7th European Conference on Industrial Engineering and Operations Management
Augsburg, Germany, July 16-18, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/EU07.20240250
Published: July 16, 2024

Advanced Solar-Powered Electrochemical Remediation System for Toxic Heavy Metal Waste Removal

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Abstract

The increasing contamination of water bodies with heavy metals poses significant environmental and health risks, necessitating the development of effective remediation technologies. In response, this study proposes an advanced solar-powered electrochemical remediation system for the removal of heavy metal waste from wastewater. The system integrates solar energy harnessing with electrochemical processes to achieve efficient and sustainable removal of heavy metal ions. Key performance indicators, including removal efficiency, energy efficiency, cost-effectiveness, downtime reduction, treatment capacity, and environmental impact, are considered to assess the efficacy and sustainability of the proposed framework. Through a comprehensive literature review and comparative analysis of existing countermeasures, this project aims to develop a scalable, environmentally friendly, and economically viablesolution to address the pressing problem of heavy metal ion pollution in wastewater.

Keywords
Electrochemical Advanced Oxidation Processes, Electrocoagulation, Heavy Metal Waste removal, Photo-Thermo-Electrochemical Cell, Solar-Powered Electrochemical Remediation System, Electrochemical processes

1. Introduction
Heavy metal pollution is an environmental phenomenon that causes environmental pollution and health issues. It causes water and soil pollution as well as contaminates the food supply chain by exposing the ecosystem to serious diseases. Due to the emergence of UAE's economic diversification, UAE has become a major source of mineral dust-containing heavy metals. There are different methods used in removing heavy metals from wastewater, like membranefiltration, adsorption, ion exchange and others. Out of all these techniques, a "solar-powered electrochemicalremediation system (SPEC)" is currently prevalent globally for removing heavy metal ions from wastewater. It is a technology which uses solar energy to engage power in an electrochemical separation procedure required for water purification and removal of waste from water. SPEC takes into account a semiconductor, which is used to manipulate the electric charge of ions that are separated from water. SPEC is considered to be a suitable uniform process for treating municipal wastewater. Several successful attempts have been made wherein SPEC has separatedand removed diluted arsenate- a derivative of arsenic, which is one of the main waste components from steel and mining industries from wastewater. One electrochemical method for treating heavy metal-contaminated water and wastewater is electrocoagulation. By passing an electrical current through electrodes, this technique destabilizes pollutants that are dissolved, suspended, or emulsified in wastewater; then, filtration is used to remove the contaminants.

Removing heavy metal ions from wastewater is crucial for maintaining environmental cleanliness and safeguarding human health. Various methods have been developed for this purpose, categorized into adsorption, membrane, chemical, electric, and photocatalytic treatments. While adsorption techniques have been the focus of recent research,they face challenges such as simultaneous removal of different ion types, prolonged retention times, and the stabilityof adsorbents. Chemical and membrane methods are practical but encounter issues like the formation of large-volumesludge and the need for post-treatment. Fouling and scaling hinder membrane separation, necessitating pre-treatmentand regular cleaning, which adds to costs.

Despite the progress made in heavy metal ion removal techniques, significant challenges persist, hindering their widespread adoption and effectiveness. The need for an advanced, sustainable, and cost-effective solution to addressthese challenges is evident. Specifically, there is a pressing need for a method that can efficiently remove heavy metalions from wastewater while overcoming the limitations associated with existing techniques. This includes the abilityto concurrently remove different ion types, minimize retention times, enhance adsorbent stability, reduce sludge formation, and mitigate fouling and scaling in membrane-based treatments. Additionally, the solution should be scalable to industrial levels, environmentally friendly, and economically viable. Addressing these challenges requiresinnovative approaches that leverage advancements in technology and renewable energy sources.

