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Original Article

Comparative evaluation of remediation technologies to optimize greywater quality within a circular economy framework

Evaluación comparativa de tecnologías de remediación para optimizar la calidad de aguas grises en economía circular

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Abstract

Introduction: greywater contains contaminants that disrupt ecological balance, reduce water availability for productive uses, and limit access to water in certain regions. Treating this wastewater is essential to reduce environmental impacts and promote sustainable resource management.
Objective: to compare the efficiency of electroremediation (ER), phytoremediation (PR), and electro-phytoremediation (EPR) for greywater treatment under a circular economy approach in Los Otates, Huanímaro, Guanajuato.
Methodology: greywater was treated using ER, PR, and EPR systems, with Zantedeschia aethiopica applied in PR and EPR. Fifteen physicochemical parameters were analyzed, including phosphates, nitrates, dissolved oxygen, pH, and electrical conductivity. Treatment performance was assessed through the Water Quality Index (WQI).
Results: PR achieved the highest WQI reduction (59.59%), followed by EPR (40.32%) and ER (27.4%). Electrokinetic processes produced iron and aluminum hydroxide coagulates, which enhanced contaminant removal. Calcium oxalate crystals recovered from Z. aethiopica were repurposed for insecticidal applications, reinforcing the circular economy concept.
Conclusions: Phytoremediation was the most effective technology for improving greywater quality, while electrokinetic processes provided additional removal mechanisms. The combination of treatment and resource recovery supports sustainable water management, contributing to environmental restoration and improved living conditions in vulnerable communities.

Keywords: greywater, Environmental Pollutants, Zantedeschia aethiopica, Calcium Oxalate, Water Quality

Resumen

Introducción: las aguas grises contienen contaminantes que alteran el equilibrio ecológico, reducen la disponibilidad de agua para usos productivos y limitan el acceso a este recurso en diversas regiones. Su tratamiento es esencial para mitigar impactos ambientales y fomentar la gestión sostenible de los recursos hídricos.
Objetivo: comparar la eficiencia de la electrorremediación (ER), fitorremediación (PR) y electrofitorremediación (EPR) en el tratamiento de aguas grises bajo un enfoque de economía circular en la comunidad de Los Otates, Huanímaro, Guanajuato.
Metodología: se trataron aguas grises mediante sistemas de ER, PR y EPR, utilizando Zantedeschia aethiopica en PR y EPR. Se analizaron quince parámetros fisicoquímicos, incluyendo fosfatos, nitratos, oxígeno disuelto, pH y conductividad eléctrica. La eficacia del tratamiento se evaluó mediante el Índice de Calidad del Agua (ICA).
Resultados: la PR alcanzó la mayor reducción del ICA (59,59%), seguida por la EPR (40,32%) y la ER (27,4%). Los procesos electrocinéticos generaron coágulos de hidróxidos de hierro y aluminio, que favorecieron la remoción de contaminantes. Los cristales de oxalato de calcio extraídos de Z. aethiopica se reutilizaron con fines insecticidas, reforzando el concepto de economía circular.
Conclusiones: la fitorremediación fue la tecnología más eficaz para mejorar la calidad de las aguas grises, mientras que los procesos electrocinéticos aportaron mecanismos complementarios de remoción. La combinación de tratamiento y aprovechamiento de subproductos respalda la gestión hídrica sostenible, contribuyendo a la restauración ambiental y al mejoramiento de las condiciones de vida en comunidades vulnerables.

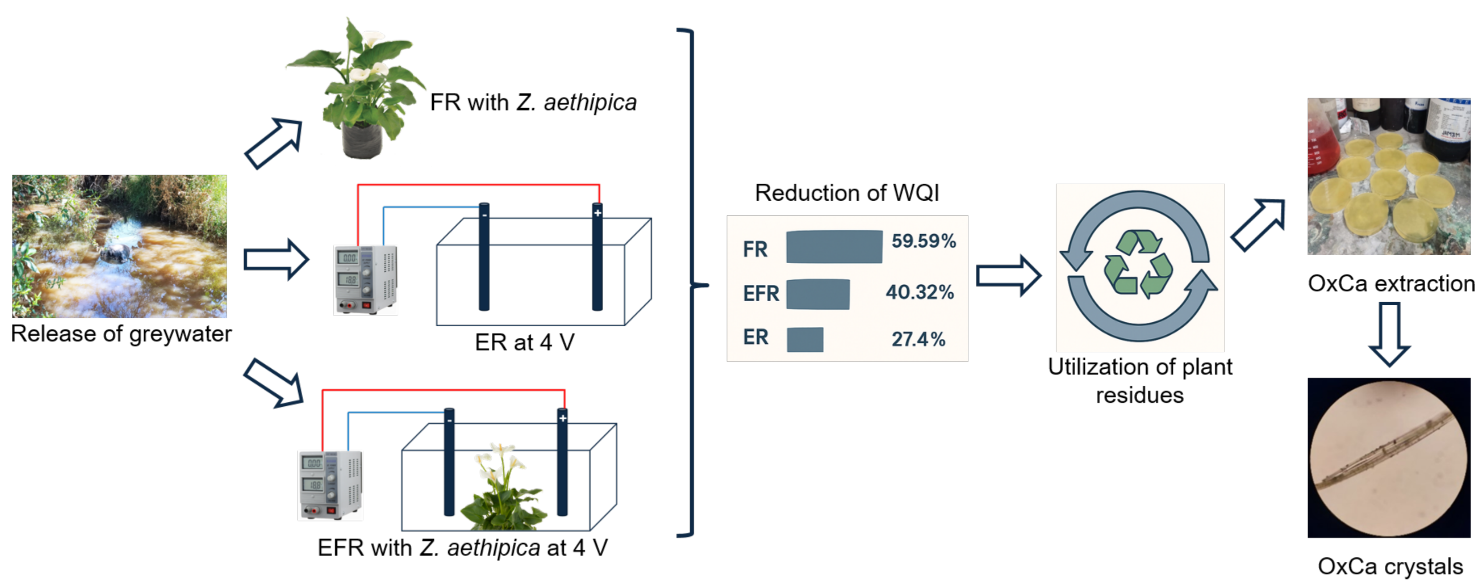
Palabras clave: aguas Grises, Contaminantes Ambientales, Zantedeschia aethiopica, Oxalato de Calcio, Calidad del Agua.

Spanish version

Why was it conducted?
This study was conducted to evaluate and compare three technologies (electroremediation (ER), phytoremediation (FR), and electro-phytoremediation (EFR)) for the treatment of greywater under a circular economy approach, aiming to improve water quality, promote sustainable practices, and explore the reuse of treated plant biomass in vulnerable communities.

What were the most relevant results?
The most relevant results showed that FR, using Zantedeschia aethiopica, achieved the highest efficiency by reducing the Water Quality Index (WQI) by 59.59%, followed by EFR with a 40.32% reduction, and ER with 27.4%. Electrokinetic processes produced iron and aluminum hydroxide flocs that were essential in contaminant removal. Additionally, calcium oxalate crystals were extracted from Z. aethiopica and repurposed for insecticidal use, reinforcing the circular economy model.

