Vol. 23, No. 3(2024) IA24341
Revista Mexicana de Ingeniería Química

Evaluation of an electrooxidation and UV system with solar energy for the treatment of washing machine greywater for toilet and urinal discharges

Evaluación de un sistema de electrooxidación y UV con energía solar para el tratamiento de aguas grises de lavadoras en descargas de inodoros y urinarios

Z.Y. Medrano-Hurtado[1]*, A. Marcelo-Medrano[2], A.A. Jumilla-Corral[3], P. Mayorga-Ortiz[4]
[1]Departamento de Ciencias Básicas, Instituto Tecnológico de Mexicali, Mexicali, México.
[2]Imperial Valley College, Imperial, Imperial, California, U.S.
[3]Departamento de Ingeniería Eléctrica-Electrónica, Instituto Tecnológico de Mexicali, Mexicali, México.
[4]Departamento de Ingeniería Eléctrica-Electrónica, Instituto Tecnológico de Mexicali, Mexicali, México.
Received: May 24, 2024; Accepted: August 26, 2024

Abstract

This study addresses the challenges of water scarcity and the need for sustainable water management by developing a system for treating greywater from washing machines using electrooxidation (EO) with titanium and stainless steel electrodes. The integration of photovoltaic solar energy and ultraviolet (UV) radiation enhances disinfection and the degradation of organic contaminants, with the goal of reusing the treated water for toilet and urinal discharges. The system used a high-density polyethylene ($HDPE$) reactor with a 290 L capacity, equipped with four electrodes powered by three 100 W solar panels. Key parameters such as current density (j) and treatment time were evaluated by monitoring turbidity, conductivity, and pH of the water. The optimal operating condition was determined to be at a j of 5.87 $\frac{A}{m^2}$ and a treatment time of 30 min, achieving a reduction in turbidity from 12.3 NTU to 7.72 NTU, conductivity (σ) from 2,130 $\frac{\mu S}{cm}$ to 2,000 $\frac{\mu S}{cm}$, and a final pH of 7.99 U. The results demonstrate that the EO process, combined with photovoltaic solar energy and UV radiation, is an efficient and sustainable solution for greywater treatment, enabling reuse and contributing to water resource conservation.
Keywords: greywater treatment, washing machine, toilet, electrooxidation process, photovoltaic solar energy, ultraviolet radiation.

Resumen

Este estudio aborda la escasez de agua y la necesidad de una gestión sostenible desarrollando un sistema de tratamiento de aguas grises de lavadoras mediante electrooxidación (EO) con electrodos de titanio y acero inoxidable. La integración de energía solar fotovoltaica y radiación ultravioleta (UV) mejora la desinfección y la degradación de contaminantes orgánicos, permitiendo la reutilización del agua tratada en inodoros y urinarios. Se utilizó un reactor de polietileno de alta densidad (PAD) de 290 L, equipado con cuatro electrodos y alimentado por tres paneles solares de 100 W. Se evaluaron la densidad de corriente (j) y el tiempo de tratamiento, monitoreando la turbidez, la conductividad eléctrica (σ) y el pH del agua. La mejor condición operativa se logró con una j de 5.87 $\frac{A}{m^2}$ y un tiempo de tratamiento de 30 min, logrando reducir la turbidez de 12.3 NTU a 7.72 NTU, la σ de 2,130 $\frac{\mu S}{cm}$ a 2,000 $\frac{\mu S}{cm}$, y alcanzando un pH final de 7.99 U. Los resultados demuestran que el proceso de EO, combinado con energía solar fotovoltaica y UV, es una solución eficiente y sostenible para el tratamiento de aguas grises, contribuyendo a la conservación de los recursos hídricos.
Palabras clave: tratamiento de aguas residuales grises, lavadora, inodoro, proceso de electrooxidación, energía solar fotovoltaica, radiación ultravioleta.

*Corresponding author. *E-mail*: zulmamh@itmexicali.edu.mx;
https://doi.org/10.24275/rmiq/IA24341
ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

In the current global context, wastewater treatment (*WWT*) systems must evolve beyond mere pollutant removal to meet rising standards for environmental sustainability and public health protection. This global issue is exacerbated by increasing pressure on water resources, highlighting the urgent need for sustainable water management practices and the advancement of innovative *WWT* technologies, as emphasized by the UNESCO World Water Assessment Programme (2020). Traditionally, *WWT* has relied on biological and physicochemical methods, which, despite their essential role in water purification, face significant challenges, including high operational costs and the generation of harmful byproducts. Studies by Pérez Carrión (1980) and Reyes López (2016) indicate that these methods can produce secondary waste products that pose health risks, such as respiratory issues for those exposed in treatment facilities.

Physicochemical processes, which often use coagulants and synthetic polymers, can generate toxic compounds during chemical reactions, increasing handling risks, as noted by Reyes López (2016). In contrast, biological methods like activated sludge systems and natural treatment approaches, while effective, are highly sensitive to variations in contaminant loads and environmental conditions, which can limit their reliability and efficiency.

In response to these challenges, electrochemical technologies have emerged as promising alternatives. These technologies are effective in removing a broad spectrum of organic and inorganic contaminants without the need for harmful chemical reagents, thereby minimizing environmental impact. Electrooxidation (*EO*) stands out among these technologies due to its simplicity, energy efficiency, and reduced sludge production. *EO* has been extensively studied for its ability to treat various contaminants, including phenols, tannins, dyes, and heavy metals, as demonstrated by Belaid *et al*. (2013) and Murugananthan *et al*. (2007). The technology operates by applying direct current to electrodes, inducing chemical reactions that efficiently degrade pollutants.

Studies by Fu and Wang (2011) and Reyes López (2016) further highlight the limitations of traditional methods compared to EO, particularly regarding operating and maintenance costs. The integration of photovoltaic solar energy (*PV* energy) into *EO* systems represents a significant advancement, as it reduces both the carbon footprint and operating costs associated with energy consumption. This aspect has been validated by Qiao and Xiong (2021) and Liu *et al*. (2022), who demonstrated the scalability and efficiency of electrochemical systems across various applications, from domestic to industrial settings. Chaplin (2019) also underscores the global potential of these technologies in advancing sustainable water treatment practices.

EO processes typically involve the use of durable electrode materials like titanium coated with metal oxides, graphite, boron-doped diamond (*BDD*), or stainless steel, as highlighted by studies from Taqieddin *et al*. (2023), Ben Kacem *et al*. (2022), and Garcia-Segura et al. (2018). These materials enable the efficient degradation of a wide range of contaminants, as detailed by Stirling *et al*. (2020) and Petrovic *et al*. (2023).

Domestic *WW*, including greywater (*GW*) from washing machines (*WM*), presents unique treatment challenges due to its composition. *GW* can constitute up to 75% of household *WW*, making its effective treatment crucial for efficient water management (Li *et al*., 2009; Friedler, 2008). Various studies, including those by Garduño, Gutiérrez, and Bulnes (2016), Leal *et al*. (2011), Eriksson *et al*. (2002), and Niño Rodríguez and Martínez Medina (2013), have detailed the complexity of *GW* composition and the challenges it presents for treatment and reuse.

In Mexico, *GW* from *WM* represents a significant portion of household water use, with automatic *WM* present in over 70% of homes, accounting for 37% of total household water consumption (Salgado, Güitrón de los Reyes, & López, 2018). This water, though low in contaminants, is rarely recycled, underscoring the need for effective treatment technologies. The distinction between potable water and treated *GW* is critical for safe domestic use, especially for non-potable applications like toilet flushing, which uses significant water volumes per flush (Bautista Rivera, 2020; Secretaría de Medio Ambiente y Recursos Naturales, 2022).