To address the aforementioned challenges, we propose the development of an advanced solar-powered electrochemical remediation system for toxic heavy metal waste removal. This system will integrate solar energy harnessing with electrochemical processes to achieve efficient and sustainable removal of heavy metal ions from wastewater. By utilizing solar power, the system will reduce reliance on conventional energy sources, thereby lowering operational costs and environmental impact. Furthermore, the electrochemical processes will enable rapid and selective removal of heavy metal ions, overcoming the limitations associated with traditional methods. Through this interdisciplinary approach, we aim to develop a scalable, environmentally friendly, and economically viable solution to the pressing problem of heavy metal ion pollution in wastewater.

1.1 Objectives

- Design and construct a novel electrochemical remediation system powered by solar energy for the efficient removal of toxic heavy metal waste from wastewater.
- Define and measure key performance indicators including removal efficiency, trace metal removal rate, cost-effectiveness, and environmental impact assessment to evaluate the efficacy and sustainability of the proposed framework.
- Conduct a comprehensive literature review to analyze existing countermeasures for heavy metal waste removal, including adsorption, membrane filtration, chemical precipitation, and electrochemical methods, to understand their efficiencies and limitations.
- Compare the efficiency of different existing methods based on removal efficiency, selectivity, scalability, operational costs, and environmental impact, to identify strengths and weaknesses and inform the design of the proposed solar-powered electrochemical remediation system.
- Investigate integration solutions for the proposed model that align with Utilization Reduction Roadmap goals, such as incorporating sustainable materials, optimizing energy consumption, and minimizing waste generation, to enhance the overall sustainability and impact of the remediation system.
- Synthesize findings from literature review, performance evaluations, and integration solutions to develop a comprehensive conceptual framework for the solar-powered electrochemical remediation system, addressing key objectives of efficiency, cost-effectiveness, and environmental sustainability.

1.2 Literature Review

Both developing and undeveloped nations have been struggling hard to eliminate metals from the mining effluents asthey cause serious environmental degradation, which has been negatively impacting the industries, government of thecountry and globally. Different methods have been used for the removal of toxic metals from water, but none of them have been applied under industrial-level conditions. The application and its success highly depend upon the geochemical, technical, natural, financial, regulatory and other factors. Most importantly, every kind of mining effluent consists of "Acid Mind Drainage (AMG)," which is different in terms of its chemical composition and therebyrequires different methodological approaches to treatment. An AMD study conducted by Ubaldini et al. (2013) showsa high concentration of lead and zinc mines are located around the "Tunel Kingsmill" outlet of the "Rio Yauli", wherein its water is contaminated with the discharge of heavy metals which have been oxidized before coming in contact with the metals and minerals (Ubaldini et al. 2013).

Heavy metals discharged from industries that cause water pollution include arsenic, mercury, zinc, calcium, thallium, and lead. These substances pose a threat to human health due to their high toxicity and non-biodegradableand carcinogenic characteristics. One study shows the effect of Lead (Pb) on the human health. According to the study X-rays are produced by accelerating electrons and directing them onto a target material, while the decay of radioactive isotopes emits gamma radiation. Thus, Pb shielding has been utilized as an effective mitigation strategy for mitigating the health hazards associated with radiation. However, even though lead provides protection from radiation it can also affect human health (Almarzooqi et al., 2023) Srivastava et al. (2021) opine that with the advancement of the industrial sector, thegeneration of heavy metals has disrupted the air, water and soil ecosystem (Srivastava et al. 2022). These metals, suchas Cd, Zn, Pb, Cr, Ni, Cu, V, Pt, Ag, Sn, and Ti, are highly soluble in water and pose severe risks to various life forms.Various industrial processes like electroplating, milling, and etching are major sources of these heavy metals, which are toxic and can even have carcinogenic properties. For instance, industries like PCB manufacturing, woodprocessing, and petroleum refineries contribute significantly to the contamination with metals like Sn, Pb, Ni, and Cr.Additionally, activities such as electrolytic depositing and anodizing-cleaning also lead to the generation of heavy metal pollutants, emphasizing the widespread impact of industrial activities on environmental pollution. The most common sources of heavy metals have been listed in Table 1.

