanic cells depends on the materials used in the prototype, such as:

The dimensions of the containers are approximately 7 cm high×13.2 cm long×11 cm wide and can hold 1.0164 liters of gray water, as shown in Figure 1.

Applying a redox process, it will be possible to transform the greywater from chemical energy to electrical energy by quantifying the electrical potential generated, which will depend on the characteristics of the cell and the characteristics of the domestic wastewater.

Figure 1. Plastic box with six galvanic cell spaces



(a) (b)

Figure 2. (a) Copper; (b) Galvanized iron plates

Figure 3. Plate separators are used in the design of the prototypes of galvanic cells

2.1.2 Materials

Electrodes

·Cathode: Copper (Cu) plates, with a surface area of 43.5 cm² (7.5 cm×5.8 cm) and a thickness of 0.5 mm., positive electrode material (+) as shown in Figure 2(a).

·Anode: Galvanized Iron (Zn) plates with the same area and thickness as the cathode, negative electrode material (-), as shown in Figure 2(b).

·Container: High-density polypropylene (PP) plastic containers, as shown in Figure 1, resistant to corrosion and electrochemical conditions. The dimensions of recycled plastic box are 7 cm×13.2 cm×11 cm, with 6 spaces for cells and a plastic lid, as shown in Figure 3 and Figure 4. This container can be made of any other material that has characteristics of electrical insulation, waterproofing, and moisture resistance for temperatures between -10℃ and 50×. Volume per cell 113.9 cm^3.

·Electrolyte: Pre-treated gray water, pH adjusted to 7.5, and conductivity optimized by addition of NaCl to reach a concentration of 0.1 M.

·Salt bridge: Tube containing agar-agar and saturated KCl solution to maintain charge neutrality and allow ion transfer between compartments.

·82 cm×65 mm spacers.

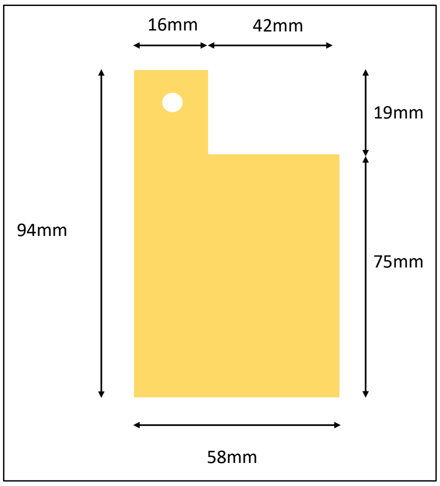


Figure 4. Dimensions of copper and galvanized iron electrodes

2.1.3 Construction and assembly

Graywater preparation

·Filter graywater to remove suspended solids using a fine mesh filter (<0.5 mm).

·Adjust pH to 7.5 using HCl or NaOH.

·Add NaCl until a concentration of 0.1 M is reached to optimize conductivity.

Converting gray water (Figure 5) into a useful electrolyte for electrochemical applications, such as galvanic cells or microbial fuel cells (MFCs), involves a process of pretreatment and adjustment to optimize its electrochemical properties (Figure 6). Initial filtration, pH and conductivity correction, and removal of inhibitory contaminants are essential steps to ensure efficient operation in applications such as galvanic cells or microbial fuel cells. This process not only converts a disposable resource into a useful energy source but also contributes to sustainable water management.

Galvanic cell assembly

• Place the copper electrode on the lateral of the container and the galvanized iron electrode on the contrasting side, ensuring they do not touch, as shown in Figure 7.

• Connect the salt bridge between the two compartments of the container to maintain charge neutrality.

• Pour the pre-treated gray water into the container, completely covering the electrodes.

Connecting the cells in series

• Connect one cell's positive (copper) terminal to the next cell's negative (zinc) terminal in a series using alligator clips and lead wires, as shown in Figure 8.

• To obtain 5 volts, connect at least 5 galvanic cells in series, as shown in Figure 9.

• The prototype was designed and built according to the greywater—electrolyte and galvanic cell parameters, as shown in Figure 10.

• A multimeter will measure the resulting voltage and current to correspond to the indicators corresponding to the experiments and tests.