GW reuse is increasingly recognized as a key strategy for reducing potable water demand and managing *WW* more efficiently, especially in arid regions and urban areas, as indicated by the UNESCO World Water Assessment Programme (2020). The reuse of *GW*, particularly from *WM*, aligns with sustainability goals, reducing water consumption and environmental impact (United Nations, 2015). However, this practice also poses challenges, such as disease risk and the presence of xenobiotic organic compounds (*XOCs*). A comprehensive approach, including appropriate treatment technologies like membrane bioreactors and constructed wetlands, is essential to ensure sanitary safety and environmental protection, as noted by Li, Wichmann, and Otterpohl (2009), Awasthi, Gandhi, and Rayalu (2023), and Pidou *et al*. (2007).

The implementation of clear guidelines and risk assessments for *GW* reuse is crucial for public acceptance and technical feasibility, supported by

research from Jefferson *et al*. (2000) and Shi, Wang, and Jiang (2018). Standards such as the Official Mexican Standard NOM-003-SEMARNAT-1997 and guidelines from the California State Water Resources Control Board (2016) provide frameworks for safe *GW* reuse, ensuring compliance with safety and environmental regulations (Ottosson & Stenström, 2003). Additionally, Karpiscak, M. M., Foster, K. E., & Schmidt, N. (1990) highlight the potential 30% water savings when using *GW* for toilet and urinal flushing.

The primary objective of this study is to evaluate the efficiency and feasibility of an *EO* and *UV* system powered by solar energy for treating *GW* from *WM*. The system aims to make treated *GW* suitable for reuse in toilet and urinal discharges, promoting water conservation and sustainability. The study specifically focuses on optimizing the *EO* process, utilizing titanium mesh and *AISI* 316 stainless steel electrodes, and integrating *UV* radiation to enhance disinfection and the degradation of organic contaminants.

This paper is structured as follows: Section 2 details the materials and methods employed, including the design and setup of the treatment system, characterization of *GW*, and the operating parameters of the *EO* process. Section 3 presents the experimental results, highlighting key findings such as reductions in turbidity, electric conductivity (σ), and organic contaminants. Section 4 discusses these findings in comparison with existing literature, emphasizing the advantages and limitations of the proposed system. Finally, Section 5 concludes the study by summarizing the key insights, offering recommendations for future research, and suggesting potential applications for domestic and industrial *WWT*.

2 Methodology

2.1 Prototype design

In this study, a prototype system was developed for the treatment of domestic *GW* from *WM*, aimed at reusing it in toilet and urinal discharges using the *EO* process, based on previous research (Medrano *et al*., 2022; Medrano *et al*., 2019). The GW The *GW*, containing soap and textile dye residues, was analyzed to determine physicochemical characteristics such as *pH*, σ, turbidity, and color. These measurements were essential for adjusting *EO* process parameters and ensuring effectiveness.

Initially, the samples were filtered to remove large particles before undergoing the *EO* process. During treatment, key physicochemical variables were monitored (as shown in Table 1) to assess the impact of electric current, electrode spacing, and treatment duration. Optimal operating conditions were established with a current density (j) of 5.87 $\frac{A}{m^2}$, with measurements taken at intervals of 0, 15, 30, and 45 min, allowing *pH* to vary naturally throughout the treatment.

The effectiveness of the treatment was assessed by comparing physicochemical parameters before and after the *EO* process. Laboratory analyses, conducted by "DÍA AMBIENTAL Diseño y Asesoría Ambiental," provided data on changes in *pH*, turbidity, and σ. According to Report No. 24 – 2605, the *EO* process significantly improved water quality, demonstrating a reduction in the analyzed parameters and validating the process's effectiveness.

The *EO* system was implemented using a High-Density Polyethylene (*HDPE*) electrolytic cell with a capacity of 290 *L*, equipped with four electrodes: two titanium mesh anodes and two *AISI* 316 stainless steel cathodes, arranged alternately and connected in parallel with a 7 *cm* separation between them. These electrodes were connected to three 100 *W* polycrystalline *PV* panels, operating at a maximum power voltage (*Vmp*) of 19.06 *V* and a maximum power current (*Imp*) of 5.26 *A*. Figure 1 presents a schematic diagram of the electrolytic reactor prototype, while Figure 2 shows actual photographs of the prototype, specifically a) Side view, and b) Internal view.

Table 1 details the parameters measured and the system conditions controlled during the experiments.

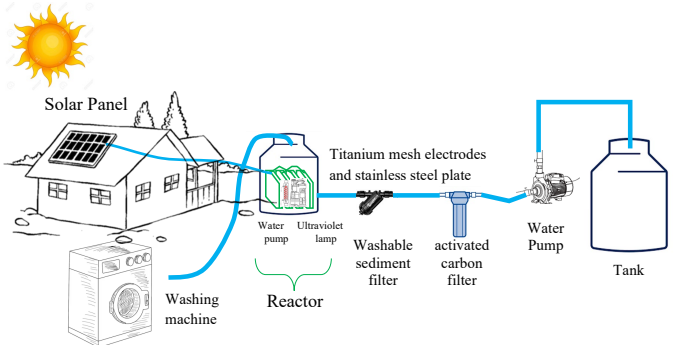
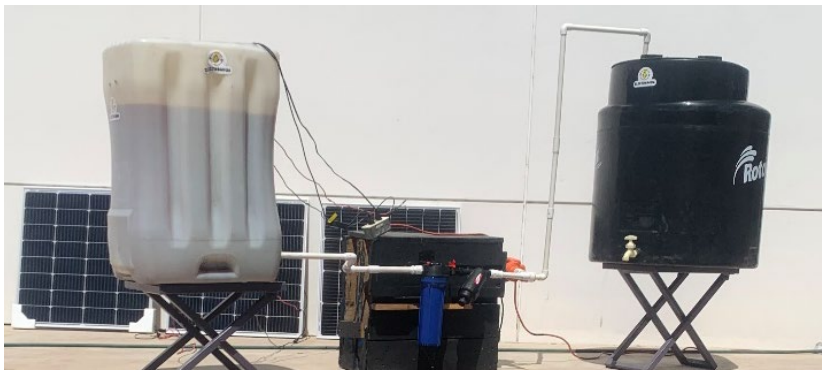


Fig. 1. Schematic representation of the electrolytic reactor prototype.

a)



b)

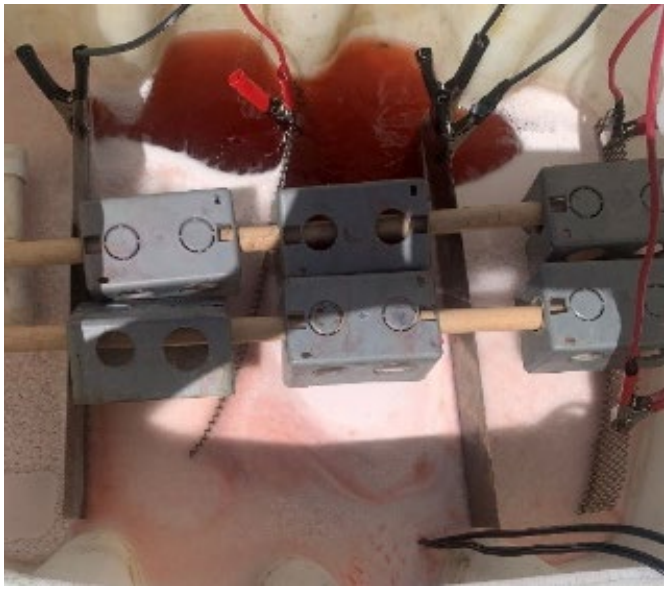


Fig. 2. Electrolytic reactor prototype: a) Side view, b) Internal view of the reactor.

Table 1. System parameters and conditions (self-prepared).