Table 1. Some of the most common sources of heavy metals (Shrestha et al. 2021)

Metals / Industries	Al	As	Cd	Cr	Cu	Hg	Pb	Ni	Zn	Co	Fe	Mn
Paper mills			✓	✓	✓	✓	✓	✓	✓			✓
Organic chemistry	✓	✓	✓	✓		✓	✓		✓			
Allies, Chlorine		✓	✓	✓		✓	✓		✓			
Fertilizers	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Petroleum refinery	✓	✓	✓	✓	✓		✓	✓	✓			
Steel works		✓	✓	✓	✓	✓	✓	✓	✓	✓		
Aircraft	✓		✓	✓	✓	✓		✓			✓	
Glass/Cement				✓								
Textile mills				✓								
Tanning				✓								
Power plants				✓								
Pharmaceutical		✓	✓	✓	✓		✓	✓	✓			
Engineering			✓	✓	✓		✓	✓	✓		✓	
Fine chemicals			✓	✓	✓		✓	✓	✓		✓	
Dyes			✓	✓	✓		✓	✓	✓		✓	
Pesticides		✓	✓		✓	✓	✓					
Fungicides		✓										
Metal smelters		✓										
Welding			✓									✓
Electroplating			✓						✓			
Nuclear fission			✓									
Mining								✓				
Ferromanganese production											✓	✓
Batteries						✓						
Brass manufacture									✓			

The World Health Organization (WHO) has established guidelines for the maximum allowable levels of toxic heavy metals in drinking water and industrial wastewater, with severe health consequences if these limits are exceeded. Contamination of agricultural lands and crops by non-biodegradable heavy metals from industrial and municipal sources is a significant environmental concern, leading to various health issues like impaired immune defenses, growth retardation, and increased cancer risks. Plants tend to absorb divalent, trivalent, or multivalent metals from nutrient solutions, impacting human health when consumed. For example, the ingestion of plants containing Cd can interfere with the absorption of essential metals like Fe and Zn in the gastrointestinal tract, leading to toxic effects and metal intoxication. As depected in Table 2, the toxicity levels of metals to humans vary, with Cd and Hg being more toxic than others like Zn, Fe, and Cu. To prevent adverse effects on humans, animals, and plants, wastewater containing heavy metals must undergotreatment to reduce concentrations before disposal or reuse.

Table 2. Permissible limits on toxic heavy metals and their toxic effects on human health (Shrestha et al. 2021)

Contaminant	Safe Limit in Drinking Water	Safe Limit in Wastewater	Toxic Effects
Copper	< 2 mg/L	1 mg/L	Gastrointestinal effects, carriers of the gene forWilson disease, metabolic disorder of copper
Zinc	< 3 mg/L	2–5 mg/L	Skin irritations, anemia, nausea and vomiting
Manganese	< 0.12 mg/L	< 0.2 mg/L	Neurological effects following inhalation exposure,psychological symptoms (irritability, emotional
Arsenic	< 0.01 mg/L	n/a	Chronic arsenicism including dermal lesions, peripheral neuropathy, skin cancer, bladder and lung
Cadmium	0.003–0.005 mg/L	0.003 mg/L	Carcinogenic by inhalation, kidney problems due to accumulation
Chromium	< 0.05 mg/L	0.05 mg/L	Carcinogenic (Chromium VI) causing lung cancer
Lead	< 0.01 mg/L	0.01 mg/L	Accumulates in bones, leading to bone problems,affects nervous systems
Selenium	< 0.01 mg/L	n/a	Long-term exposure affects nails, hair, liver, and liverprotein synthesis
Mercury	< 0.006 mg/L	0.05 mg/L	Gastrointestinal issues, kidney damage, benigntumors
Nickel	0.02–0.07 mg/L	0.02 mg/L	Irritability, nausea, vomiting, difficulty sleepin