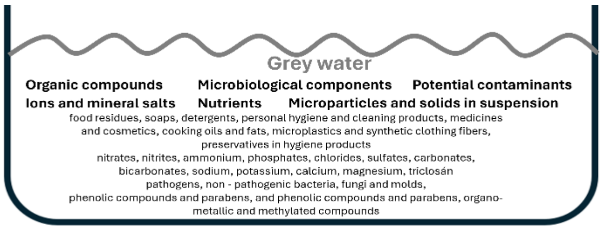


Figure 5. Greywater components

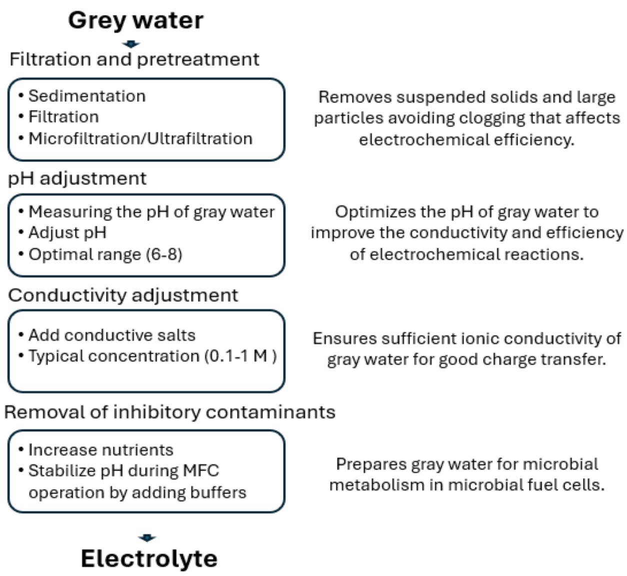


Figure 6. Process for converting gray water into electrolyte

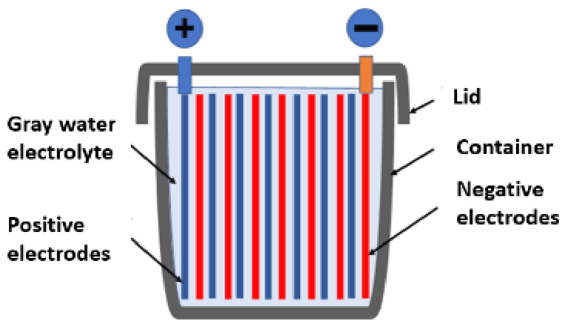


Figure 7. Design of the galvanic cell prototype with gray water

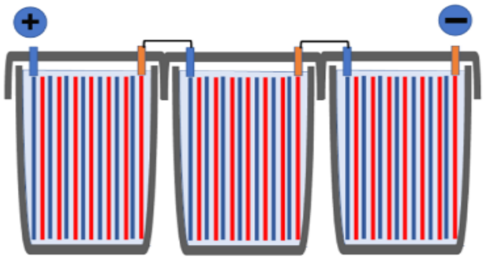


Figure 8. Basic connection

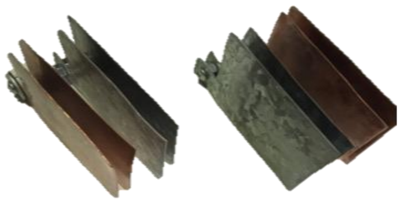


Figure 9. Galvanic plate cell separators

Figure 10. Assembled electrodes for energy generation

2.1.4 Measurements and monitoring

Instruments

·Digital multimeter to measure total voltage and current generated by the series of galvanic cells.

·Data logger to record voltage and current data every 5 minutes during short-term performance tests and at 2-hour intervals for long-term tests.

Testing

·Perform 42 tests per cell of each prototype every 5 minutes.

·Perform 70 tests for each prototype with no load every 5 minutes.

·Perform 70 tests for each prototype with load (different LEDs) every 2 minutes, recording the brightness level.

·Perform 85 tests measuring the capacity of Prototype 1 with an electrical load for 168 continuous hours.

- 1 Led off - no brightness.
- 2 Led on - low brightness.
- 3 Led on - medium brightness.
- 4 Led on - high brightness.

The sample used for testing the prototype design consists of six additional replicas, which were numbered from 1 to 7, including the prototype, in which the electrical measurements of each test were performed. A total of 267 experimental measurements were performed on the 7 prototypes. To ensure the reproducibility of the proposal, the design, dimensions, materials, construction, and assembly of the prototype galvanic cell are presented.

The replicated results can evaluate this design and its reproducibility with a validated prototype. Statistical significance can be determined by considering the sufficiency of samples with the number of tests (42+70+70+70+85=267), which provides a robust data set for meaningful statistical analysis, and the measurement intervals that allow for varying tests in different no-load and loaded conditions at different time intervals, to evaluate the performance of the prototype.

2.2 Mathematical formulas

To understand the process of power generation with a galvanic cell using copper (Cu), galvanized Iron (predominantly Zinc, Zn), and gray water as electrolytes, it is necessary to address some formulas and basic mathematical concepts in electrochemistry [16].

2.2.1 Cell potential (E°_{cell})

The potential of a galvanic cell is estimated using the standard reduction potentials of the electrodes involved. The general reaction is:

$$Zn\ (s) \rightarrow Zn^{2+}(aq) + 2e \tag{1}$$

$$Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s) \tag{2}$$

These equations are electrochemical semi-reactions representing the oxidation and reduction processes that occur at the electrodes of a galvanic cell constructed entirely of zinc (Zn), as Eq. (1) and copper (Cu) electrodes as Eq. (2) these reactions describe chemical energy transformation into electrical energy through electron transfer reactions [15].

This semi-reaction occurs at the cathode, where copper is reduced. Copper ions in Cu^{2+} aqueous solution gain two electrons and are deposited as solid copper Cu(s) on the electrode.

The standard cell potential E°_{cell} in Eq. (3) is calculated as:

$$E^{\circ}_{cell} = E^{\circ}_{cathode} - E^{\circ}_{anode} \tag{3}$$

where, $E^{\circ}_{cathode}(Cu^{2+}/Cu) = +0.34\ V$, $E^{\circ}_{anode}(Zn^{2+}/Zn) = -0.76\ V$. Therefore, $E^{\circ}_{cell} = +0.34\ V - (-0.76\ V) = 1.1\ V$.

These semi-reactions are a fundamental part of the electrochemical process in a galvanic cell. Through the reduction of copper at the cathode and the oxidation of zinc at the anode, electrons can be transferred via an external circuit, generating electricity. This principle is the basis for various technological applications, from batteries to fuel cells.

2.2.2 Current intensity (Ohm's law)

The current generated I in an external circuit can be determined by Ohm's Law as Eq. (4):

$$I = VR \tag{4}$$

where, V is the cell potential E°_{cell}, R represents the overall resistance of the circuit.

2.2.3 Energy and power

The power P produced in a circuit is calculated using Eq. (5):

$$P = IV \tag{5}$$

The energy E generated during a time t is calculated using Eqs. (6) and (7):

$$E = P \cdot t \tag{6}$$

$$E = IVt \tag{7}$$

2.2.4 Electrode reaction

Organic redox reactions involve half-reactions at each electrode (Anode and Cathode) where organic compounds act as reactants. In the oxidation half-reaction (Eq. (1)), the reactant loses electrons, while in the reduction half-reaction (Eq. (2)), the reactant gains electrons. These reactions are illustrated in Figure 11.

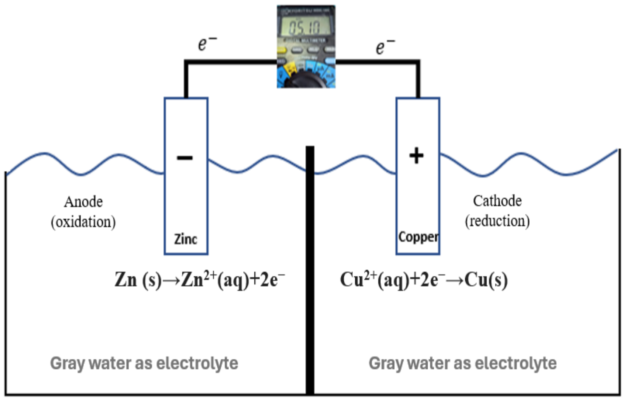


Figure 11. Electrode reaction

2.2.5 Electron transfer

The number of moles of electrons n transferred is related to the amount of substance oxidized or reduced is calculated using Eq. (8):

$$Q = nF \tag{8}$$

where, Q is the amount of charge transferred in Coulombs.