What do these results contribute?
These results demonstrate the high potential of these technologies (particularly phytoremediation) for treating greywater while promoting sustainable resource management. They also highlight the added value of integrating circular economy principles, where treated biomass can be reused for economic and environmental benefits, contributing to improved environmental quality and the well-being of vulnerable communities.



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Introduction

The constant increase in the global population has brought with it a growing demand for water and, consequently, an increase in pollution of water resources, which affects their quality and availability for human consumption. Water pollution encompasses physico-chemical and biological alterations of its original parameters, leading to the degradation of water bodies and rendering them toxic to both the environment and human health (1).

Industrialization and progress have generated increased water consumption both in productive activities and daily life, while synthetic wastes and human residues negatively affect the quality of freshwater bodies (2). Wastewater originating from domestic, industrial, and community activities contains both liquids and solid residues and can mix with surface water, groundwater, or rainwater (3).

So called greywater comes from showers, bathtubs, laundry sinks, washbasins, and kitchen sinks; its reuse can represent between 43% and 70% of the volume currently discarded as wastewater (5). Although it contains lower levels of fecal contamination compared to blackwater, it still poses health risks due to the presence of chemical compounds and pathogenic microorganisms (4).

Wastewater is physically characterized by its total solids content, odor, temperature, density, color, and turbidity (3). Biodegradable organic matter also affects the color, odor, and taste of water, besides promoting the proliferation of pathogenic microorganisms (6). Contaminants such as nitrogen, phosphorus, carbon, and dissolved oxygen affect the stability of aquatic ecosystems and human health, with nitrogen and phosphorus being the primary contributors to eutrophication (4).

In Mexico, the regulation of wastewater is based on the Constitution of the United Mexican States and the National Waters Law, supplemented by official standards such as NOM-001-SEMARNAT-2021 and NOM-127-SSA1-2021, which establish limits for contaminants. The National Water Commission (CONAGUA) uses the Water Quality Index (WQI) to assess water quality, a tool that expresses this parameter in a simplified way through a single numeric value summarizing water condition based on various parameters. Its purpose is to facilitate the interpretation of water quality through a scale from 0 to 100 for proper classification (8).

The country faces serious problems related to the pollution of rivers, lakes, and groundwater, with only 47.5% of wastewater receiving adequate treatment, generating negative impacts on public health and the environment (7). In Guanajuato, these problems are aggravated by population growth, industrial activity, and insufficient infrastructure, which intensify soil and water body contamination (9).

Electroremediation and phytoremediation are innovative techniques for wastewater treatment. Electroremediation uses electrical energy to induce physicochemical and electrochemical processes that enable contaminant removal. Phytoremediation uses plants to remove or contain contaminants from the environment through mechanisms such as phytostabilization, phytostimulation, phytovolatilization, phytodegradation, phytofiltration, and phytoextraction (10).

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Zantedeschia aethiopica is a semi-aquatic plant native to southern and eastern Africa, notable for its potential in phytoremediation processes, showing high capacity to retain arsenic in comparative studies with other species. Besides its ornamental function, this plant has potential applications as an anti-algal agent, bioinsecticide, and in constructed wetland systems designed for wastewater treatment (4).

Rapid human and economic growth, combined with improper water use, has caused severe deterioration of aquatic environments due to the discharge of tons of biologically active substances without considering their effects. Wastewater and greywater contain contaminants that negatively impact ecosystems by modifying properties such as toxicity, color, odor, and taste of water. Greywater constitutes between 50% and 80% of total domestic wastewater and does not include urine or feces. It is often discharged without regard to environmental repercussions (11–13).

Globally, Mexico is the second-largest generator of wastewater and greywater after China and faces serious problems due to insufficient treatment of these waters. An undetermined volume of contaminated water is not collected and ends up lost in drains or illegally discharged, carrying pathogens, heavy metals, hygiene product residues, and pesticides (45). Water sources such as rivers and aquifers cannot absorb or neutralize this pollutant load, rendering them incapable of sustaining aquatic life and preserving ecological balance (14).

In Guanajuato, river contamination from industrial and domestic discharges has limited access to water for productive activities, and in some regions, surface waters are virtually unavailable. In the community of Otates, municipality of Huanímaro, greywater is discharged directly into a local stream, affecting ecological balance and posing risks to human health.

Human activity has introduced a wide variety of organic compounds, many highly toxic, into aquatic ecosystems, causing significant pollution. Inadequate management of greywater and wastewater encourages the proliferation of pathogenic microorganisms that can cause diseases such as diarrhea and gastroenteritis. These pathogens can come from both infected humans and animals, which may be ill or asymptomatic carriers (15).

An important challenge in managing greywater lies in its mixing with wastewater and the homogeneous treatment given in treatment plants. This approach ignores the fact that greywater, having lower contaminant levels, is easier to treat and recycle. Although it contains microorganisms, differentiated health risk assessments are necessary, especially for water from multi-family dwellings (16).

To ensure efficient and sustainable treatment of greywater, alternative technologies are required to allow its reuse or discharge with good quality, minimizing energy consumption and secondary contaminant generation (17). In this context, phytoremediation emerges as a promising and low-cost solution. This method uses plants to degrade, assimilate, or detoxify heavy metals and other contaminants. Unlike conventional technologies, phytoremediation requires no additional energy, is economical, and has proven effective in reducing the contaminant load of domestic wastewater (18).

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Among plants with the greatest phytoremediation potential is calla lily (Zantedeschia aethiopica), an aquatic species excelling in phytoextraction and phytostabilization processes. Various studies have shown that this plant acts as a natural, efficient, and economical adsorbent for heavy metals such as manganese and performs notably in domestic wastewater treatment (19).

For example, Z. aethiopica has been used to remove arsenic from water using horizontal subsurface flow constructed wetlands with batch feeding at low arsenic concentrations (34±11 μg/L), determining that the presence of the plant increased arsenic retention by about 20% (33).

Similarly, Z. aethiopica, together with Canna indica, has been studied in laboratory-scale artificial wetlands to reduce organic matter (BOD, COD, and thermotolerant coliforms), with reduction values ranging from 85% to 90% (34).

Additionally, it is used ornamentally in residential gardens, as well as in public gardens and parks. It can also be used as a potted plant to beautify patios or indoor spaces (35).

Another important use identified for Z. aethiopica is as a bioinsecticide, due to the presence of chemical compounds such as calcium oxalate, which may serve as a defense mechanism against herbivores. Calcium oxalate crystals form inside specialized cells called idioblasts. These crystals are present in almost all parts of the plant, including roots, leaves, stems, fruits, seeds, floral organs, anthers, and root nodules (36, 37).

Zantedeschia irritates the skin upon contact similarly to other members of the Araceae family, due to the presence of calcium oxalate (CaOx) crystals in the form of raphides (needle-like shapes). CaOx crystals are involved in functions such as regulating cellular pH, gravity perception, mechanical support, and plant defense against herbivores. Needle-shaped crystals mechanically pierce animals that consume them, and this effect is enhanced by proteolytic toxins. Some plants have been observed to produce CaOx as an induced defense response (23–25).