Parameters to measure:	Parameters to control:	Operating conditions
Total current consumed in the system. Voltage between anode and cathode.	Turning the process on and off (ON/OFF).	Type of Reactor: Batch. Sample: *WW* with soap and textile paint. Volume: 290 *L*. Physical dimensions of the electrolytic reactor: TVC (closed vertical tube) Capacity 290 *L*; Size: $1.20 \times 0.60 \times 0.40$ *m*. Number of electrodes: 4 (2 titanium mesh electrodes, 2 *AIS I* 316 stainless steel electrodes). Separation between electrodes: 7 *cm*. Electrode surface area $[2(ab + ac + bc)]$: Dimensions of the titanium mesh (anodes): $30cm \times 60cm \times 0.1cm$. As a solid plate: 3618 cm^2. Dimensions of the holes: $1.781cm \times 0.247cm \times 0.1cm$. Number of holes (diamond shape). In the Horizontal Axis (Width of 30 *cm*): 16 holes. In the Vertical Axis (Height of 60 *cm*): 173 holes. Total Number of Holes in the Mesh: $2,768$ cm^2. Surface area of the titanium mesh: $3618\ cm^2 - 2,768\ cm^2 = 850\ cm^2$. Dimensions of the stainless steel plate (cathodes): $30 \times 60 \times 0.158$ *cm*. Surface Area of the Solid Plate: 3628.44 cm^2. Voltage: 12 *VDC*. Current: 5.26 *ACD*. EO cycle time: 15, 30, and 45 *min*.

Moreover, additional details on the experimental setup can include the methods for preparing and calibrating the equipment, ensuring consistent data collection. To ensure accurate and reliable results, each sample was processed under controlled laboratory conditions, with all instruments calibrated according to manufacturer specifications.

2.2 *Justification of operating parameters in electrooxidation with UV integration*

The selection of operating parameters for the *EO* system integrated with *UV* radiation was based on extensive preliminary testing and a comprehensive review of existing literature. Previous studies, such as those conducted by García-Segura *et al*. (2018), have demonstrated that a j of approximately 5.87 $\frac{A}{m^2}$ is optimal for removing a broad spectrum of contaminants while maintaining adequate energy efficiency. Similarly, the chosen treatment times were determined to balance effective contaminant removal with operational efficiency, as supported by the research of Liu *et al*. (2022) and Qiao & Xiong (2021).

The *GW* treatment system, derived from domestic *WM* use, was designed to condition the water for reuse in toilet and urinal flushes. The implementation of a *UV* lamp complements the *EO* process by providing an additional layer of disinfection, essential for inactivating pathogenic microorganisms such as bacteria, viruses, and protozoa. This mechanism relies on *UV* radiation's ability to induce irreversible damage to the nucleic acids of these organisms, preventing their replication and survival. This integration is crucial to ensure that the treated water meets the microbiological standards required for non-potable applications.

2.2.1 *Justification of selected parameters*

- *pH*: The *pH* is a critical parameter affecting the chemical stability of the water and the corrosion of materials in plumbing systems. Maintaining a *pH* within a neutral range is essential to minimize corrosion and preserve the integrity of installations. Additionally, *pH* can influence the formation of reactive species during the *EO* process, thereby affecting the treatment's efficacy.

- *Turbidity*: The turbidity, which measures the water's opacity caused by suspended particles, is a key indicator of the clarification process's effectiveness. Low turbidity not only improves the water's aesthetic appearance but is also fundamental for optimizing *UV* light penetration and, consequently, disinfection efficiency.

- *Electrical conductivity* (σ): The σ indicates the concentration of dissolved ions in the water, which is vital for assessing salinity. Proper control of electrical conductivity helps prevent mineral buildup on the surfaces of discharge systems, ensuring their long-term functionality.

- *Color*: The water's color can indicate the presence of organic and inorganic compounds, including detergent residues and other contaminants. Reducing color is desirable not only for aesthetic reasons but also as an indicator of the *EO* process's effectiveness in degrading these compounds.

While the selected parameters do not directly measure disinfection efficiency, their monitoring provides valuable information about the treated water's quality. Reducing turbidity and color facilitates greater *UV* light penetration, improving disinfection effectiveness. Thus, the combination of *EO* and *UV* offers a comprehensive approach that maximizes contaminant removal and ensures an adequate level of disinfection, making the water safe for use in toilet and urinal flushes, meeting the required quality standards for these specific applications.

2.3 *Technical details of the equipment used*

The equipment used, including the *HDPE* electrolytic cell and the *PV* panels, was selected for its durability and efficiency. Titanium mesh anodes and *AISI* 316 stainless steel cathodes were chosen for their corrosion resistance and long operational life, essential for maintaining system integrity under prolonged use. The *PV* panels, with a combined capacity of 300 *W*, were configured to maximize energy capture and minimize power losses, providing a reliable energy source for continuous operation.

2.4 *Data analysis procedures*

Data analysis was performed using statistical software (e.g., *ANOVA*) to determine the significance of the observed changes in water quality parameters. The collected data were systematically processed, with all statistical analyses conducted using standardized methods to ensure the accuracy and reliability of the findings. This included validation against established benchmarks for water quality, ensuring the reproducibility of results across different samples and conditions.

2.5 *Limitations and safety considerations*

The study faced several limitations, including the controlled laboratory environment that may not fully replicate real-world conditions. Additionally, the

handling of chemicals and equipment required strict adherence to safety protocols to prevent accidents and ensure the well-being of all personnel involved. All experimental procedures complied with institutional safety guidelines, and proper waste disposal measures were implemented to minimize environmental impact.

2.6 Discussion expansion

The discussion of the results should be expanded to include a comparative analysis with previous studies. For instance, the observed reduction in turbidity and σ aligns with findings by Fu and Wang (2011) on the effectiveness of EO in treating complex WW streams. Moreover, the study's results can be positioned within the broader context of sustainable WWT technologies, emphasizing the advantages of EO over traditional methods, such as its lower environmental impact and operational flexibility.

3 Results and discussion

The EO process, powered by PV energy, has proven effective for treating GW from WM in domestic settings. This system has significantly evolved from an initial electrocoagulation (EC) model described by Medrano-Hurtado et al. (2022). In the initial phase, the system used four aluminum electrodes, with two configured as anodes and two as cathodes, operating in a 290 L $HDPE$ reactor. This initial model was powered by a 280 W polycrystalline PV panel, providing a Vmp of 32.27 V and a Imp of 8.69 A.

To enhance the efficiency of GW treatment, the system was adapted to implement the EO process. The same 290 L reactor was retained, but the electrode configuration was updated, replacing the former aluminum electrodes 2024 $T351.250$ (two of which were used as sacrificial electrodes) with two titanium mesh electrodes as anodes and two $AISI$ 316 stainless steel electrodes as cathodes. Additionally, three new 100 W PV panels were added, each with a Vmp of 19.06 V and an Imp of 5.26 A, to improve energy efficiency. An UV lamp was also incorporated into the system, enhancing disinfection and improving the quality of treated water. To further optimize disinfection and clarify the water, a component similar to the TARARIUM aquarium filter, which has proven effective in keeping the water free of impurities and unpleasant odors, was included.

This transformation reflects progress towards greater efficiency and sustainability, demonstrating a commitment to developing environmentally friendly technological solutions. This new configuration has the potential for broader implementation, offering a practical and efficient solution for WW management in residential areas.

3.1 Initial system configuration and modifications

The WWT system initially utilized an EC process, equipped with four aluminum electrodes, including two anodes and two cathodes, operating in a 290 L $HDPE$ reactor. This system was powered by a 280 W polycrystalline PV panel with a Vmp of 32.27 V and a Imp of 8.69 A. To improve the system's efficiency and sustainability, it was subsequently adapted to an EO process. This modification involved replacing the aluminum electrodes, two of which were sacrificial, with two titanium mesh electrodes as anodes and two $AISI$ 316 stainless steel electrodes as cathodes. Additionally, three new 100 W PV panels were incorporated, each providing a Vmp of 19.06 V and an Imp of 5.26 A. An UV lamp was also added to the system, further enhancing the disinfection capabilities and overall quality of the treated water. To improve water clarity and reduce odors, a filtration component similar to the TARARIUM aquarium filter was included (Medrano-Hurtado *et al*., 2022).