2.2.6 Mass and charge balance

The Mass balance is calculated using Eq. (9):

$$\text{Mass of dissolved Zn} = \frac{QM_{Zn}}{nF} \tag{9}$$

where, M_{Zn} is the molar mass of zinc.

To calculate the maximum current without resistance (ideal) is calculated using Eq. (10):

$$I = 1.10\ VR \tag{10}$$

Assuming the following values: $R=10\ \Omega$, $I=1.10\ V\ 10\ \Omega=0.11\ A$.

Power: $P=1.10\ V \times 0.11\ A=0.121\ W$.

These calculations can be adjusted according to the concentration of ions present in the gray water, other impurities and its effective ionic conductivity.

These formulas and concepts provide a basis for the analysis and optimization of galvanic cells using copper and galvanized iron with gray water as an electrolyte. The specific properties of the gray water in each case must be considered to obtain accurate and efficient results in power generation. To achieve Stability and charge transfer, other electrode materials that do not corrode quickly and offer good conductivity could replace copper and galvanized iron. These materials could be stable in the long term and improve the cell's efficiency.

2.3 Data processing

The data collected from the measurements are recorded in a dataset and processed according to the equations determined using the theoretical basis of the operation of galvanic cells and the literature related to the experiment.

1. Sorting and categorization

This approach is used to process qualitative and quantitative data related to the electrical parameters derived from the experimental evaluations.

2. Manual registration

Is applied to register the data about the different experiments to be carried out.

3. Computerized process

Excel tables and statistical formulas are used to perform various useful mathematical and statistical calculations to obtain the results.

2.3.1 Data analysis

The standard deviation was applied to quantify the spread of the voltage and to know the degree of dispersion or variability obtained of data values concerning the average value of the voltages obtained by each cell and by each prototype. For the calculation of the Standard Deviation, the Eq. (11) was used:

$$SD = \sqrt{\frac{\sum (x - \bar{x})^2}{(n-1)}} \tag{11}$$

x is the sample average value, and n is the sample size.

Median: The middle of a set of numbers.

Mode: The value that repeats or occurs most often in an array or range of data.

Average $\bar{x}$: The average (arithmetic mean) of a group of values.

2.3.2 Ethical considerations

The following ethical and environmental considerations were considered.

·The generation of electricity from an electrochemical source has been carried out using materials and components that do not cause environmental damage: copper, iron, gray water, and other materials that do not pollute the environment.

·The casing of galvanic cells is recycled, which also contributes to reducing pollution caused using plastic materials.

·There were no heavy metals or corrosive acids that require special disposal and treatment procedures as electronic waste that pollutes the environment.

3. RESULTS

To gather the data, experiments have been carried out in which the phenomenon has been carefully observed, and measurements of the generated or resulting electrical potential have been made. A multimeter with a current calibration certification was used for the measurements. The experiment results carried out during the tests and measurements of the values of the variable electrical potential measured in volts have been made. To carry out the tests, the following experiments were considered:

Prototype 1: first model designed and built

Prototypes 2, 3, 4, 5, 6, and 7 are replicas of prototype 1 to verify the experiment's reproducibility, as shown in Figure 12.

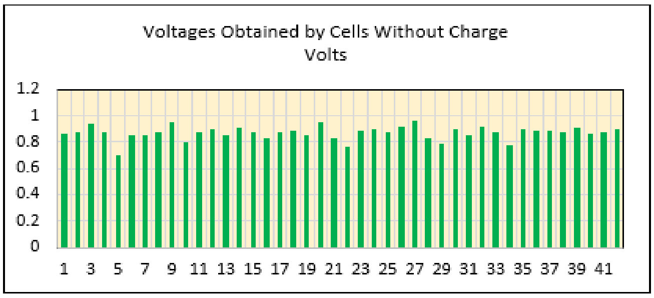


Figure 12. Voltages in cells without load

Figure 12 shows the results of the measurements of electrical parameters of electrochemical energy generation reusing domestic gray water. After having built the Prototype, the following tests have been carried out:

Test 1 Cell voltage - No load

Measurement of the generated voltage, without load, for each cell has been carried out. The summary and results are presented in Table 1.

Table 1. Statistical data obtained by cell without load

Max	Min	Median	Mode	Average	Std dev
0.96	0.7	0.87	0.87	0.8702	0.0508

Test 2 Cell voltage per prototype - No load

Tables and figures are presented for each prototype, indicating the voltage measurement results for each cell, the date, time, prototype number, the statistical results, and a photo of the measured voltage. See Tables 2-9 and Figures 13-18.

Table 2. Prototype 1 – Model: Without charge

Test	Charge	Prototype Number	Cell Number	No load (Volts)
1	No	1	1	0.86
2	No	1	2	0.88
3	No	1	3	0.94
4	No	1	4	0.87
5	No	1	5	0.70
6	No	1	6	0.85