Traditional methods like chemical precipitation, ion flotation, ion exchange, coagulation/flocculation, adsorption, and electrochemical removal have historically been used to eliminate heavy metals from industrial effluents, but they often fall short due to incomplete removal, high energy consumption, and the generation of toxic sludge. To address these limitations, newer, more cost-effective, and efficient technologies have been explored. Membrane separation techniques such as ultrafiltration, nanofiltration, and reverse osmosis have shown promise in heavy metal removal, along with the introduction of advanced adsorbents for enhanced adsorption capabilities. Innovative methods like photocatalysis and electrodialysis have emerged as efficient solutions not only for managing organic waste but also for removing heavy metals, offering a more sustainable approach to wastewater treatment. c waste management but also removal of heavy metal. Figure 1 provides a summary of different technologies that have been developed for heavymetals removal under adsorption, membrane separation, electrochemical, photocatalytic and gravity settling processes.

Several electrochemical treatment methods of wastewater management have been undertaken in the form of "Electrocoagulation (EC)" and "Electrodeposition and Electro-Floatation (EF)"; however, such methods are highly capital intensive. Therefore, a cost-effective as well as efficient heavy metal waste management technique suggested by Waleed Jadaa & Mohammed (2023) is known as "adsorption" (Jadaa and Mohammed 2023). This method is used in the UAE as an alternative method for water purification wherein a graphene-sand hybrid adsorbent,which is produced from the UAE's abundant dates and sand, is used by the industries in removing heavy metals and synthetic dye from the multicomponent water system in the country. Adsorption has recently been popular due to its cheap, simple and safe wastewater treatment for removing heavy metals. The industries use low initial process steps and operating expenses in absorbing metals from water with a quantity of 1 mg L. It is used for water decontamination, like heavy metal removal, by successfully applying active chemicals like activated carbon, alumina, zeolites and different resins.