3.2 Preliminary analyses and system stability

Preliminary analyses revealed stable performance metrics, indicating the system's viability and effectiveness. The initial characterization of GW, measured at 0 min (before the start of the EO process), showed a pH of 8.30 U, turbidity of 12.3 NTU, and σ of $2,130\ \frac{\mu S}{cm}$. The stability of these values over time suggests that the EO system is not only effective but also reliable for continuous operation. The transition from EC to EO marked significant progress toward a more efficient and sustainable water treatment solution, demonstrating the system's adaptability to different operating conditions.

3.3 Mechanisms and chemical reactions of electrooxidation (EO)

3.3.1 Mechanisms of electrooxidation (EO)

The EO is an electrochemical process in which an electric current is applied to electrodes immersed in a WW solution, inducing chemical reactions. This process generates reactive species, such as hydroxyl radicals ($\bullet OH$), which are highly oxidizing and play a crucial role in the degradation of organic contaminants present in GW.

- *Generation of hydroxyl radicals:* At the anode, the oxidation of water produces hydroxyl radicals according to the following reaction:

$$H_2O \rightarrow \bullet OH + H^+ + e^-$$

These hydroxyl radicals are potent oxidizing agents capable of attacking and decomposing a

wide variety of organic compounds present in the *WW*, such as detergents and dyes.

- *Oxidation of organic contaminants:* Hydroxyl radicals react with organic contaminants, breaking down carbon-carbon bonds and other functional groups. For example, a common reaction involves the oxidation of a compound with an alcohol group:

  $$R{-}C(OH){-}CH_2{-}R^{'} \bullet OH \rightarrow R{-}C(O){-}R^{'} + H_2O$$

  Here $R-C(OH)-CH_2-R^{'}$ represents a typical organic compound that is converted into a carbonyl (aldehyde or ketone) upon oxidation.

- *Complete Mineralization***:** The ultimate goal of *EO*is the complete mineralization of organic contaminants, resulting in the formatting of CO_2 and H_2O:

  $$R + \bullet OH \rightarrow CO_2 + H_2O$$

  This reaction indicates the total breakdown of organic matter.

- *Additional Electrochemical Reactions*: The *EO* process with titanium and stainless steel electrodes also includes other electrochemical reactions. At the anode, molecular oxygen can be generated:

  $$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

  At the cathode, oxygen reduction can occur:

  $$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

  These reactions help maintain the overall balance in the solution and contribute to the effectiveness of the *EO* process.

3.3.2 *Key chemical reactions*

The *EO* process with titanium and stainless steel electrodes also involves other important electrochemical reactions. These reactions include the generation of molecular oxygen at the anode and the reduction of oxygen at the cathode, contributing to the overall effectiveness of the process.

- *Anode oxidation:*

  $$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

  This reaction is crucial for generating molecular oxygen and hydroxyl radicals.

- *Cathode reduction:*

  $$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

  This reaction helps maintain a balance in the solution and reduce *pH*, which is beneficial for the treatment process.

3.3.3 *Factors influencing the EO process*

Operational factors, such as *j*, electrode type, and treatment time, significantly impact the efficiency of the *EO* process. *j* controls the rate of hydroxyl radical generation, while electrode type influences the durability and effectiveness of the process. Treatment time determines the extent of contaminant oxidation.

- *Current density* (*j*): *j* is a critical parameter as it directly influences the generation of reactive species, such as hydroxyl radicals ($\bullet OH$), which are essential for the oxidation of contaminants. An appropriate *j* maximizes the production of these radicals while minimizing energy consumption. In this study, a *j* of 5.87 $\frac{A}{m^2}$ was selected, based on comprehensive literature reviews and previous studies, including García-Segura et al. (2018), who identified the $5-6\ \frac{A}{m^2}$ range as optimal for the efficient oxidation of complex organic compounds in *WW*. Our results confirmed that this *j* effectively reduced turbidity and σ in *GW*, indicating efficient contaminant removal.

- *Electrode materials:* Titanium mesh and *AISI* 316 stainless steel electrodes were selected for their corrosion resistance and ability to withstand high current densities without degrading, which is essential for maintaining process efficiency over time.

- *Treatment time:* Treatment time determines the extent of exposure of contaminants to the generated free radicals, thus influencing the degree of oxidation. While longer treatment times generally lead to more thorough contaminant removal, they also increase energy consumption and the risk of electrode degradation. This study employed treatment times of 15, 30, and 45 min, following findings from Murugananthan *et al.* (2007), which indicated that this range effectively balances contaminant removal with energy efficiency. Our findings showed that significant reductions in turbidity and σ were achieved at 30 min, with diminishing returns observed at 45 min, suggesting an optimal treatment duration.

3.4 *Characterization of wastewater*

Before implementing the *EO* process, the *GW* from *WM* was characterized to determine its physicochemical properties. Initial measurements indicated a *pH* of 8.30 *U*, turbidity of 12.3 *NTU*, and σ of 2,130 $\frac{\mu S}{cm}$. These baseline parameters provided crucial data for comparison with post-treatment results and were essential for evaluating the effectiveness of the *EO* treatment (Medrano-Hurtado *et al.*, 2022).

3.5 Efficiency of the electrooxidation process

The *EO* process demonstrated significant effectiveness in reducing key contaminants in *GW*. After treatment periods of 15, 30, and 45 min, notable improvements in water quality were observed. The recorded *pH* values were 8.05 U, 8.11 U, and 7.99 U, respectively, with a j of 5.87 $\frac{A}{m^2}$. A marked reduction in turbidity was observed, initially increasing from 12.3 NTU to 14.8 NTU (due to soap agglutination) and then decreasing to 7.72 NTU. σ showed a steady decrease from 2,130 $\frac{\mu S}{cm}$ to 2,000 $\frac{\mu S}{cm}$ during the same period. These results align with the expected effectiveness of *EO*, especially under near-neutral *pH* conditions, corroborating its suitability for *GW* treatment. Similar studies, such as those conducted by Murugananthan et al. (2007), Fu and Wang (2011), and Garcia-Segura *et al.* (2018), have demonstrated comparable reductions in turbidity and σ, validating the *EO* process as an efficient method for treating various types of *WW* (Murugananthan, Yoshihara, Rakuma, Uehara, & Shirakashi, 2007; Fu & Wang, 2011; Garcia-Segura, Ocon, & Chong, 2018). These results are summarized in Figure 3.

Figure 3 illustrates the reduction in turbidity as a function of treatment time. An initial decrease in turbidity is observed due to the agglomeration of particles caused by the increase in treatment time, followed by a significant reduction, which evidences the efficiency of the *EO* process in the removal of suspended solids. The blue line represents the initial values, while the green and red lines indicate the values obtained after 15 and 30 *min* of treatment, respectively. It is noteworthy that, at the end of 45 *min*, turbidity was reduced to 7.72 NTU, which represents a considerable improvement in water quality.

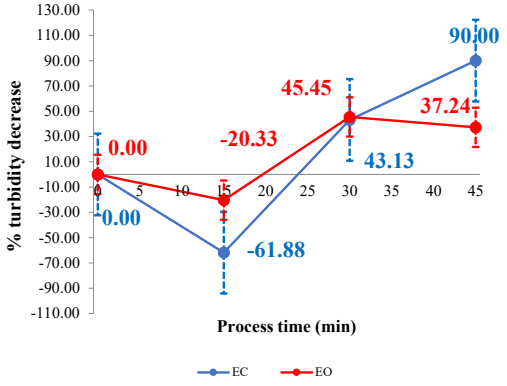
A steady reduction in σ from 2,130 $\frac{\mu S}{cm}$ to 2,000 $\frac{\mu S}{cm}$ was also observed, along with a slight decrease in *pH*, stabilizing at 7.99 U. Detailed results are presented in Figure 4.

A steady reduction in σ from 2,130 $\frac{\mu S}{cm}$ to 2,000 $\frac{\mu S}{cm}$ is observed, indicating effective removal of dissolved ions. On the other hand, the *pH* showed a tendency to stabilize around 7.99 U, which suggests that the *EO* process maintains a slightly alkaline condition, suitable for the use of treated water in toilet and urinal flushes.