Table 3. Prototype 1: No load

Max	Min	Median	Mode	Average	Std dev	Volt
0.94	0.70	0.87	0.87	0.8500	0.0800	5.1

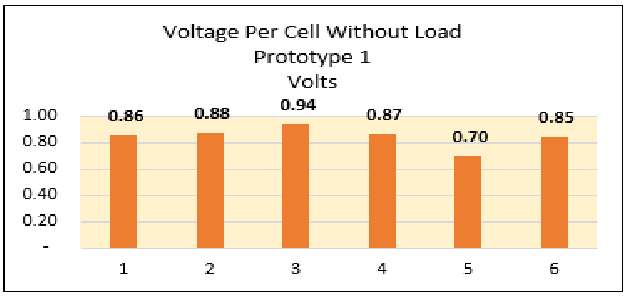


Figure 13. Prototype 6: No load

Table 4. Prototype 2: No load

Max	Min	Median	Average	Std dev	Volt
0.95	0.80	0.88	0.8750	0.0501	5.25

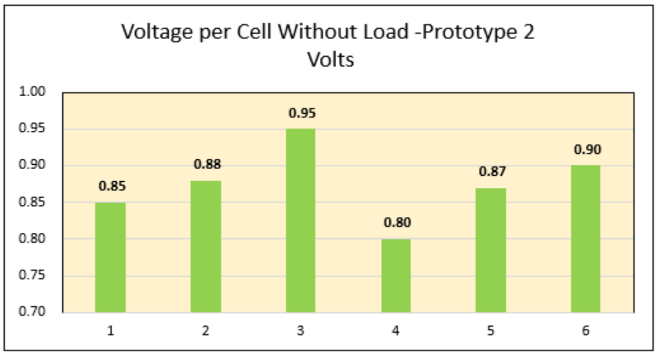


Figure 14. Prototype 2: Without load

Table 5. Prototype 3: No load

Max	Min	Median	Average	Std dev	Volt
0.91	0.83	0.87	0.8700	0.0283	5.22

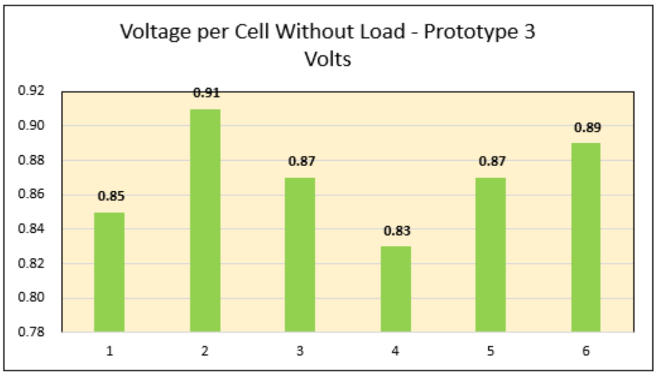


Figure 15. Prototype 3: No load

Table 6. Prototype 4 voltages: No load

Max	Min	Median	Average	Std dev	Volt
0.95	0.77	0.87	0.8650	0.0625	5.19

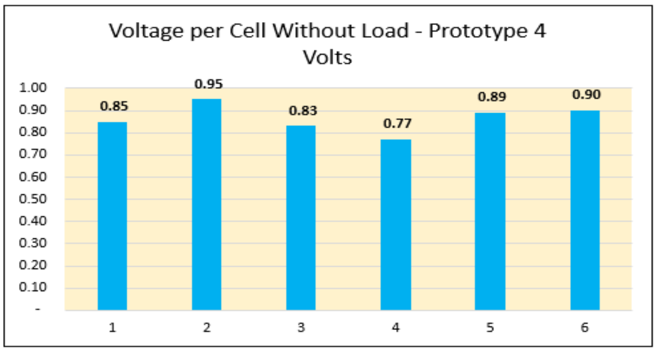


Figure 16. Prototype 4: No load

Table 7. Prototype 5: No load

Max	Min	Median	Average	Std dev	Volt
0.96	0.79	0.8850	0.8700	0.0618	5.27

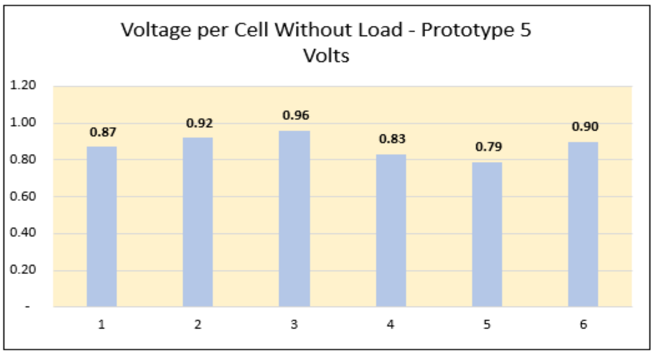


Figure 17. Prototype 5: No load

Table 8. Prototype 6: No load

Max	Min	Median	Average	Std dev	Volt
0.92	0.78	0.87	0.8683	0.0496	5.21

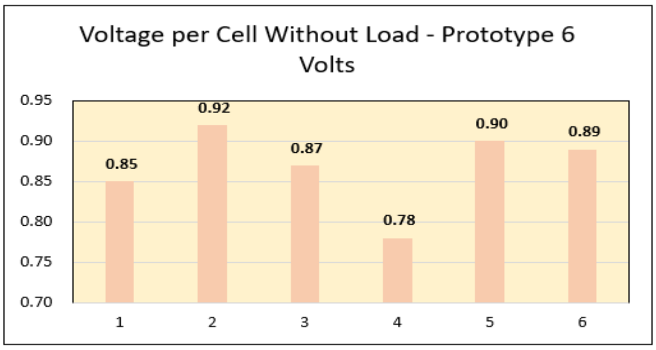


Figure 18. Prototype 6: No load

Table 9. Prototype 7: No load

Max	Min	Median	Average	Std dev	Volt
0.91	0.86	0.88	0.8850	0.0187	5.31

Test 3 Prototyping total voltage - No load

The general results of the total voltage measurement tests in each Prototype without load are presented, having made ten measurements per prototype every 5 minutes. The statistical results of the measurement in the seven prototypes are presented, as shown in Table 10.

Table 10. All prototypes: No load

Max	Min	Median	Average	Std dev
5.32	5.10	5.22	5.2254	0.0626

Test 4 Prototyping voltage - Loaded

LEDs (Light-emitting diodes) were used to conduct electrical load tests. These are semiconductor electronic devices that emit light when connected to a voltage source as long as the source supplies a voltage equal to or greater than the LED's bias voltage.

The electrical charge: LEDs of different colors will allow us to verify the presence of sufficient electrical potential generated, measured in Volts, to achieve the operation of said devices.

The results of 10 measurements with load for each Prototype are presented, indicating the date, time, load, prototype number, number of cells, connection, voltage with load, and operation, as shown in Figure 19.