Another potential use of Z. aethiopica is as a bioindicator of environmental pollution, specifically Cr^{6+}, showing nonspecific physiological effects such as growth inhibition and reduction at concentrations of 300 mg/kg and 200 mg/kg of Cr^{6+} (38).

Two cycloartanes and ten sterols have been identified in Z. aethiopica, along with three lignans and ten phenylpropanoids, which have shown good anti-algal activity for some aromatic compounds in assays (39). Therefore, its use represents a viable alternative for advancing toward more sustainable management of contaminated waters.

Circular economy is a strategic approach aimed at maximizing resource use and minimizing waste generation through reuse, recycling, and material valorization, promoting the regeneration of natural systems and efficient use of materials and energy (28, 29). This model contrasts significantly with the traditional linear paradigm of "extract, produce, and discard," as it prioritizes the creation of closed loops that favor sustainability and reduce environmental impact (30, 31).

It is characterized as an economic system that replaces the linear model by incorporating practices such as reduction, reuse, recycling, and material recovery at all levels of the production and consumption chain. Its goal is to achieve sustainable development benefiting present and future generations by fostering environmental quality, economic growth, and social equity (42).

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The integration of the circular economy in wastewater management not only contributes to the recovery of degraded ecosystems but also creates economic opportunities by transforming waste into usable resources, promoting sustainable and equitable practices in affected communities (32).

The purpose of this research was to compare electroremediation, phytoremediation, and electro-phytoremediation technologies for treating greywater from a stream in the community of Los Otates, Huanímaro, Guanajuato, under a circular economy approach, by evaluating the reduction of dissolved organic compound loads through these techniques, integrating Zantedeschia aethiopica, and sustainably utilizing the plants used after treatment, promoting their reuse within circular economy schemes.

Materials and methods

Greywater sampling

The study was conducted using greywater from a stream in the community of Los Otates, in the municipality of Huanímaro, Guanajuato, located in the northern area of the municipality. Domestic wastewater from household cleaning activities in the community flows into this stream. Among the activities that generate the most domestic wastewater are laundry and dishwashing; these activities were identified during reconnaissance visits. Therefore, a representative sampling was carried out following the procedure described in the technical standard PROY-NMX-AA-003-2019.

Preparation of Z. aethiopica

To prepare the Z. aethiopica plants, young specimens of the species were used and placed in plastic containers measuring 60 cm in height and 25 cm in diameter. The containers were filled with water without completely submerging the plants, to encourage the development of roots and rhizomes. No soil or substrate was added. The plants were kept in containers for 30 days, with the water being changed every two weeks to ensure proper development.

Physicochemical characterization of the water

The following parameters of the collected water were determined using the Backpack Lab kit from HANNA Instruments®: phosphates, nitrates, CO_2, total hardness, and dissolved oxygen (DO). For the parameters pH, oxidation-reduction potential (ORP), % dissolved oxygen saturation, dissolved oxygen (DO) concentration, electrical conductivity (EC), absolute conductivity, resistivity, total dissolved solids (TDS), salinity, and turbidity, the multiparameter device HI9829 from HANNA Instruments® was used. The parameter values were recorded for analysis.

Treatment Design

The following treatments were established: phytoremediation (PR), electroremediation (ER), and the combination of both, electro-phytoremediation (EPR). For the PR process, the previously prepared Z. aethiopica specimens were placed in glass aquariums, which were filled with 2.3 liters

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of the collected greywater and placed in an environment free from external disturbances at room temperature. The treatment was performed in triplicate and maintained for five days, monitoring the physical condition of the plants. Figure 1 shows the root and rhizome system in contact with the greywater during the PR process.

Figure 1 – Root and rhizome system in contact with greywater during the phytoremediation process. **Source:** Authors**.**

For the ER process, a KEYSIGHT® power supply, alligator clips, aquariums, aluminum electrodes measuring 12.5 x 2.5 cm, and 2.3 liters of collected greywater per aquarium were used. The electrodes were connected in parallel using alligator clips and kept submerged to one-third of their depth in the greywater, with a current of 4 V supplied in 2 hour intervals per day. The voltage was kept constant, the treatment was conducted in triplicate, and it lasted for five days. Figure 2 shows the setup of the ER treatment.

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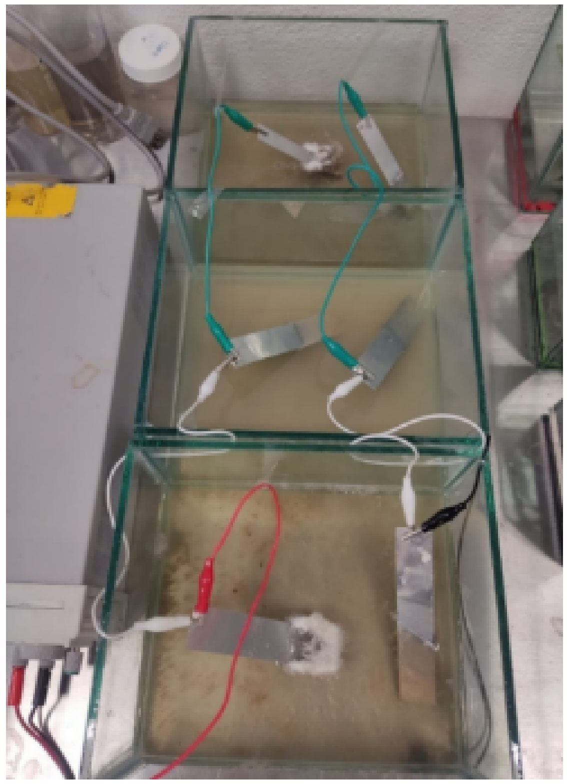

Figure 2. Electroremediation process in operation, showing contact with the electric current and electrodes, as well as initial changes in the water. **Source:** Authors.

For the EPR process, a KEYSIGHT® power supply, alligator clips, aquariums, aluminum electrodes measuring 12.5 x 2.5 cm, previously conditioned Z. aethiopica specimens, and 2.3 liters of collected greywater per aquarium were used. The electrodes were connected in parallel using the alligator clips, and a 4 V current was applied for 2 hours per day, keeping both the plants and electrodes submerged to one-third of their depth in the greywater. The treatment was performed in triplicate and lasted for five days. Figure 3 shows the setup of the EPR treatment.

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Figure 3. Setup of the elements in the electro-phytoremediation process. **Source:** Authors

Monitoring of Zantedeschia aethiopica

During the PR and EPR treatments, leaf color changes were analyzed. Fully developed leaves from the conditioned plants were selected as controls due to their stable color and were used as a reference. Regular observation of the leaves allowed for the identification of any changes in color, which could indicate potential issues with the plant's health.

Periodic leaf counts were also conducted on the Z. aethiopica specimens used in the treatments. The number of fully developed visible leaves on each plant was recorded, and underdeveloped leaves were monitored and included in the count once they reached full development. This tracking helped evaluate the adaptation and health of the plants.