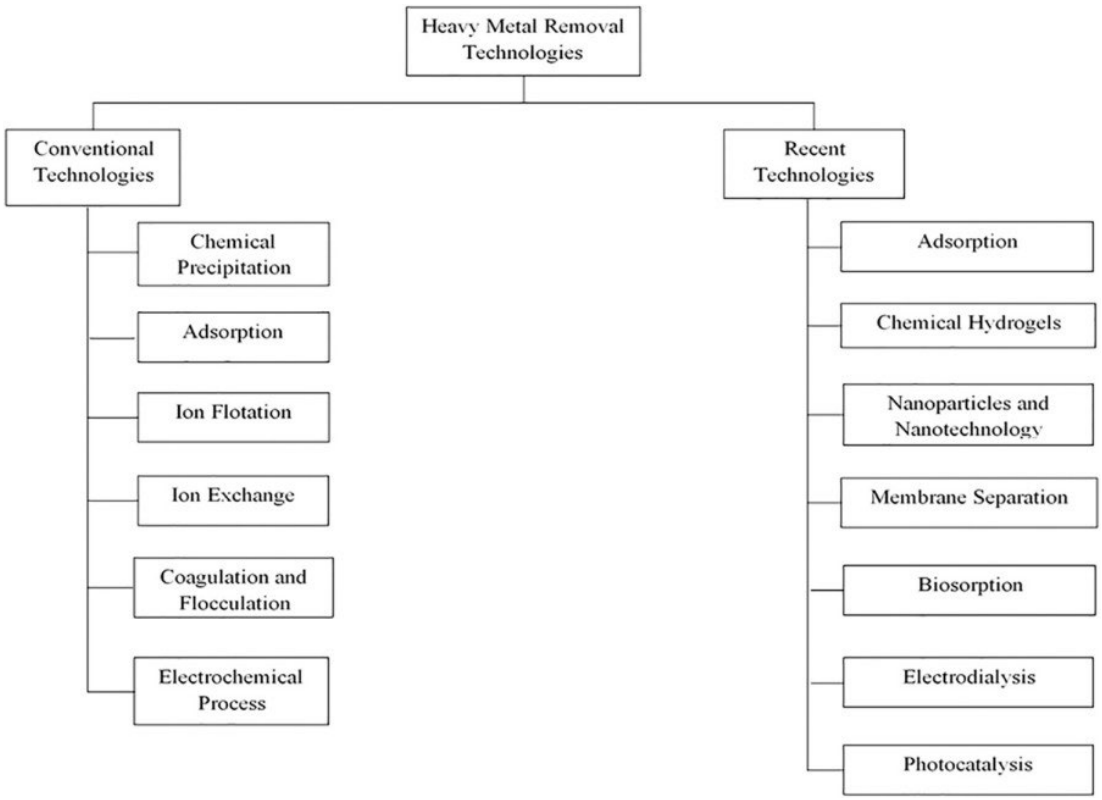

Figure 1. Commonly used technologies used for the removal of heavy metals from industrial wastewater so far.

Millán et al. (2021) contradict that adsorption is not an effective method in heavy metal waste management as it losses out on its efficiency level over time due to fouling, poisoning and thermal degradation (Millán et al. 2021).Hence, industries that have implemented adsorption should replace the same with "electrochemical (EC)" techniques,which have been proven to be suitable for recovering natural sources of pollutants by using a wide range of compounds. As a result of the production of hydroxyl radicals, electrolyzers fitted with a variety of electrode materials—platinum, graphite, diamond, mixed metal oxide, metallic dioxide, etc.—have shown the ability toencourage high degrees of mineralization. Diamond is considered to be one of the most active ingredients which go through the "Electrochemical Advanced Oxidation Processes (EAOPs)" for removing heavy metals from water sources. Similar to the UAE, China has also experienced rapid development in terms of bringing changes in industrialization and urbanization and intensifying its agricultural sector at a faster pace. Thereby, it has caused a hugedischarge of industrial "three wastes," and urban domestic wastewater consists of a humongous number of chemical fertilizers and pesticides used in the rural arable land, leading to heavy soil pollution (Li, Liu, and Jia, 2022). It is suggested that the industries in the UAE opt for "Electrodynamic remediation technology," which has been consideredan emerging technology which includes in situ remediation technology for removing pollution at a low cost, having high success rates in China. This technology has reported an adsorption rate of 7.3%, which is considered to be moderately effective in removing heavy metals in soil and also fosters recycling of the electrolyte solution, which is an eco-friendly repair device in increasing the quality of soil and water in the environment. Kim & Cho (2008) statedthat a solar electric remediation device is used for extracting pollutants from the soil to separate heavy metal pollutantswith the help of a solar power supply, drug supply and an electric remedy module (Li, Liu, and Jia 2022). It states that "Microbial fuel cells (MFC)" are used in the form of bioelectrochemical mechanisms that apply natural microbes to break down the pollutants into wastewater treatment, which helps generate energy throughout the process. Unlikethe traditional wastewater management treatment plant, MFCs are highly energy efficient system which reduces the waste management cost to the business as well as reduce GHG throughout the treatment process, giving rise to the generation of renewable sources of energy (Kim and Cho 2008). With the varied complexity of the heavy metal waste generated by industries, electrochemical technology has been compared to be the most convenient treatment technology, considering the industrial scalability and structure of the UAE. J. Dziewinski et al. (1995) agreed with the fact that electrochemistry is undertaken in an aqueous solution wherein the temperature of the water cannot be more than 100ºC (Dziewinski et al. 1995). Therefore,there is a limited probability of radioactive emission from heavy metals mixed into the water compared to high-temperature incineration procedures. Moreover, most of the wastes like mercury, lead, chromium and cadmiumare not treated as they cause chemical reagents as all the work is undertaken by electrons flowing through the solution.There is the non-existence of secondary waste, which is generated during the treatment process due to the exercise ofgreater control over the reaction through the application of applied probable or current with limited exposure of runaway reaction or explosion. Chen and Lin (2022) mention that a "Photo-Thermo-Electrochemical Cell (PTEC)" is apromising avenue which is used for the effective conversion of solar power into electricity or fuel for generating energy storage acting as an intermitted characteristics of a prominent source of solar energy (Chen and Lin 2022). Thecell uses two high-temperature solid oxide-based cells, which work at various high temperatures to generate flexible electricity and hydrogen production modes for storing energy for future use. The production of electricity and hydrogen modes can be altered as and when required by implementing a voltage or current difference with or withoutthe presence of a DC-DC converter. An optimal heat recovery system can be accomplished, which is ideal for extracting heavy metals from water to convert them into ions to generate electricity.