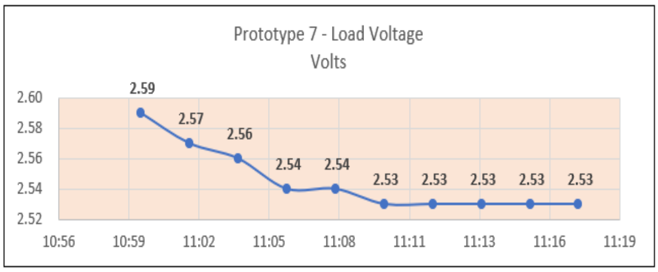
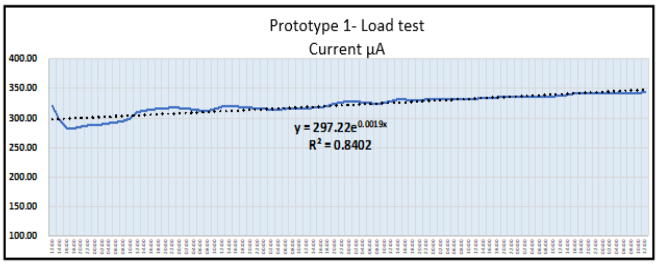


Figure 19. Prototype No. 7: Loaded

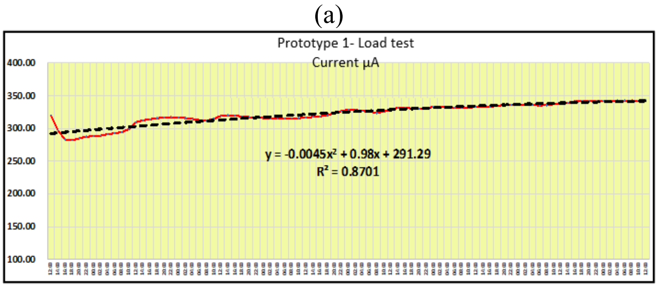
Test 5 Prototype 1 capacity – Load

This test was carried out for 168 consecutive hours (7 days), recording 85 measurements with intervals of every 2 hours. It consisted of a Prototype 1 test with four red LEDs as an electrical load. The test number, date, hours of operation, time, voltage, current, and result with load and power dissipation were recorded. The Load Result column indicates the luminosity level of the LEDs, starting with high brightness, luminosity 4, and then after 116 hours of operation, the voltage tended to decrease, and at 168 hours, the luminosity dropped to level 3, the recorded data is found in Table 11. The test culminates when Luminosity 3 is observed in the LEDs since this thesis aims to generate electrical energy of electrochemical origin by reusing domestic gray water, which was demonstrated.

The curves of the current trend lines as a function of time have been drawn from the data in exponential and polynomial versions, the results of which are shown in Figure 20(a) and 20(b).



(a)



(b)

Figure 20. Graphical representation of prototype 1 with load with polynomial equations (a) and (b) of current in μA

The coefficient of determination R-squared of the polynomial equation is greater than the exponential equation. Therefore, it represents the current with greater approximation and will adopt the polynomial trend line equation to calculate the capacity of Prototype 1 for the load and conditions described in the test performed. Then we pose Eq. (12) for the current trend line as a function of time, where the current is represented by the ordinate axis and the time by the abscissa axis, therefore the instantaneous current.

$$i = -0.0045t^2 + 0.98t + 291.29 \quad (12)$$

The dissipated capacity of prototype one as a function of current and time will be expressed in Eqs. (3)-(5):

$$Capacity = C = \int_0^t i\, dt$$
$$C = \int_0^{168} (-0.0045t^2 2 + 0.98t + 291.29)dt \quad (13)$$

For the resolution of the integral, we will use the Formula of Eq. (6):

$$\int u^m du = \frac{u^{m+1}}{m+1} + C, \; m \neq -1 \quad (14)$$

The capacity of prototype 1 by resolving the definite integral in Eq. (6) and therefore we have: $C = -0.0015t^3 + 0.49t^2 + 291.29t$

Solving, the result can be expressed in μAh or mAh: C=55,654.032μAh dissipated in 168 hours; C=55.65mAh dissipated in 168 hours.

According to the results, applying galvanic cells to reuse domestic gray water allows electrochemical energy generation. The main research hypothesis states that electrochemical energy is generated, which is demonstrated as follows, where the generated voltage *Hi* is greater than zero, so the voltage generated by the Prototype must be greater than zero, being the average generated voltage Hi=5.1907 Volts>0, then the research hypothesis is true, and the null hypothesis is rejected as false.

A specially designed and built galvanic cell prototype demonstrates that electrochemical energy is generated by reusing domestic greywater. The galvanic cell prototype must show that by reusing domestic gray water, the electrochemical energy of a certain voltage is generated. Table 12 shows that voltage generation has occurred, and it is concluded that the specific hypothesis in question is true.

Table 11. Voltage measurement on each Prototype: No load

Parameters	Values	Interpretation
Maximum	5.32	Significant voltage is observed.
Minimum	5.10	A slight difference is observed with respect to the maximum, reaching 4.13%, which does not prevent the prototypes from working in parallel.
Median	5.22	It represents the mean in terms of voltage.
Mode	5.22	Most of the prototypes present in this generated value of voltage.
Average value	5.2254	It is the average value of voltage generated by the different Prototypes.
Standard deviation	0.0626	This standard deviation value is acceptable. It is presented due to inaccuracies in the manual construction procedure of each Prototype. As the process becomes more precise in terms of plate dimensions, the adjustment of the electrical contact in the terminals improves, and the variations inherent to the assembly are reduced, greater equality will be achieved in the generated voltages, and this standard deviation value will decrease.

Through experimental tests, the electrical parameters of the electrochemical energy are determined and generated by reusing domestic gray water in galvanic cells. Electrochemical energy's electrical parameters must be determined through experimental tests. This energy is generated by reusing domestic gray water in galvanic cells.

Data has been obtained that determines the resulting values of the electrical parameters of the electrochemical energy generated by reusing domestic gray water in galvanic cells. Therefore, it is concluded that the specific hypothesis in question is true.