Root visualization was performed by inspecting the number and general condition of roots during the treatment periods. The plants were examined for signs of detachment, breakage, rotting, and the growth of new roots. This assessment was carried out at the beginning and end of each treatment to monitor root development and health.

Observation of Coagulates

After completing the electrokinetic treatments (ER and EPR), coagulate formation was monitored using a Zuzi® microscope, and images were recorded using ISCapture® software. Representative coagulates from each electrokinetic treatment were selected and observed at 40x magnification, and photographic documentation was performed.

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Calculation of the Water Quality Index (WQI)

To calculate the WQI, the methodology proposed for the Brown Index was used (43). This is a variation of the NSF (National Sanitation Foundation) index, which uses nine parameters and a weighted geometric mean to summarize and simplify all available water quality information into a single numerical value (40). This index was developed to determine the WQI of rivers and streams (41), making it suitable for this study. Moreover, the Brown Index allows for the use of a greater number of parameters in the WQI calculation, so it was adapted to the fifteen physicochemical parameters analyzed in this study: pH, EC, TDS, total hardness, nitrates, phosphates, turbidity, CO_2, DO, mVpH, ORP, % DO saturation, absolute conductivity, resistivity, and salinity.

The standard reference values for these parameters were established in accordance with NOM-001-SEMARNAT-2021 and NOM-127-SSA1-2021. The resulting WQI value was compared with a scale ranging from zero to over one hundred, as illustrated in Table 1, classifying water quality into levels ranging from excellent, good, poor, very poor, to unfit for human consumption. This procedure was carried out for each of the treatments.

Table 1. Water Quality Index values proposed by Brown (44).

Range	Status
0-25	excellent
26-50	good
51-75	poor
76-100	Very poor
100	Unsafe for compsumption

Extraction of calcium oxalate from Z. aethiopica

After completing the PR and EPR treatments, 300 g of fresh parts of Z. aethiopica, such as leaves, stems, and rhizomes, known to accumulate CaOx, were collected. These were then ground until a homogeneous paste was obtained, which was mixed with 500 mL of distilled water and stirred for 30 minutes at room temperature. The mixture was filtered to separate the solids from the liquid solution and concentrated to 300 mL at 50°C using a double boiler. To precipitate the CaOx, the pH of the concentrated solution was adjusted to 4–5 using glacial acetic acid and concentrated nitric acid. The adjusted solution was left to rest in Petri dishes for 24 hours at room temperature to allow the formation of CaOx crystals. The formed crystals were observed under a Zuzi® microscope at 50x magnification, and images were recorded using ISCapture® software.

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Results and discussion

WQI results after the treatments

According to the characterization of greywater, a high level of organic pollutants was detected, compromising the ecological balance. Nitrate and phosphate levels exceeded the limits established by Mexican environmental regulations by up to 400%. These contaminants promote algal growth by reducing oxygen levels in the water and causing eutrophication.

Table 2 shows the WQI results before and after the treatments. The WQI of the untreated water (241.97) indicates very poor water quality and high pollution levels, meaning it is unfit for human consumption. After the ER process, a decrease in WQI was observed, reaching a value of 175.65. In the case of PR, the WQI decreased to 97.77, shifting the classification from water unfit for human consumption to very poor water. Finally, the combination of both processes, EPR, resulted in a WQI of 144.39. All three treatments show improvement, though significant pollution remains, exceeding Brown's weighting scale. However, these values are noticeably lower than the WQI of untreated water.

Table 2. WQI Results After Treatments

General WQI Results					
PARAMETERS	Standard value	Control (untreated)	ER	PR	EPR
pH	8.5 pH units	6.61	8.6	7.46	7.72
EC	300 µS/cm	1171.28	1478.33	1050	1055
TDS	1000 mg/L	584.142	740.33	523.6	528
Total hardness	500 mg/L	157.52	108.3	178	170
Nitrates	11 mg/L	30.95	10	10	10
Phosphates	1 mg/L	4.61	3.3	3	5
Turbidity	3 NTU	42.428	31.33	1.9	4.7
CO_2	10 mg/L	90.47	0	51	43.8
Disolved oxygen	6 mg/L	4.75	1.82	4.6	2.25
mVpH	8.5 pH units	31.91	25.83	2.466	4.1
ORP	200 mV	64.68	77.9	71.2	66.83
% D.O. saturation	80 %	31.7	31.7	31.7	31.7
Absolute conductivity	50 µS/cm	864.14	1422	786.6	1046
Resistivity	0.5 kΩ·cm	0.00087	0.0007	0.00093	0.000936
Salinity	0.99 g/L	0.58	0.74	0.52	0.52
WQI		241.97	175.65	97.77	144.39

Source: Authors

Figure 4 shows the final percentages of each of the treatments developed. It can be observed that the PR treatment achieved the greatest reduction in WQI (59.6%), followed by EPR with a 40.33% decrease, and finally ER with a 27.41% reduction.

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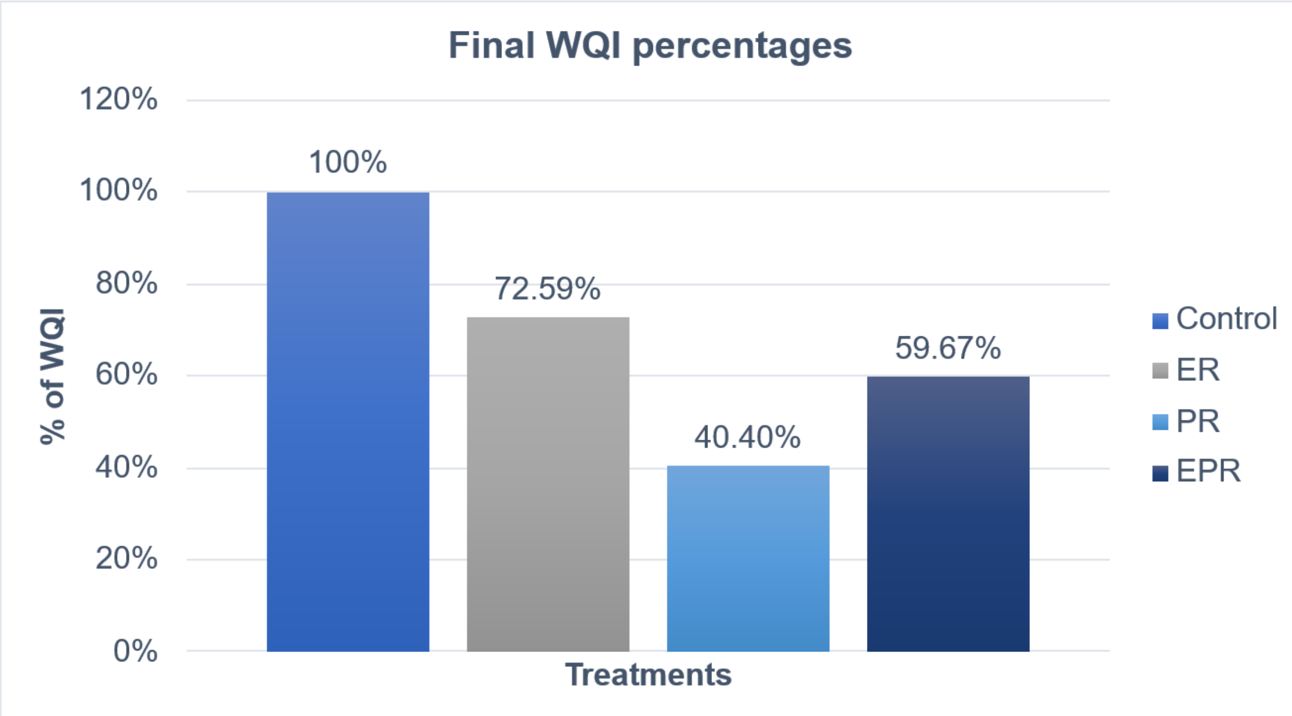

Figure 4. Final percentage for each of the treatments developed**. Source:** Authors.