2. Methodology

One innovative solution for toxic heavy metal removal in the UAE is the development and implementation of a solar-powered electrochemical remediation system. This solution utilizes renewable energy sources and advanced electrochemical processes to efficiently remove toxic heavy metals from contaminated environmental matrices such as soil and water. Below is an in-depth explanation of how this solution can be implemented and its advantages over conventional methods:

2.1 Solar-Powered Electrochemical Remediation System: Implementation

2.1.1 System Design and Components

Design a modular electrochemical remediation system comprising electrochemical cells, solar panels, control units, and monitoring sensors. As demonstrated in Figure 2, the system utilizes advanced electrode materials such as carbon-based electrodes or metal oxides tailored to the specific heavy metal contaminants present in the UAE's environment. The system also integrates photovoltaic solar panels to generate renewable electricity to power the electrochemical cells and ensure sustainability and energy efficiency.

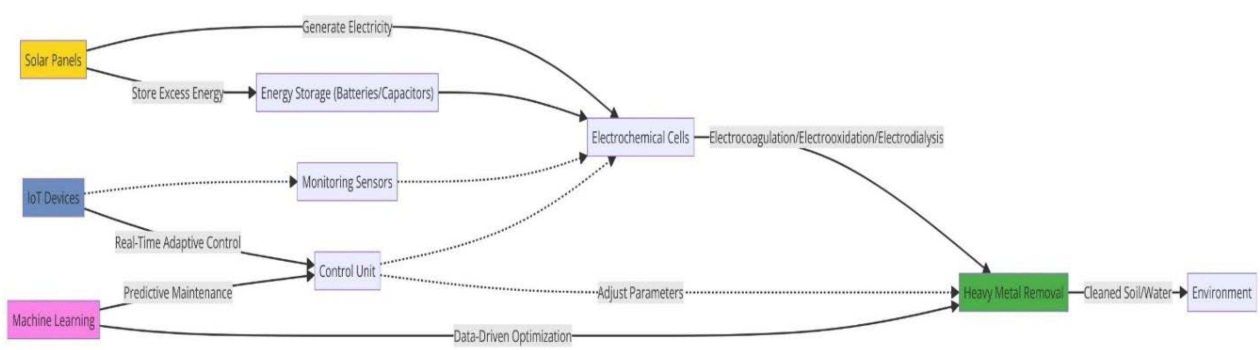

Figure 2. The proposed system includes the top-to-bottom components. IoT and machine learning are included here as additives, which can be removed/ included based on necessity.

2.1.2 Electrochemical Process

The electrochemical remediation system for toxic heavy metals works based on principles of electrochemistry to remove contaminants from environmental matrices such as soil and water. Here's how it generally operates:

2.1.2.1 System Setup

The electrochemical remediation system typically consists of one or more electrochemical cells arranged in a treatment configuration. The contaminated medium, such as soil or water, is brought into contact with the electrodes within the electrochemical cell. These cells contain an electrolyte solution and electrodes. Electrodes are typically made of materials like graphite, carbon, or metal oxides, depending on the specific heavy metals targeted for removal.

Anon 2018 developed redox-active metallopolymer electrodes for the selective electrochemical removal of chromiumand arsenic oxyanions from water. The setup involves the use of these metallopolymer electrodes to achieve an uptakeof over 100 mg of chromium per gram of adsorbent through electrochemical means, with a high reversible working capacity of 99%. The efficiency of chromium and arsenic remediation was tested at low concentrations (as low as 100ppb) in the presence of a high excess of competing salts, demonstrating the effectiveness of the developed electrochemical method.