3.6 Experimental design and statistical analysis

3.6.1 Experimental design

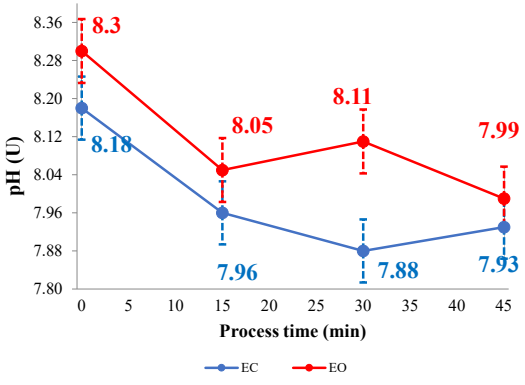
To evaluate the influence of residence time on the efficiency of the *EO* process in *GW* treatment, a full factorial Design of Experiments (*DoE*) was utilized. This approach allows for analyzing all possible combinations of the experimental factor levels. In this study, residence time was the main factor, with four levels: 0, 15, 30, and 45 *min*.



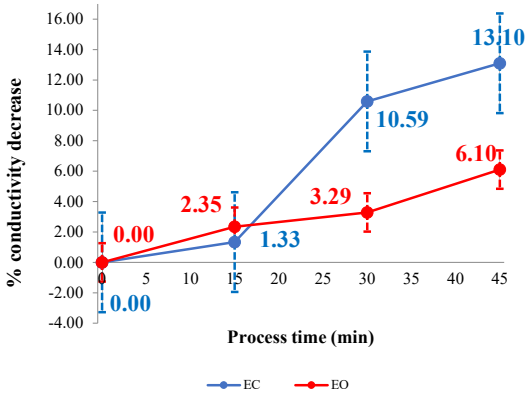
a)

b)

Fig. 3. Turbidity: a) % turbidity reduction, b) Color variation.



a)



b)

Figure 4 shows the variation in σ and *pH* of treated water.

Table 2. Initial values of the response variables.

Variable	Initial value
pH	8.30 U
σ	2,130 $\frac{\mu S}{cm}$
Turbidity	12.30 NTU

Note: Initial values represent the water conditions prior to the application of the EO process. These parameters were crucial in establishing a baseline and evaluating the effectiveness of the treatment.

- *Mathematical arrangement*: The mathematical arrangement of the full factorial design is: 4^1 where 4 represents the levels of the residence time factor. Each combination of these levels was replicated to ensure the reliability of the results.

3.6.2 *Response variables*

The response variables measured in the experiment were:

- Turbidity: An indicator of the amount of suspended particles in the water.
- σ: A measure of the number of dissolved ions in the water.
- pH: An indicator of the acidity or alkalinity of the water.

These measurements were crucial for evaluating the effectiveness of the EO treatment. The initial values of these variables are presented in Table 2, providing a baseline for comparison with post-treatment results.

3.6.3 *Experimental results*

During the EO process, the following trends were observed:

- Turbidity: Initially increased to 14.8 NTU due to soap agglutination, but decreased to 7.72 NTU by the end of the treatment.
- σ: Showed a constant decrease from 2,130 $\frac{\mu S}{cm}$ to 2,000 $\frac{\mu S}{cm}$.
- pH: Showed a slight downward trend, stabilizing at 7.99 U.

3.6.4 *Analysis of Variance (ANOVA)*

An $ANOVA$ was performed to determine the statistical significance of the effects of residence time on the response variables. $ANOVA$ helps evaluate whether the observed differences between treatments are significant or attributable to chance. The formula used for calculating removal efficiency was:

$$Removal\ Efficiency\ (\%) = \left(\frac{C_o - C}{C_o}\right) \times 100$$

where:

C_o= Initial turbidity

C= Final turbidity

Sum of Squares (SS):

$$SS = \sum \left(X_i - \overline{X}\right)^2$$

where:

X_i= Individual observed values of the variable

$\overline{X}$= Mean of the observed values $\left(\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i\right)$

n= Number of observations

Degrees of Freedom (df):

$$df = n - 1$$

Mean Square (MS):

$$MS = \frac{SS}{df}$$

F-value:

$$F = \frac{MS_{treatments}}{MS_{error}}$$

P-value: Calculated from the F-value to determine significance.

Table 3. $ANOVA$ for Turbidity

Source of Variation	SS	df	MS	F-value	P-value
Residence Time	60.32	3	20.11	5.92	0.008
Error	27.10	8	3.39		
Total	87.42	11			

Table 4. *ANOVA* for σ

Source of Variation	SS	df	MS	F-value	P-value
Residence Time	24.32	3	8.11	4.22	0.019
Error	15.20	8	1.90		
Total	39.52	11			

Table 5. *ANOVA* for *pH*.

Source of Variation	SS	df	MS	F-value	P-value
Residence Time	0.23	3	0.077	5.87	0.021
Error	0.10	8	0.012		
Total	0.33	11			

The *ANOVA* results (see Tables 3, 4, and 5) for each response variable show that residence time has a significant effect ($p < 0.05$) on all evaluated response variables. In particular, a significant reduction in turbidity and σ was observed, as well as a trend towards a more neutral *pH* with longer residence times. These results indicate that the *EO* process is an effective method for improving the quality of treated water, consistent with previous studies in the literature.

In summary, the full factorial design allowed for a comprehensive evaluation of the impact of residence time on the efficiency of the *EO* process, while the *ANOVA* provided statistical evidence of the relevance of this factor. These results support the feasibility of *EO* as an effective technique for *GW* treatment.

3.7 Response variables and data analysis

3.7.1 Measurement of response variables

In this study, three key response variables were selected: *pH*, turbidity, and σ. These variables were chosen because they are critical indicators of the quality of treated water and reflect the effectiveness of the treatment process.

- *pH*: The *pH* is an essential parameter that indicates the acidity or alkalinity of the solution. In *EO* processes, *pH* can influence the formation and stability of reactive species such as hydroxyl radicals ($\bullet OH$). Additionally, a controlled *pH* is vital to prevent equipment corrosion and ensure the safety of treated water use. *pH* was measured before and after treatment using a calibrated *pH* meter, and its evolution was monitored throughout the process.

- *Turbidity*: Turbidity measures the amount of suspended particles in the water, which may include solids, microorganisms, and other contaminants. It is a visual and quantitative parameter of water clarity. Reducing turbidity is a primary objective in water treatment, as it indicates the removal of suspended solids and other visible contaminants. A turbidimeter was used to measure initial and final turbidity, and any changes during treatment were documented.

- σ: The σ indicates the amount of dissolved ions in the water. This parameter is crucial for evaluating the removal of salts and other ionic contaminants during treatment. A decrease in σ suggests the effective removal of these contaminants. σ measurements were taken with a conductometer, ensuring accurate readings before and after the treatment process.

3.7.2 Detailed data analysis and comparison

Statistical analyses of the response variables were conducted to determine the significance of the changes observed during the treatment. Techniques such as *ANOVA* were used to evaluate the influence of operational factors, such as *j* and treatment time, on the response variables. The results showed significant changes in all variables, confirming the effectiveness of the *EO* process.

3.7.3 Comparison with other methods

To contextualize the results of *EO*, its effectiveness was compared with other *WWT* methods, such as *EC* and biological methods.

- *EC*: The *EC* is a process that uses sacrificial electrodes, typically aluminum or iron, to form in situ coagulants that agglomerate contaminants. While effective for the removal of suspended solids and some heavy metals, *EC* often produces a large amount of sludge, leading to higher handling and disposal costs. Additionally, *EC* may be less effective for the degradation of dissolved organic contaminants compared to *EO*.

- *Biological Methods*: Biological treatments, such as activated sludge and biological filters, are

widely used for the removal of biodegradable organic matter. However, these methods have significant limitations, such as sensitivity to fluctuations in contaminant loads and the need for strict control of operating conditions. Furthermore, they are not effective for the removal of recalcitrant or toxic organic contaminants.