According to these results, the PR process is the most suitable, as it showed a 59.59% reduction in WQI compared to the untreated water, followed by the EPR treatment, with a 40.32% decrease, and finally, ER achieved a 27.4% reduction in the WQI. However, some parameters, such as pH, EC, absolute conductivity, TDS, hardness, ORP, resistivity, and salinity, showed significant increases.

In the case of the pH increase, this may be due to the formation of metal hydroxides during the electrokinetic processes, because of the reactions associated with the wear of the electrodes (20). Additionally, pH can increase in acidic wastewater but decrease in alkaline waters (21), while the increase in EC and absolute conductivity in ER could be attributed to the presence of electrolytes such as NaCl or $CaCl_2$, the generation of ions, or the electrolysis of dissolved salts (20).

The increase in TDS in the ER process may be due to ion generation, which, when added to the water as dissolved solids, are produced by the electric current applied to the aluminum electrodes. Likewise, the formation of coagulates may contribute to the increase in dissolved solids. On the other hand, the increase in total hardness and ORP could be the result of aluminum ion release (22), which can react with other chemical species in the water, such as calcium and magnesium.

Similarly, the increase in resistivity could be attributed to the formation of aluminum hydroxides, which may react with calcium and magnesium ions present in the water. Additionally, an increase in pH can be directly related to a rise in this parameter. Finally, the formation of coagulates could have a concentrating effect on the salts in the water, which explains the increase in salinity.

Results of Zantedeschia aethiopica monitoring

The color of the leaves went from a vibrant, shiny green in the untreated controls—indicating good plant health—to a slight loss of color and shine after the PR process, although no significant

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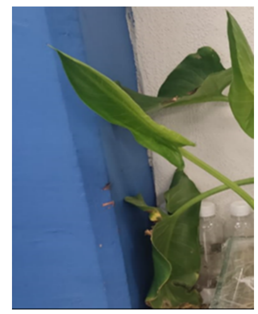
changes were observed. After EPR, the leaves took on a deeper green tone with reduced shine and greater saturation in a matte green shade, suggesting weakening due to exposure to both treatments. These changes are presented in Table 3.

Table 3 – Changes in plant coloration throughout the processes.

Evidence of leaf color after the treatments			
Photographic record			
Process	Untreated	PR	EPR

Source: Authors.

On the other hand, the leaf count of the plants used in the treatments at the end of the processes showed significant variations, as shown in Table 4.

Table 4. Variables in the number of leaves throughout the processes.

Number of Leaves in *Zantedeschia aethiopica* **Specimens**			
Process	**Number of Leaves**		
	Specimen 1	**Specimen 2**	**Specimen 3**
Control	3	3	4
After PR	2	3	3
Before EPR	1	4	3

Source: Authors.

Regarding the roots, the changes are documented in Table 5. The roots recorded in the control specimens appeared healthy, with a white color and firm thickness. However, after the PR treatment, there was a reduction in the number of healthy roots, and a color change was observed, turning yellowish. On the other hand, with the EPR treatment, although the number of roots initially decreased at the beginning of the process, the remaining roots showed adaptability by the end of the treatment, developing a greater number of new roots.

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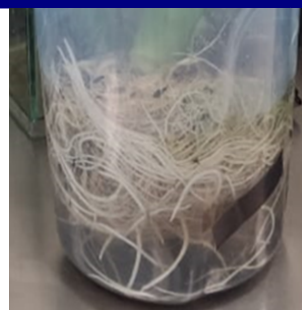
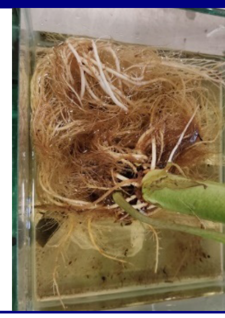
Table 5. Changes in roots throughout the processes

Root changes during the processes			
Photographic record			
Process	Untreated	PR	EPR

Source: Authors.

Coagulation results

Tables 5 and 6 show the coagulates obtained after the ER and EPR processes, along with structural details of their morphology. The generated coagulates exhibited an irregular and amorphous structure, with color tones ranging from reddish-brown to grayish-white. This coloration is attributed to the presence of iron and aluminum ions, respectively. In both processes, ER and EPR, the grayish-white color predominated, which is likely due to the wear of the aluminum electrodes used during the treatments. Table 7.

It is important to note that the most common coagulates generated in electrokinetic processes are iron and aluminum hydroxides. These ions, released during the reactions, form long chains of polyhydroxides, which play a fundamental role in the removal of contaminants present in water (26).

The elimination of contaminants occurs mainly through two mechanisms: chemical complexation, where the contaminants bind to the hydroxides, and electrostatic attraction, which allows the capture of charged particles (27).

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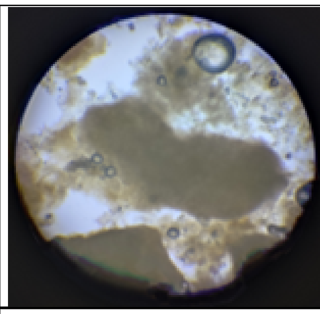
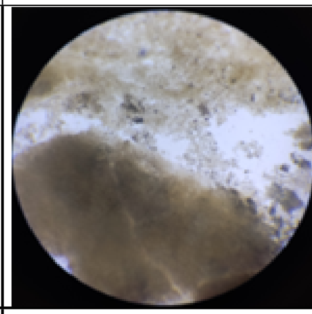
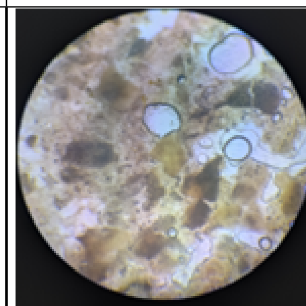
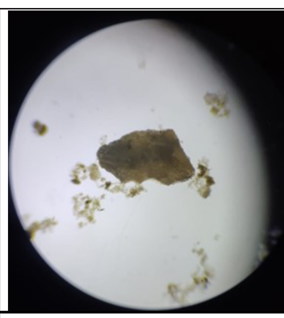
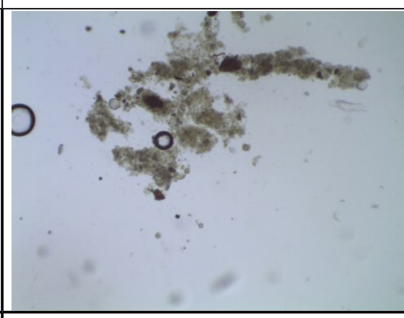
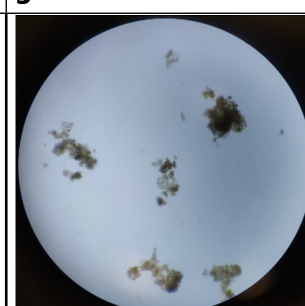
Table 6 – Coagulates generated after ER

Coagulates Resulting from ER			
Repetition	**1**	**2**	**3**
40x Magnification Record			
Characteristics	Round and clustered shapes, predominantly grayish-white in color	Large clusters with weak structure, predominantly reddish-brown in color	Multiple small structures with high firmness, reddish-brown and grayish-white in color

Source: Authors.