In the Tables and Figures presented, the results of the measurements of the voltages generated by the 7 Prototypes are shown; having carried out the measurement of voltages without load of the cells individually presents the following results in Table 12, the measurement of total voltages of the Prototypes with six cells connected in series complies with Kirchhoff's Voltage Law.

Having observed that the energy generated is of a small power scale and the Prototype is harmless to people and the environment, which is useful since the electrical risk is minimal or null.

In the 42 galvanic cells, reusing domestic gray wastewater, it has been possible to generate various voltage values with the following results without load:

Minimum generated voltage:	0.70 Volts.
Maximum generated voltage:	0.96 Volts.
Generated Voltage Median:	0.87 Volts.
Generated Voltage Mode:	0.8700 Volts.
Average generated voltage:	0.8702 Volts.
Std deviation of voltage:	0.0508 Volts.

In the Prototype, 6 individual cells that have been conditioned and connected in series are used so that, according to Kirchhoff's Voltage Law, a significantly higher voltage is obtained. As a result, the following values of total voltages without load have been obtained in the 7 Prototypes:

Minimum generated voltage:	5.10 Volts.
Maximum generated voltage:	5.32 Volts.
Median Voltage generated:	5.22 Volts.
Generated Voltage Mode:	5.22 Volts.
Average generated voltage:	5.2254 Volts.
Std deviation of voltage:	0.0626 Volts.

Table 12. Prototype capability test

Measure Type	Voltage	Current	Dissipated Power
Minimum	1,716 Volts	282,000 **μ**A	487,014 **μ**W
Maximum	1,735 Volts	343,700 **μ**A	596,320 **μ**W
Average	1,729 Volts	322,353 **μ**A	557,508 **μ**W

Table 13. Voltages were obtained from the prototype and cells in no-load tests

Prototype	Cell1	Cell2	Cell3	Cell4	Cell5	Cell6
P1	0.86	0.88	0.94	0.87	0.7	0.85
P2	0.85	0.88	0.95	0.80	0.87	0.90
P3	0.85	0.91	0.87	0.83	0.87	0.89
P4	0.85	0.95	0.83	0.77	0.89	0.90
P5	0.87	0.92	0.96	0.83	0.79	0.90
P6	0.85	0.92	0.87	0.78	0.90	0.89
P7	0.89	0.88	0.91	0.86	0.87	0.90

3.1 Data analysis

For the experiment, measurements of the prototype and its six replicas were carried out, making a total of 7 prototypes, for this, 182 tests were performed without load and with load, as a result, voltage measurements were obtained in cells 1, 2, 3, 4, 5, 6 of each prototype, these measurements were performed on different days per prototype and at different times, the time intervals of the repeated measurements were 5 minutes per prototype without load and with load. The time intervals of the prototypes without load and with load connected the cells in series were 2 minutes, as shown in Tables 13-15.

Table 14. Voltages obtained from testing the prototypes without load with the cells connected in series

P	T1	T2	T3	T4	T5	T6	T7	T8
P1	5.11	5.10	5.11	5.10	5.11	5.10	5.10	5.10
P2	5.26	5.26	5.25	5.26	5.26	5.25	5.25	5.25
P3	5.21	5.21	5.22	5.22	5.21	5.22	5.22	5.22
P4	5.20	5.21	5.20	5.20	5.20	5.20	5.19	5.19
P5	5.20	5.21	5.20	5.20	5.20	5.20	5.21	5.21
P6	5.28	5.28	5.28	5.28	5.28	5.27	5.27	5.27
P7	5.31	5.31	5.32	5.32	5.32	5.31	5.31	5.31

Table 15. Voltages obtained from testing the prototypes under load with the cells connected in series

	T1	T2	T3	T4	T5	T6	T7	T8
P1	2.59	2.56	2.55	2.54	2.54	2.53	2.53	2.53
P2	2.37	2.28	2.27	2.27	2.26	2.25	2.25	2.25
P3	1.90	1.88	1.87	1.87	1.86	1.86	1.84	1.84
P4	3.47	3.46	3.45	3.45	3.44	3.44	3.43	3.43
P5	1.86	1.84	1.83	1.83	1.82	1.81	1.80	1.80
P6	2.44	2.43	2.43	2.42	2.42	2.40	2.38	2.38
P7	2.59	2.57	2.56	2.44	2.44	2.43	2.43	2.43

Table 16. Voltages obtained with the cells in series of the prototype with load tests

Measures	Voltage (V)	Current (A)	Power Dissipation (µW)
Average of capacity test performed every two hours after 168 operating hours	1.729	322.35	557.51

Prototype capacity with load tests were carried out, the measures were recorded every two hours, accumulating 168 hours. Table 16 shows the averages obtained for the Voltage (V), Current (A), and Power dissipation(µW).

To validate the power generation, a detailed statistical analysis of the data obtained was performed. Statistical techniques as t-tests, and descriptive analysis are used to validate the results and check the significance of the measurements.

Calculation of mean and standard deviation

Eq. (11) was used to calculate the mean μ and standard deviation σ, so the results are shown in Table 17:

Table 17. Voltages obtained from the prototype cells in no-load tests

Parameters	With Load	No Load
Mean (μ)	2.395	0.863
Standard Deviation (σ)	0.569	0.065

t-Test

The Eq. (15) for the t-statistic for two independent samples is considered to evaluate the significance:

$$t = \frac{\overline{X1} - \overline{X2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (15)$$

where, s_1^2 and s_2^2 are the variances of the two samples; n_1 and n_2 are the sizes of the two samples.

The results are: *t*-statistic: -20.65903967930556; p-value: 1.7335671402908094e-28.

The results obtained after applying descriptive statistics and a t-test are analyzed to determine the reliability and accuracy of the measurements. The unloaded voltage has a mean of approximately 0.863 V, with a standard deviation of 0.052, suggesting high precision measurements. The average voltage with load is approximately 2.395 V, with a relatively high standard deviation of 0.569, indicating greater variability under load conditions. After statistically evaluating the data, the results obtained are significant, considering that the t-test (-20.66) and the p-value (1.73e-28) show the difference between the on-load and off-load voltages supporting the hypothesis of power generation with the prototype tests and its replicates.