In comparison, *EO* stands out for its ability to degrade a wide range of organic contaminants and does not produce significant waste sludge. Moreover, *EO* is more effective for water disinfection, making it suitable for applications where pathogen removal is crucial. Our study's results indicate that *EO*, using titanium and stainless steel electrodes, provides an effective and sustainable alternative for *GW* treatment, with significant advantages over traditional methods in terms of contaminant removal efficiency and minimization of secondary waste.

3.8 Comparison with Electrocoagulation and the literature

The comparative analysis between *EO* and *EC* processes highlighted the superior efficiency of *EO* in terms of energy consumption and treatment quality. While *EC* reduced turbidity from 160 *NTU* to 16 *NTU* and σ from 1,275 $\frac{\mu S}{cm}$ to 1,108 $\frac{\mu S}{cm}$, *EO* achieved a turbidity reduction from 12.3 *NTU* to 7.72 *NTU* and σ from 2,130 $\frac{\mu S}{cm}$ to 2,000 $\frac{\mu S}{cm}$. The *pH* change was also more favorable with *EO*, achieving a more stable and neutral *pH* range, ideal for water reuse. These findings are consistent with the literature, emphasizing the advantages of *EO* in minimizing secondary waste generation and operational costs compared to traditional methods (Murugananthan *et al*., 2007; Fu & Wang, 2011).

Murugananthan *et al*. (2007) conducted a study that explored the effectiveness of electrochemical processes, such as *EC*, in removing contaminants from *WW*. This study is referenced to compare the results of *EC* in terms of turbidity and σ reduction with those obtained by *EO* in the present study.

Fu and Wang (2011) focused on the removal of heavy metal ions and other contaminants using various water treatment techniques, including electrochemical processes. This reference is used to highlight the superior energy efficiency and treatment quality achieved by *EO* compared to traditional methods like *EC*.

3.9 Advantages and environmental impact

The *EO* offers several significant advantages over *EC*, particularly in terms of energy efficiency, operational flexibility, and reduced environmental impact. One of the main advantages of *EO* is the use of inert electrodes, such as titanium mesh and *AISI* 316 stainless steel. These materials are highly resistant to corrosion and are not consumed during the process, minimizing the generation of secondary waste. This is in stark contrast to the large amount of sludge produced by the aluminum electrodes used in *EC*. The reduction of waste not only decreases the operational costs associated with the handling and disposal of these materials but also mitigates environmental impact, aligning with sustainable water management practices.

Furthermore, the integration of *PV* energy into the *EO* system further enhances its sustainability. By using *PV* panels to generate the energy needed for the process, dependence on conventional energy sources is reduced, contributing to a significant reduction in the carbon footprint. This not only makes the system eco-friendlier but can also reduce long-term operational costs, as solar energy is a renewable resource and generally cheaper than grid electricity.

Chaplin (2019) highlights that electrochemical technologies, such as *EO*, have great potential to advance water treatment globally. The ability to operate with solar energy and the use of durable and resistant materials make these systems particularly suitable for applications in regions with high solar radiation. Additionally, the operational flexibility of *EO* allows it to adapt to different conditions and *WWT* requirements, expanding its applicability in various industrial and domestic contexts.

In summary, *EO* not only improves the efficiency of water treatment compared to more traditional methods but also offers significant environmental benefits. The reduction in waste generation, along with the use of solar energy, positions *EO* as a sustainable and effective option for *WW* management, contributing to the global goal of more conscientious and responsible water resource management.

3.10 Versatility and future applications

The versatility of the *EO* process is demonstrated by its ability to treat a wide variety of *WW* types, including those containing specific contaminants such as textile dyes and soaps. The generation of reactive species, including free radicals, during the *EO* process allows for the effective degradation of a broad spectrum of pollutants. This capability positions *EO* as a promising technology for diverse treatment scenarios, both in domestic and industrial settings.

Future research should prioritize optimizing system parameters, such as *j*, electrode material, and treatment time, to maximize the efficiency and effectiveness of the process. Additionally, exploring the scalability of *EO* technology is crucial to ensure its practical application in larger-scale operations. Another promising avenue for future studies is the integration of *EO* with other advanced

treatment processes, such as electroperoxidation and Electrofenton. These combinations could significantly enhance the removal of persistent organic pollutants and other challenging contaminants, thereby improving the overall quality of treated water.

Advancements in *EO* technology, supported by recent studies like those of Taqieddin *et al.* (2023), suggest that the integration of these processes can lead to more comprehensive and sustainable *WWT* solutions. Such innovations could offer viable alternatives to traditional methods, addressing both environmental and operational challenges. The continued development and refinement of *EO* and related technologies hold the potential to revolutionize *WW* management, making significant contributions to environmental conservation and public health protection.

3.11 Interpretation of results and observed differences

The differences observed in the treatment results using *EO* compared to other methods, such as *EC*, can be attributed to several factors. One of the main factors is the nature of the electrodes used; titanium mesh and *AISI* 316 stainless steel electrodes are highly resistant to corrosion and do not degrade during the process, minimizing the generation of secondary waste. This contrasts with the aluminum electrodes used in *EC*, which generate a significant amount of sludge.

Additionally, the choice of j and treatment time influences the formation and stability of reactive species such as hydroxyl radicals ($\bullet OH$). In this study, a j of 5.87 $\frac{A}{m^2}$ was selected, based on comprehensive literature reviews and previous studies, such as those by García-Segura et al. (2018). Our results confirmed that this j effectively reduces turbidity and σ in *GW*, indicating efficient contaminant removal.

Another notable difference is the efficiency of *EO* for water disinfection. While *EC* is effective in removing suspended solids and some heavy metals, *EO* is more efficient at degrading dissolved organic contaminants and eliminating pathogens. This aspect is crucial for applications where pathogen removal is essential, such as the use of treated water for toilet and urinal flushing.

These differences highlight the importance of careful selection of materials and operating conditions to optimize treatment efficiency. The results of this study suggest that *EO*, with the use of inert electrodes and the integration of *PV* energy, offers a sustainable and effective alternative for *GW* treatment, with significant advantages over traditional methods in terms of energy efficiency and minimization of secondary waste.

Conclusion

The study confirms the feasibility and effectiveness of the *EO* process powered by *PV* energy for treating *GW* from *WM*, with the purpose of reusing it for toilet and urinal flushing. Utilizing titanium mesh anodes and *AISI* 316 stainless steel cathodes, a significant reduction in turbidity, σ, and the color of contaminants present in the water was achieved. This system stands out not only for its ability to efficiently treat *WW* but also for its contribution to sustainable water management by reducing energy consumption and minimizing the generation of secondary waste, thus validating *EO* technology as an efficient and sustainable option for *WWT* and reuse.

The *DoE* methodology allowed for the identification and optimization of the most influential operating parameters, such as j and treatment time. The *ANOVA* showed that these factors have a statistically significant impact on the response variables, improving the quality of treated water with increased residence time. These findings, consistent with existing literature, underscore the importance of precise control over operating conditions to maximize the efficiency of the *EO* process.

Additionally, the integration of *PV* energy not only reduces operational costs and the carbon footprint but also facilitates the adoption of autonomous and sustainable treatment systems, especially in regions with high solar radiation. The use of inert and durable electrodes helps decrease the generation of secondary waste, enhancing the system's long-term sustainability and viability.

In conclusion, this study provides a solid foundation for the development and implementation of *EO* systems in *WW* management, highlighting their potential for water resource conservation and the promotion of water reuse practices. Future research is recommended to explore the scalability of the system, optimize its operating parameters, and evaluate its combination with other advanced treatment processes, with the goal of further improving the efficiency and sustainability of the process. *EO* technology presents itself as a promising and versatile alternative for treating different types of *WW*, particularly for its ability to generate reactive species that enable the degradation of specific contaminants.

Future work

Although the results indicated that *EO* treatment significantly reduces the turbidity, σ, and color of contaminants, further testing is needed to optimize the process. Future work should focus on

investigating variables such as j, treatment time, electrode separation, and the composition of WW to maximize treatment efficiency and minimize energy consumption. Additionally, conducting Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) tests will be essential. These tests will provide a quantitative assessment of the organic load and the effectiveness of the EO process in breaking down organic pollutants.