Table 7 – Coagulates generated after EPR

Coagulates Resulting from EPR			
Repetition	**1**	**2**	**3**
40x Magnification Record			
Characteristics	Few conglomerated forms, predominantly grayish-white in color	Small and weak unions, predominantly grayish-white in color	Small and dispersed structures, reddish-brown and grayish-white in color

Source: Authors.

Obtaining CaOx

After the extraction of CaOx, a slightly turbid liquid solution was obtained with visible suspended crystals. The characteristics of these crystals are detailed in Table 8, where the formation of structures with diverse morphologies is identified, including styloids, raphides, and druses, which exhibit elongated and spherical shapes.

Figure 5 illustrates the predominant particulate material, composed mainly of smaller crystals. This complexity in the crystalline structures suggests variability in the mechanisms of crystal formation and growth, which may be influenced by the conditions used during the extraction process.

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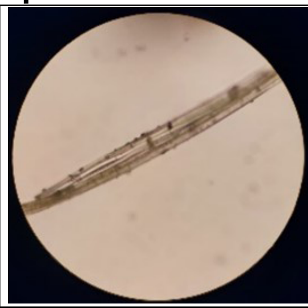
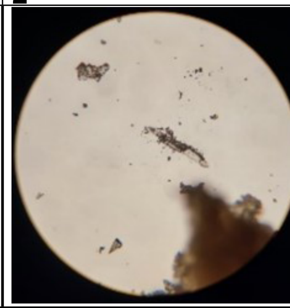
Table 8 – CaOx Crystals

Resulting Crystals			
Containers	1	2	3
50x Magnification Record			
Characteristics	Crystals with raphide-like needle shape (raphides)	Styloid-shaped crystals	Clustered crystals with druse-like shape

Source: Authors.

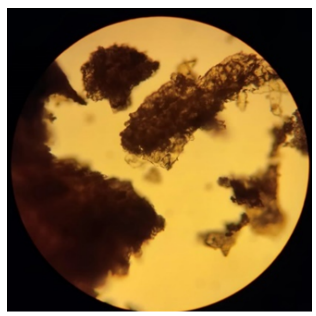


Figure 5 – CaOx crystals with druse shapes. **Source:** Authors.

Conclusions

This research allowed for a comprehensive comparison of electrorremediation, phytoremediation, and electro-phytoremediation technologies for the treatment of greywater under a circular economy approach.

The results showed that phytoremediation using Zantedeschia aethiopica was the most effective technique, reducing the Water Quality Index by nearly 60%. This finding aligns with previous studies highlighting the potential of plants to remove contaminants from wastewater (34, 35).

The efficiency of phytoremediation in this study may be explained by the intrinsic capacity of Z. aethiopica to adsorb and assimilate heavy metals and other organic compounds. Prior research has demonstrated that plants with high biomass and well-developed root systems can act as natural filters and extraction agents (23). However, natural variability in plant growth and health could lead to differences in process performance, potentially affecting reproducibility under real conditions if the parameters for plant conditioning are not standardized and controlled.

Similarly, the combination of techniques in electro-phytoremediation also proved effective, showing intermediate performance between the individual treatments. This combination leverages the synergistic potential of both methods; nevertheless, the interaction between the applied current and

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plant viability could present challenges that must be considered for real-world applications. Some studies indicate that prolonged exposure to electric currents may induce stress in plant biomass, affecting contaminant uptake capacity (20). Therefore, it is necessary to optimize operational parameters such as current intensity and frequency to minimize adverse effects on the process.

On the other hand, electrorremediation showed more limited results in terms of efficiency, but no less relevant. This lower performance may partly be due to the wear of aluminum electrodes, which can release ions that react with other compounds in the water, influencing parameters such as hardness, ORP, and salinity. Previous investigations have shown that electrode degradation can generate undesirable byproducts and limit the large-scale application of this technology (22, 26).

Beyond the technical results, this research demonstrates that adopting sustainable technologies such as ER, PR, and EPR not only helps mitigate water pollution but also generates positive economic and social impacts in resource-limited communities. In this regard, circular economy promotes production models focused on efficient resource use and regeneration of natural systems through closed loops (31). This vision is reinforced by the argument that technological decentralization fosters social equity and community empowerment (29), highlighting the key role of circular solutions in environmental education and the transition toward resilient and sustainable development models (32).

Moreover, the sustainable utilization of plants used in these processes lays the foundation for their reuse within circular economy frameworks, strengthening the potential of these technologies as ecological and sustainable alternatives for wastewater management.

The implementation of these techniques will not only contribute to improving water quality but also promote more responsible and sustainable practices to address water pollution in vulnerable communities such as Los Otates in Huanímaro, Guanajuato. The techniques developed in this research could be implemented in modular systems as treatment units adapted to the water volumes generated in communities. Additionally, these systems could be integrated with renewable energy sources, such as solar panels, to power electrokinetic treatment systems and reduce reliance on conventional energy.

Likewise, community members could be engaged through training workshops focused on the maintenance and monitoring of treatment systems to foster self-management of greywater. In this context, modules on circular economy could be included, highlighting the reuse of biomass used in treatments to produce bioinsecticides and generate economic benefits for community members. These findings underscore the importance of continuing to explore innovative approaches that integrate circular economy principles in domestic wastewater treatment.

CrediT authorship contribution statement

Erick Rodolfo López Almanza, Alejandro González Barbosa Curación de datos, Conceptualización – Ideas, Análisis formal, Adquisición de financiación. Aaron Guerrero Campanur, Investigación, Metodología: Alejandro González Barbosa. Administración de proyectos. Recursos, Supervisión, Visualización – Preparación.