The voltage disparities are significant between the conditions with and without load, where the results without load present greater precision in the tests performed, while the measurements with load show more variability, which allows the possibility of optimizing the process and improving the measurements, also these results agree with the results of previous specialized research, agreeing that it is important to minimize errors by controlling the load conditions since it is observed that there is evidence of diversity in the application by the presence of external interferences that affect the stability of the system under load conditions. For Logan et al. [20, 21], due to the loading situations, electrochemical systems can present variability, which, for better system stability and reliability, makes it necessary to optimize the system.

3.2 Errors analysis

It has been crucial for the application of the methodology to analyze and control systematic and random errors because these methods guarantee that the results are reliable and significant.

Systematic

The possible systematic errors of this research that could have occurred are due to:

·Measurement system failures.
·Unstable loading conditions.
·Incorrect calibration of the measuring devices.

For which the following actions were considered to ensure consistency:

·The use of regularly calibrated measuring equipment.
·The repetition of tests.
·Controlled test conditions.

Random

Also, to mitigate the influence of random errors such as:

·Variations in energy sources.
·Environmental changes
·External interferences.

The following actions were performed:

·Combinations with multiple measurements
·Averaging of the measurements.

3.3 Life cycle analysis

The prototype's environmental impact will be measured with the life cycle assessment (LCA), and the environmental effects of the graywater power generation technology, including the fabrication of copper electrodes and galvanic cells, the use of greywater as an electrolyte, and the maintenance and final disposal of the components, will be examined.

A life cycle analysis (LCA) was carried out to assess the environmental impact of the prototype, through:

- The assessment of the environmental effects derived from the technology for power generation with graywater.
- The production of copper electrodes and galvanic cells,
- The use of gray water as an electrolyte,
- The conservation and final disposal of the components.

Steps considered

Extraction and processing of copper, zinc, and other metals.

Creation and construction of galvanic cells and electrodes.

- Generation of energy with gray water.
- Replacing electrodes and components that have worn out.
- Recycling and disposal of end-of-life materials.

Data on each life cycle stage was collected for the life cycle inventory:

Materials

Copper extraction and processing requires an equivalent amount and energy: 8 kilograms of CO_2 eq per kilogram of copper. The amount and energy of zinc used in galvanized iron are equivalent to extraction and processing: 4 kilograms CO_2 eq per kilogram of zinc.

Production

Electrode production and galvanic cell assembly: 2 kg CO_2 eq.

Assembly and production: 3 kg CO_2 eq.

Gray water treatment

Reduce the organic load and the amount of energy used at each stage (extraction, manufacturing, operation and dismantling), taking into account the amount of water used in the operation and pre-treatment of graywater, as well as greenhouse gas emissions and pollutants during extraction, manufacturing and operation.

Conservation

Consider material replenishment: one kilogram of CO_2 eq per annual maintenance cycle.

Decommissioning considers recycling of copper and zinc: -2 kg CO_2 eq without CO_2.

3.4 Life cycle impact assessment

To perform this assessment, impact categories are used to evaluate the environmental impact:

The carbon dioxide equivalent in climate change (kg CO_2-eq) is evaluated as if 2 kg of each is considered in a cell, 8 kg CO_2-eq/kg×2 or 16 kg CO_2-eq is extracted, while 4 kg CO_2-eq/kg×2 or 8 kg CO_2-eq is extracted.

The total CO_2-eq of 2 kg CO_2-eq is used to manufacture galvanic cells.

With an annual energy operation generating a profit of 0.2 kg CO_2-eq/kWh×1000 kWh = -200 kg CO_2-eq.

Approximately 1 kg CO_2 eq is retained each year, while the dismantling and recycling of copper and zinc equals 2 kg CO_2 eq.

Table 18. Life cycle analysis of the prototype

LCI	Elements	Carbon Dioxide Equivalent (kg)	Total Carbon Dioxide Equivalent (kg)
Extraction (E)	Copper Zinc	8 kg CO_2-eq×2 4 kg CO_2-eq×2	16 kg CO_2-eq. 8 kg CO_2-eq.
Manufacturing (M)	2 (Galvanic cells)	1 kg CO_2-eq×2	2 kg CO_2-eq
Operation (O)*	-	-	-200 kg CO_2-eq.
Maintenance (Ma) *	-	-	1 kg CO_2-eq.
Decom & Recycle	-	-	-2 kg (Cu y Zn)
Total Balance *			
Extraction & Mfg.	24 kg (Cu & Zn) +2 kg (Man)		26 kg CO_2-eq.
Reduction	-200 kg CO_2-eq. (O) -2 kg (En)+1 (Ma.)		-201 kg CO_2-eq.
Net impact	26 kg CO_2-eq. -201 kg CO_2-eq		-175 kg CO_2-eq
(*) Annual			

The LCA (Table 18) reveals that while the suggested technology produces noteworthy environmental advantages by recycling gray water and harnessing renewable energy sources for energy production in the extraction, manufacturing, and maintenance phases, it also leaves a substantial environmental trace across the whole life cycle. When compared to traditional technologies, this solution offers a more sustainable option, particularly if recycling and by-product treatment procedures are improved.

The result of -175 kg CO_2-eq indicates a high efficiency in CO_2 emission reduction, which confirms its suitability for applications in sustainable energy management and water treatment systems and its role in ambitious environmental strategies.

4. DISCUSSION

Current environmental problems indicate that humanity's relationship with nature must change. Scientific data and media reports suggest that if the trend in energy use is not reversed, humanity is heading toward environmental destabilization and possibly its own destruction. Anthropogenic intervention has been identified as the main cause of many of these problems, implying that the solution also lies in human actions. The current scenario poses a challenge to innovate and create sustainable living systems that gradually replace the current ones, leading us to a point of no return. Clean energies and energy generation with less environmental impact emerge as vital alternatives. The guiding research question addresses the possibility of generating electrochemical energy by reusing domestic graywater, which is not only a sustainable alternative but also a way to mitigate the environmental impact of wastewater treatment. The literature on electrochemical power generation from greywater and the design and construction of a prototype for this purpose have proven to be fundamental steps in moving toward this goal. Innovation in using galvanic cells for domestic graywater reuse and electrochemical power generation represents considerable potential for a change in current energy practices.