BOD and COD measurements are vital for understanding the levels of biodegradable and non-biodegradable organic compounds in the treated water. BOD testing will help determine the amount of dissolved oxygen needed by aerobic biological organisms to break down organic material, providing an indication of the biodegradable fraction. COD testing, on the other hand, measures the total quantity of oxygen required to oxidize both biodegradable and non-biodegradable organic matter. Together, these parameters give a comprehensive view of the treatment's efficiency in reducing the organic load, which is crucial for assessing the suitability of treated water for discharge or reuse.

The inclusion of BOD and COD tests will also help in evaluating the potential environmental impact of the treated water. Ensuring that the effluent meets regulatory standards for organic pollutants is essential for protecting aquatic ecosystems and human health. Furthermore, understanding these metrics can aid in refining the EO process, potentially leading to the development of more efficient treatment protocols.

Future research should also explore the integration of EO with advanced oxidation processes such as electroperoxidation (EP) and Electrofenton (EF). These processes can enhance the degradation of persistent organic pollutants that are resistant to conventional treatment methods. Identifying the optimal electrode materials and configurations for these combined processes will be critical for improving treatment efficiency and reducing operational costs. Ultimately, the integration of EP and EF could offer more comprehensive solutions for WWT, significantly improving the removal of persistent organic contaminants and providing a more robust treatment. These advancements could pave the way for scalable and economically viable systems that can be implemented in various WWT applications, thereby contributing to sustainable water management practices.

It is also essential to explore the scalability of the system for application in industrial and municipal environments. Larger-scale tests will allow for the evaluation of the technical and economic viability of the system, as well as its potential to be implemented in different geographic and climatic contexts. An economic model should be developed that considers the costs of installation, operation, and maintenance, assessing the long-term return on investment.

The implementation of any WWT technology should be accompanied by a comprehensive environmental impact assessment. This includes analyzing the system's carbon footprint, managing generated waste (including possible solid waste and sludge), and evaluating the system's overall life cycle. The goal is to ensure that the adoption of advanced technologies like EO, EP, and EF is not only effective in terms of treatment but also sustainable from an environmental perspective.

Lastly, it is recommended to conduct complementary investigations on the characterization of by-products generated during the EO process, including the identification and quantification of intermediate species and final products. Additionally, exploring the combination of EO with physical separation technologies, such as membranes and adsorption, could offer comprehensive solutions for the treatment of complex WW.

References

Acosta, G., Coy, C., Bourdón, A., & Cuervo, E. (2013). Electrocoagulation as an efficient treatment for the removal of heavy metals in wastewater. *Universidad Militar Nueva Granada, 9(2), 306-317.* https://doi.org/10.18359/rfcb.389

Aquarium filter for 40 to 150 gallon tank, U-V fish tank, green clean machine, submersible, powerful pump, 400 GPH canister filter for pond, turtle, saltwater tank

Awasthi, A., Gandhi, K., & Rayalu, S. (2023). Greywater treatment technologies: A comprehensive review. *International Journal of Environmental Science and Technology*, 20(5), 1234-1256. https://doi.org/10.1007/s13762-023-04940-7

Bani-Melhem, K., & Al-Kilani, M. R. (2023). A comparison between iron and mild steel electrodes for the treatment of highly loaded grey water using an electrocoagulation technique. *Arabian Journal of Chemistry*, 16(10), 105199. https://doi.org/10.1016/j.arabjc.2023.105199

Bautista Rivera, D. (2020). Proposal with a point of agreement to urge SEMARNAT to modify by CONAGUA NOM-009-CONAGUA-2001 to reduce the flush volume of toilets to 4.5 liters. Retrieved from http://sil.gobernacion.gob.mx/Archivos/Documentos/2020/11/asun_4104957_20201105_1604594383.pdf

Belaid, Ch., Khadraoui, M., Mseddi, S., Kallel, M., Elleuch, B., & Fauvarque, J. F. (2013). Electrochemical treatment of olive mill wastewater: Treatment extent and effluent phenolic compounds monitoring using some uncommon analytical tools. *Journal of Environmental Sciences*, 25(1), 220-230. https://doi.org/10.1016/S1001-0742(12)60037-0

Ben Kacem, S., Clematis, D., Chaâbane Elaoud, S., Barbucci, A., & Panizza, M. (2022). A flexible electrochemical cell setup for pollutant oxidation in a wide electrical conductivity range and its integration with ultrasound. *Journal of Water Process Engineering, 46*, 102564. https://doi.org/10.1016/j.jwpe.2022.102564

California State Water Resources Control Board. (2016). Title 22, Division 4. Environmental Health. Standards for the use of recycled water.

Casado, J., Fornaguera, J., & Galán, M. I. (2006). Pilot scale mineralization of organic acids by electro-Fenton® process plus sunlight exposure. *Water Research*, 40(13), 2511-2516. https://doi.org/10.1016/j.watres.2006.04.047

- Chaplin, B. P. (2019). The Prospect of Electrochemical Technologies Advancing Worldwide Water Treatment. ACS Sustainable Chemistry & Engineering. https://doi.org/10.1021/acs.accounts.8b00611.

Delgadillo, O., Camacho, A., Pérez, L. F., & Andrade, A. (2010). *Wastewater treatment using constructed wetlands*. Centro Andino para la Gestión y Uso del Agua (Centro AGUA), edición: Nelson Antequera Durán, Cochabamba – Bolivia.

Eriksson, E., Auffarth, K., Henze, M., & Ledin, A. (2002). Characteristics of grey wastewater. *Urban Water*, 4(1), 85-104. https://doi.org/10.1016/S1462-0758(01)00064-4

Fewtrell, L., & Bartram, J. (Eds.). (2001). *Water quality: Guidelines, standards and health. Risk assessment and management for water-related infectious disease*. IWA Publishing. Recuperado de http://www.who.int/water_sanitation_health/dwq/whoiwa/en/

Filali, H., Barsan, N., Souguir, D., Nedeff, V., Tomozei, C., & Hachicha, M. (2022). Greywater as an alternative solution for a sustainable management of water resources—A review. *Sustainability*, 14(2), 665. https://doi.org/10.3390/su14020665

Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, 92(3), 407-418. https://doi.org/10.1016/j.jenvman.2010.11.011

Garcia-Segura, S., Ocon, J. D., & Chong, M. N. (2018). Electrochemical oxidation remediation of real wastewater effluents — A review. *Process Safety and Environmental Protection, 113*, 48-67. https://doi.org/10.1016/j.psep.2017.09.014

Garduño Lomelí, R. F., Gutiérrez Albarrán, J. R., & Bulnes Petrowitsch, M. M. (2016). *Manual for use, operation, maintenance and construction, Washing station with greywater management by subsurface infiltration*. SARAR Transformación, S.C. Mexico. Retrieved January 1, 2024, from https://sswm.info/sites/default/files/reference_attachments/GARDU%C3%91O%20et%20al%202016.%20Estaci%C3%B3n%20de%20lavado%20y%20manejo%20de%20aguas%20grises.pdf

Jefferson, B., Laine, A., Parsons, S., Stephenson, T., & Judd, S. (2000). Technologies for domestic wastewater recycling. *Urban Water*, 1, 285-292. https://doi.org/10.1016/S1462-0758(00)00030-3

Karpiscak, M. M., Foster, K. E., & Schmidt, N. (1990). Residential water conservation: Casa del Agua. *Water Resources Bulletin*, 26(6), 939-946. https://doi.org/10.1111/j.1752-1688.1990.tb01428.x

Laboratory Tests. DÍA AMBIENTAL Diseño y Asesoría Ambiental. Report No. 24-2605. Retrieved from https://drive.google.com/file/d/1OUKwGkZnH7qOr38Tyt9b6-_aMzmPkkcx/view?usp=sharing