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References

1. Bashir I, Lone F, Ahmad R, Mir S, Dar Z, Ahmad S. Concerns and threats of contamination on aquatic ecosystems. In: Rehman R, Ahmad R, Qadri H, editors. Bioremediation and Biotechnology [Internet]. Springer Nature Switzerland AG; 2020 [cited 2025 Aug 18]. https://doi.org/10.1007/978-3-030-35691-0_1

2. Ejiohuo O, Onyeaka H, Akinsemolu A, Nwabor OF, Siyanbola KF, Tamasiga P, et al. Ensuring water purity: Mitigating environmental risks and safeguarding human health. Water Biology and Security [Internet]. 2024 Dec 20 [cited 2025 Aug 18];4(2):100341. https://doi.org/10.1016/j.watbs.2024.100341

3. Manasa RL, Mehta A. Wastewater: sources of pollutants and its remediation. In: Gothandam K, Ranjan S, Dasgupta N, Lichtfouse E, editors. Environmental biotechnology. Vol. 2. Environmental chemistry for a sustainable world, vol 45. Cham: Springer; 2020 [cited 2025 Aug 18]. p. 197–219. https://doi.org/10.1007/978-3-030-38196-7_9

4. Van de Walle A, Kim M, Alam MK, Wang X, Wu D, Dash SR, et al. Greywater reuse as a key enabler for improving urban wastewater management. Environmental Science and Ecotechnology [Internet]. 2023 Oct 1 [cited 2025 Aug 18]; 16:100277. https://doi.org/10.1016/j.ese.2023.100277

5. Bautista MI, Rodríguez DA, Castañeda IE, González M, Escalante JE. Tratamiento de aguas grises para viviendas de interés social popular. Pädi Boletín Científico de Ciencias Básicas e Ingenierías del ICBI [Internet]. 2023 Nov 20 [cited 2025 Aug 18];11(Especial3):151-6. https://doi.org/10.29057/icbi.v11iEspecial3.11509

6. Li B, Feng L, Chouari R, Samoili S, Giannakis S. Trace metals induce microbial risk and antimicrobial resistance in biofilm in drinking water. npj Clean Water [Internet]. 2025 Feb 3 [cited 2025 Aug 18];8(1). https://doi.org/10.1038/s41545-025-00436-8

7. Tabla-Vázquez CG, Chávez-Mejía AC, Orta Ledesma MT, Ramírez-Zamora RM. Wastewater Treatment in Mexico. In: World Water Resources [Internet]. Cham: Springer; 2020 [cited 2025 Aug 19]. https://doi.org/10.1007/978-3-030-40686-8_8

8. Kumar D, Kumar R, Sharma M, Awasthi A, Kumar M. Global water quality indices: development, implications, and limitations. Total Environment Advances [Internet]. 2024 Mar 1 [cited 2025 Aug 19]; 9:200095. https://doi.org/10.1016/j.teadva.2023.200095

9. Barrantes Barrantes EA, Cartín Nuñez M. Eficacia del tratamiento de aguas residuales de la Universidad de Costa Rica en la Sede de Occidente, San Ramón, Costa Rica. UNED Research Journal [Internet]. 2017 Mar 14 [cited 2025 Aug 15];9(1):193-7. http://dx.doi.org/10.22458/urj.v9i1.1697

10. Awa SH, Hadibarata T. Removal of heavy metals in contaminated soil by phytoremediation mechanism: a review. Water, Air, & Soil Pollution [Internet]. 2020 Jan 21 [cited 2025 Aug 15];231(2). https://doi.org/10.1007/s11270-020-4426-0

11. Wang F, Xiang L, Sze-Yin Leung K, Elsner M, Zhang Y, Guo Y, et al. Emerging contaminants: a one health perspective. The Innovation [Internet]. 2024 Jul 1 [cited 2025 Aug 15];5(4):100612. https://doi.org/10.1016/j.xinn.2024.100612

12. Khajvand M, Mostafazadeh AK, Drogui P, Tyagi RD. Management of greywater: environmental impact, treatment, resource recovery, water recycling, and decentralization. Water Science and Technology [Internet]. 2022 Jul 28 [cited 2025 Aug 15];86(5):909–37. https://doi.org/10.2166/wst.2022.226

doi: 10.25100/iyc.v27i2.14687

13. Budeli P, Sibali LL. Greywater reuse: contaminant profile, health implications, and sustainable solutions. International Journal of Environmental Research and Public Health [Internet]. 2025 May 7 [cited 2025 Aug 21];22(5):740. https://doi.org/10.3390/ijerph22050740

14. Chakraborty SK. River pollution and perturbation: perspectives and processes. In: Riverine ecology. Vol. 2. Cham: Springer; 2021 [cited 2025 Aug 15]. p. 443–530. https://doi.org/10.1007/978-3-030-53941-2_5

15. Velázquez-Chávez L, Ortiz-Sánchez I, Chávez-Simental J, Pámanes-Carrasco G, Carrillo-Parra A, Pereda-Solís M. Influencia de la contaminación del agua y el suelo en el desarrollo agrícola nacional e internacional. TIP Revista especializada en ciencias químico-biológicas [Internet]. 2022 Jan 1 [cited 2025 Aug 18];25:1–13. https://doi.org/10.22201/fesz.23958723e.2022.482

16. Perez C, Maquera C. Tratamiento de aguas grises automotrices con lechos filtrantes de cáscara de maíz y bagazo. Sciencevolution [Internet]. 2024 Dec 5 [cited 2025 Aug 21];4(12):170–80. https://doi.org/10.61325/ser.v4i12.140

17. Silva JA. Wastewater treatment and reuse for sustainable water resources management: a systematic literature review. Sustainability [Internet]. 2023 Jan 1 [cited 2025 Aug 22];15(14):1–31. https://doi.org/10.3390/su151410940

18. Ansari A, Naeem M, Gill S, AlZuaibr F. Phytoremediation of contaminated waters: an eco-friendly technology based on aquatic macrophytes application. The Egyptian Journal of Aquatic Research [Internet]. 2020 Dec 1 [cited 2025 Aug 20];46(4):371–6. https://doi.org/10.1016/j.ejar.2020.03.002

19. Nuñez E, Saboya N, Cruz M. Phytoremediation through the palustre and floating species, Zantedeschia aethiopica and Eichhornia crassipes in the treatment of domestic wastewater in the area of the natural region Quechua-Cajamarca. Revista de Investigación Ciencia Tecnología y Desarrollo [Internet]. 2019 Dec 18 [cited 2025 Aug 21];5(2). https://doi.org/10.17162/rictd.v5i2.886

20. Rodríguez Díaz YJ, Fuentes Guevara MD, Beleño Díaz ÓD, Montoya Armenta LH. Electrocoagulación como proceso de tratabilidad de aguas residuales de una planta de lácteos y cárnicos. Tecnura [Internet]. 2021 Jan 1 [cited 2025 Aug 21];25(67):26–39. https://doi.org/10.14483/22487638.15769

21. Ebba M, Asaithambi P, Alemayehu E. Development of electrocoagulation process for wastewater treatment: optimization by response surface methodology. Heliyon [Internet]. 2022 May [cited 2025 Aug 20];8(5):e09383. https://doi.org/10.1016/j.heliyon.2022.e09383

22. Kashi G. Electrocoagulation/flotation process for removing copper from an aqueous environment. Scientific Reports [Internet]. 2023 Aug 16 [cited 2025 Aug 21];13(1):13334. https://doi.org/10.1038/s41598-023-40512-y