Analysis of the findings acquired through this research is compared to previous research, allowing us to place our work in the broader context of electrochemical power generation and greywater treatment. Comparatively, the findings of this study align with previous research, such as that of Mohan et al.'s study [16], which also identified the energy potential of wastewater. However, unlike Mohan et al. [16], which focused on using fish farm wastewater, this study focused on domestic greywater, representing a more constant and accessible energy source in urban settings. The generation of voltages between 0.70 and 0.96 volts without load in this study is promising, although modest when compared to work such as that of Al Lawati et al.'s study [17], which succeeded in generating electrical power directly from chemical reactions in a galvanic cell. Nevertheless, the present study stands out for using non-polluting and recycled materials, contributing significantly to environmental sustainability, as shown by the LCA analysis results that demonstrate good efficiency with emission reduction of -175 kg CO_2-eq ideal for applications in sustainable energy management and water treatment systems.

Regarding the design and operation of the galvanic cell, our study reflects the principles described by Kordana-Obuch et al. [1] and Obaideen et al. [4], highlighting the importance of redox processes in power generation. In addition, the focus on recycled materials and graywater treatment represents an innovation over the more traditional approaches described by Filali et al. [3]. As observed in the prototypes of this study, the power generation capability of galvanic cells suggests a technical feasibility as described by Paucar and Sato [18]. However, our work is distinguished by demonstrating power generation using domestic greywater, which opens the door to renewable energy applications in residential settings. The prototypes designed in this study offer an alternative to conventional batteries that typically use heavy metals and corrosive acids, as mentioned by Karthick and Haribabu [15]. The environmentally friendly approach of this study could have significant implications for future waste management and energy sustainability.

Although our results demonstrate that it is possible to generate electric power with promising efficiency under different experimental conditions, we might consider that the small scale of the prototypes may not fully reflect the dynamics of full-scale systems and that the limited duration of the tests may not reflect the long-term system performance. In addition, we might consider as inconsistent some measurements that showed unexpected variations in voltage and current, which could have been caused by changes in gray water quality or fluctuations in ambient temperature. Although standard procedures were used to process these data, we recognize that this could affect the final interpretation of the results. The results corroborate those of Logan and Regan [20, 21], who also reported that the use of FCMs efficiently generates energy from wastewater. However, while Friedler [5] focused on greywater quality and treatment, our study extends this knowledge into the realm of power generation, addressing an important gap in the literature. Our integration of galvanic cells provides a complementary approach that has not been widely explored in the literature. Unlike Kim et al. [25], who optimized galvanic cells for wastewater in general, our graywater-specific approach offers a more specific and relevant application for domestic and commercial contexts. As demonstrated in previous studies by Jahin et al. [29], the variability in the composition of graywater can vary significantly depending on its origin, which can influence the efficiency of our electrochemical technologies with higher organic loading that can increase energy production in MFCs, while certain contaminants can inhibit electrochemical reactions.

5. CONCLUSIONS

The research demonstrated the reuse capacity of domestic graywater as an electrochemical energy source; the designed prototype produced an average no-load voltage of 5.1907 volts and demonstrated its capacity to supply energy to low-consumption devices, thus validating the practical application of this energy source. Although the energy levels generated were relatively low, its construction is safe for the environment, and the use of non-polluting materials were significant achievements with sustainable and circular economy principles, also considering the ability to produce 55.65 mAh of energy for 168 uninterrupted hours, which is considered a promising result that indicates potential for the development of more sustainable and efficient energy solutions in the future. Although the proposal is a contribution because of the materials used and the results obtained, it is possible to identify the limitations of the prototype design, which are in its small scale, which could hinder the ability to generalize its results to more extensive implementations, also the chemical composition of the graywater used which may vary in different contexts and its durability which can be tested in the long term.

The proposed technology's practical applications are wide and diverse, and it can be integrated in different contexts, such as rural areas in unprotected areas that are sometimes forgotten by the State, with the implementation of individual houses to reduce energy and water costs, residential, commercial, and industrial, which can be applied in pilot projects in these sectors and that it is possible to perfect in the real world.

For future research, it is necessary to identify areas that require further exploration, particularly in poor countries where energy does not reach, where management policies could be formulated to support the sustainable use of water and energy resources with the reuse of greywater as the proposed technology offers a practical solution to reduce dependence on non-renewable energy sources and minimize the burden on wastewater treatment systems that are sources of pollution.

It is also possible to identify specific areas for optimizing economical electrode materials and electrolyte variability conditions to improve the proposal's efficiency. Regarding scalability and durability, long-term and larger-scale further research is required to evaluate the system's durability and applicability in various environments.

Additional studies on the environmental footprint of the technology are also recommended, including more detailed life cycle analysis and impact studies in different ecosystems. Therefore, this study opens several promising avenues for future research, considering that it is evident that it is possible to generate energy from graywater using electrochemical technologies; it is important to optimize the electrode materials and operating conditions by exploring new combinations of materials that increase the efficiency and stability of the system. Optimization of the materials used in the electrodes and electrolytes can be done with nanomaterials and alloys as efficiency improvement opportunities to determine the durability of the proposal. In addition, a study of electrolyte conditions related to ionic conductivity and pH could maximize electrochemical performance.

A study that evaluates the scalability and durability of the proposal would help with its practical adoption. Longer-term and larger-scale studies can provide operational stability, and if they collaborate with industry and local communities, it would be very beneficial. Environmental assessment with the proposal is necessary to understand its impact and identify areas where the environmental footprint can be reduced, as well as how it impacts the various ecosystems.

Therefore, the proposed power generation through the prototype is feasible and promising for power generation from greywater using electrochemical technologies. The implications of this work are significant for future research, policy formulation and practical applications, which is a commitment to further explore and optimize this technology and continue contributing to the sustainable and efficient use of resources.

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