Laboratory Tests. Lab Sin Servicios Profesionales S.A. de C.V. Retrieved from https://drive.google.com/file/d/1cq-f1frbGzNJPSEkTuuX9WGSozSu3hU9/view?usp=drive_link

Lakshmipathiraj, P., Bhaskar, R., Raviatul, B., Parvathy, S., & Prabhakar, S. (2008). Removal of Cr (VI) by electrochemical reduction. *Separation and Purification Technology*, 60(1), 96-102. https://doi.org/10.1016/j.seppur.2007.07.053

Leal, L., Temmink, H., Zeeman, G., & Buisman, C. (2011). Characterization and anaerobic biodegradability of grey water. *Desalination*,

270(1-3), 111-115. https://doi.org/10.1016/j.desal.2010.11.029

Li, F., Wichmann, K., & Otterpohl, R. (2009). Review of the technological approaches for grey water treatment and reuses. *Science of The Total Environment*, 407(11), 3439-3449. https://doi.org/10.1016/j.scitotenv.2009.02.004

Linares-Hernández, I., Martínez-Miranda, V., Barrera-Díaz, C., Pavón-Romero, S., Bernal-Martínez, L., & Lugo-Lugo, V. (2011). Oxidation of persistent organic matter in industrial wastewater through electrochemical treatments. *Advances in Science and Engineering, 2(1), 21-36.* Retrieved from https://www.redalyc.org/articulo.oa?id=323627681003

Liu, J., Ren, N., Qu, C., Lu, S., Xiang, Y., & Liang, D. (2022). Recent Advances in the Reactor Design for Industrial Wastewater Treatment by Electro-Oxidation Process. *Water, 14*(22), 3711. https://doi.org/10.3390/w14223711

Medrano, Z., Medina, J., Galarza, A., Soto, J., & Santoyo, K. (2019). *Domestic wastewater treatment system by electrocoagulation. Journal CIM, 7(1), Multidisciplinary Research Colloquium 2019.* Orizaba Veracruz.

Medrano-Hurtado, Z. Y., Medina-Aguirre, J. C., Marcelo-Medrano, H., Castillón-Barraza, A., Zamora-Alarcón, R., Casillas-Lamadrid, M. E., Jumilla-Corral, A. A., & Mayorga-Ortiz, P. (2022). *Domestic wastewater treatment system by electrocoagulation using photovoltaic solar energy*. *Revista Mexicana de Ingeniería Química, 21(2), IA2809.* https://doi.org/10.24275/rmiq/IA2809

Mousset, E., & Hatton, T. A. (2022). Advanced hybrid electro-separation/electro-conversion systems for wastewater treatment, reuse and recovery: Compromise between symmetric and asymmetric constraints. *Current Opinion in Electrochemistry, 35*, 101105. https://doi.org/10.1016/j.coelec.2022.101105

Murugananthan, M., Yoshihara, S., Rakuma, T., Uehara, N., & Shirakashi, T. (2007). Electrochemical degradation of 17β-estradiol (E2) at boron-doped diamond (Si/BDD) thin film electrode. *Electrochimica Acta*, 52(9), 3242-3249. https://doi.org/10.1016/j.electacta.2006.09.073

Muthukumar, M., Thalamadai, M., & Bhaskar, R. (2007). Electrochemical removal of CI Acid Orange 10 from aqueous solutions. *Separation and Purification Technology*, 55(2), 198-205. https://doi.org/10.1016/j.seppur.2006.11.014

National Survey on Energy Consumption in Private Households (ENCEVI) 2018. (2018). Retrieved from https://www.inegi.org.mx/programas/encevi/2018/

Niño, E. D., & Martínez, N. C. (2013). *Study of domestic greywater in three socioeconomic levels of Bogotá*. Pontificia Universidad Javeriana Facultad de Ingeniería. Retrieved from http://hdl.handle.net/10554/11139

Ottosson, J., & Stenström, T. A. (2003). Faecal contamination of greywater and associated microbial risks. *Water Research*, 37(3), 645-655. http://dx.doi.org/10.1016/S0043-1354(02)00352-4

Panizza, M., & Cerisola, G. (2001). Removal of organic pollutants from industrial wastewater by electrogenerated Fenton's reagent. *Water Research*, 35(1), 3987-3992. https://doi.org/10.1016/S0043-1354(01)00135-X

Pérez Carrión, J. (1980). *State of the Art – Coagulation*. Centro Panamericano de Ingeniería Sanitaria y Ciencias Ambientales (CEPIS), 1-44.

Pidou, M., Memon, F. A., Stephenson, T., Jefferson, B., & Jeffrey, P. (2007). Greywater recycling: Treatment options and applications. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 160(3), 119-131.*

Pinto, G. O., da Silva Junior, L. C. S., Assad, D. B. N., Pereira, S. H., & de Brito Mello, L. C. B. (2021). Trends in global greywater reuse: a bibliometric analysis. *Water Science and Technology*, 84(10-11), 3257-3276. https://doi.org/10.2166/wst.2021.429

Qiao, J., & Xiong, Y. (2021). Electrochemical oxidation technology: A review of its application in high-efficiency treatment of wastewater containing persistent organic pollutants. *Journal of Water Process Engineering*, 44, 102308. https://doi.org/10.1016/j.jwpe.2021.102308

Reyes López, M. G. (2016). *The use of chlorine in domestic wastewater treatment plants: Disinfection and formation of by-products*. Master's thesis, Instituto Politécnico Nacional, Centro de Investigación Interdisciplinario para el Desarrollo Integral Regional Unidad Durango. Retrieved from http://repositoriodigital.ipn.mx/handle/123456789/23350

Salgado, R. J., Güitrón de los Reyes, A., & López, P. M. (2018). *Impact Study on the Water Supply Service to the Population of the City of Mexicali for the Supply of Water to the Constellation Brands Brewery and Short and Long-Term Supply Strategy for the Plant (first stage)*. Instituto Mexicano de Tecnología del Agua (IMTA). Available at: https://agua.org.mx/wp-content/uploads/2019/01/IMTA-Estudio-Impacto-Abastecimiento-CBI.pdf. Accessed: January 01, 2022

Secretaría de Medio Ambiente y Recursos Naturales, Comisión Nacional del Agua. (1997). *Mexican Official Standards, NOM-003-SEMARNAT-1997*. Retrieved from http://www.ordenjuridico.gob.mx/Documentos/Federal/wo69207.pdf

Secretaría de Medio Ambiente y Recursos Naturales. (2022). *Mexican Official Standard NOM-002-CONAGUA-2021, Sanitary equipment and accessories*. *Official Journal of the Federation*. Retrieved from https://www.dof.gob.mx/nota_detalle.php?codigo=5672648&fecha=29/11/2022#gsc.tab=0

Shi, K.-W., Wang, C.-W., & Jiang, S. C. (2018). Quantitative microbial risk assessment of greywater on-site reuse. *The Science of The Total Environment*, 635(2), 1507-1519. https://doi.org/10.1016/j.scitotenv.2018.04.197

Solar panel data sheet. Retrieved from http://www.solardesigntool.com/components/module-panel-solar/TrinaSolar/4967/TSM-325PD14/specification-datasheet.html

- Stirling, R., Walker, W. S., Westerhoff, P., & Garcia-Segura, S. (2020). Techno-economic analysis to identify key innovations required for electrochemical oxidation as point-of-use treatment systems. Electrochimica Acta, 338, 135874. https://doi.org/10.1016/j.electacta.2020.135874

Taqieddin, A., Sarrouf, S., Ehsan, M. F., & Alshawabkeh, A. N. (2023). New insights on designing the next-generation materials for electrochemical synthesis of reactive oxidative species towards efficient and scalable water treatment: A review and perspectives. *Journal of Environmental Chemical Engineering, 11*(6), 111384. https://doi.org/10.1016/j.jece.2023.111384

UNESCO World Water Assessment Programme. (2020). *United Nations World Water Development Report 2020: Water and Climate Change*. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000372985

United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Retrieved from https://sdgs.un.org/goals