23. Tawfik E, Fathy M, Albalawi D, Aljuaid B, Eldin D, Mahmoud S, et al. Molecular identification of Zantedeschia culture with determination of its morphometric and metabolic activities for mediterranean acclimatization. Plants [Internet]. 2022 Sep 3 [cited 2025 Aug 15];11(17):2311. https://doi.org/10.3390/plants11172311

24. Nakata P. Advances in our understanding of calcium oxalate crystal formation and function in plants. Plant Science [Internet]. 2003 Jun [cited 2025 Aug 20];164(6):901–9. https://doi.org/10.1016/S0168-9452(03)00120-1

25. Retana Sánchez K, Castro Zúñiga O, Blanco Meneses M. Determinación de la presencia de cristales de oxalato de calcio asociados a la enfermedad abiótica conocida como “Mancha Blanca” en Hylocereus costaricensis. Agronomía Costarricense [Internet]. 2019 Jul 1 [cited 2025 Aug 21];43(2). https://doi.org/10.15517/rac.v43i2.37950

doi: 10.25100/iyc.v27i2.14687

26. Solis-Marcial OJ, Talavera-López A, Ruelas-Leyva JP, Hernández-Maldonado JA, Najera-Bastida A, Zarate-Gutierrez R, et al. Clarification of mining process water using electrocoagulation. Minerals [Internet]. 2024 Apr 17 [cited 2025 Aug 21];14(4):412. https://doi.org/10.3390/min14040412

27. Boinpally S, Kolla A, Kainthola J, Kodali R, Vemuri J. A state-of-the-art review of the electrocoagulation technology for wastewater treatment. Water Cycle [Internet]. 2023 Jan [cited 2025 Aug 20];4. https://doi.org/10.1016/j.watcyc.2023.01.001

28. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. The circular economy: a new sustainability paradigm? Journal of Cleaner Production [Internet]. 2017 Feb 1 [cited 2025 Aug 21];143(1):757–68. https://doi.org/10.1016/j.jclepro.2016.12.048

29. Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: an analysis of 114 definitions. Resources, Conservation and Recycling [Internet]. 2017 Dec [cited 2025 Aug 21];127(1):221–32. https://doi.org/10.1016/j.resconrec.2017.09.005

30. Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production [Internet]. 2016 Feb [cited 2025 Aug 21];114(7):11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

31. Korhonen J, Nuur C, Feldmann A, Birkie SE. Circular economy as an essentially contested concept. Journal of Cleaner Production [Internet]. 2018 Feb [cited 2025 Aug 21];175(175):544–52. https://doi.org/10.1016/j.jclepro.2017.12.111

32. Bocken NMP, de Pauw I, Bakker C, van der Grinten B. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering [Internet]. 2016 Apr 26 [cited 2025 Aug 21];33(5):308–20. https://doi.org/10.1080/21681015.2016.1172124

33. Zurita F, Del Toro-Sánchez CL, Gutierrez-Lomelí M, Rodriguez-Sahagún A, Castellanos-Hernandez OA, Ramírez-Martínez G, et al. Preliminary study on the potential of arsenic removal by subsurface flow constructed mesocosms. Ecological Engineering [Internet]. 2012 Oct [cited 2025 Aug 21];47:101–4. https://doi.org/10.1016/j.ecoleng.2012.06.018

34. Sandoval L, Zamora-Castro S, Vidal-Álvarez M, Marín-Muñiz J. Role of wetland plants and use of ornamental flowering plants in constructed wetlands for wastewater treatment: a review. Applied Sciences [Internet]. 2019 Feb 17 [cited 2025 Aug 21];9(4):685. https://doi.org/10.3390/app9040685

35. Maroyi A. Zantedeschia aethiopica (L.) Spreng.: a review of its medicinal uses, phytochemistry, and biological activities. Asian Journal of Pharmaceutical and Clinical Research [Internet]. 2019 Jun 24 [cited 2025 Aug 21];12(8):30–6. https://doi.org/10.22159/ajpcr.2019.v12i18.34353

36.Paiva ÉAS. Do calcium oxalate crystals protect against herbivory? Naturwissenschaften [Internet]. 2021 May 27 [cited 2025 Aug 21];108(3):24. https://doi.org/10.1007/s00114-021-01735-z

37. Franceschi VR, Nakata PA. Calcium oxalate in plants: formation and function. Annual Review of Plant Biology [Internet]. 2005 Jun [cited 2025 Aug 21];56(1):41–71. https://doi.org/10.1146/annurev.arplant.56.032604.144106

38. Beltrán-Dávalos A, Rosero-Erazo C, Cargua F, Echeverría M. Potencial de Zantedeschia aethiopica L. para la rehabilitación de suelos contaminados con cromo hexavalente en zonas alto andinas de Ecuador. Acta Agronómica [Internet]. 2019 [cited 2025 Aug 21];68(2):92–8. https://doi.org/10.15446/acag.v68n2.77859

39. Tsiftsoglou OS, Stefanakis MK, Lazari DM. Chemical constituents isolated from the rhizomes of Helleborus odorus subsp. cyclophyllus (Ranunculaceae). Biochemical Systematics and Ecology [Internet]. 2018 Apr 30 [cited 2025 Aug 21];79:8–11. https://doi.org/10.1016/j.bse.2018.04.010

40. Méndez-Zambrano PV, Arcos-Logroño JP, Cazorla-Vinueza XR. Determinación del índice de calidad del agua (NSF) del río Copueno ubicado en Cantón Morona. Dominio de las Ciencias

[Internet]. 2020 Jun 25 [cited 2025 Aug 21];6(2):734–46. https://doi.org/10.23857/dc.v6i2.1245

41. Pérez JI, Nardini AG, Galindo AA. Análisis comparativo de índices de calidad del agua aplicados al río Ranchería, La Guajira-Colombia. Información Tecnológica [Internet]. 2018 Jun [cited 2025 Aug 21];29(3):47–58. http://dx.doi.org/10.4067/S0718-07642018000300047

42. Chirumalla K, Balestrucci F, Sannö A, Oghazi P. The transition from a linear to a circular economy through a multi-level readiness framework: an explorative study in the heavy-duty vehicle manufacturing industry. Journal of Innovation & Knowledge [Internet]. 2024 Aug 24 [cited 2025 Aug 21];9(4):100539. https://doi.org/10.1016/j.jik.2024.100539

43. Uddin MdG, Nash S, Olbert AI. A review of water quality index models and their use for assessing surface water quality. Ecological Indicators [Internet]. 2021 Mar [cited 2025 Sep 2];122(107218):107218. https://doi.org/10.1016/j.ecolind.2020.107218

44. Brown AW. The role of government in the encouragement of research in industry. Australian Journal of Public Administration [Internet]. 1970 Dec 1 [cited 2025 Sep 3];29(4):339–55. https://doi.org/10.1111/j.1467-8500.1970.tb00199.x

45. Abou-Shady A, Saboor Siddique M, Yu W. A critical review of recent progress in global water reuse during 2019–2021 and perspectives to overcome future water crisis. Environments [Internet]. 2023 Sep 14 [cited 2025 Sep 2];10(9):159–9. https://doi.org/10.3390/environments10090159

doi: 10.25100/iyc.v27i2.14687