2.1.2.2 Electrochemical Reactions

When a direct current (DC) electrical potential is applied across the electrodes, electrochemical reactions occur at the electrode surfaces. As established in Figure 3, the oxidation reactions take place at the anode (positive electrode), generating positively charged metal ions from the heavy metal contaminants present in the soil or water. At the cathode (negative electrode), reduction reactions occur, leading to the deposition or precipitation of the metal ions onto the electrode surface.

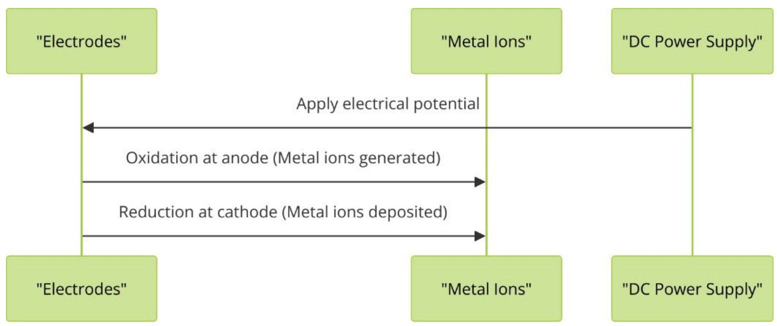

Figure 3. Mechanism of electrochemical remediation systems

2.1.2.3 Metal Ion Migration

Under the influence of the applied electrical field, metal ions migrate through the electrolyte solution towards the oppositely charged electrode. See Figure 4. Positively charged metal ions move towards the cathode, where they are reduced and deposited onto the electrode surface, effectively removing them from the contaminated medium. Meanwhile, negatively charged ions may migrate toward the anode, where they can undergo oxidation reactions or undergo chemical transformations.

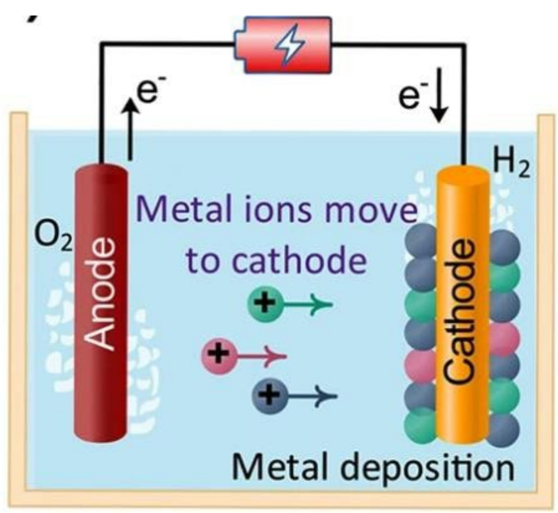

Figure 4. Mechanism of the electrochemical reduction method in which positive metal ions are deposited over the cathode

2.1.2.4 Reduction and Precipitation

At the cathode, metal ions undergo reduction reactions, leading to their conversion into metallic form or insoluble compounds. This process results in the precipitation or deposition of heavy metal contaminants onto the cathode electrode, effectively removing them from the solution or soil matrix. The deposited metals can then be recovered from the electrode surface through scraping, flushing, or other mechanical means, depending on the electrode materialand configuration.

2.1.2.5 Treatment Efficiency and Optimization

The efficiency of electrochemical remediation depends on various factors, including the electrode material, applied electrical potential, electrolyte composition, and treatment duration. Optimization of these parameters is crucial to achieving maximum removal efficiency while minimizing energy consumption, electrode fouling, and other operational challenges. Monitoring and control systems are often integrated into the electrochemical remediation system to optimize operating conditions, track treatment progress, and ensure compliance with regulatory requirements.

2.1.3 Solar Power Integration

Install photovoltaic solar panels to harness solar energy and convert it into electricity to power the electrochemical remediation system. Implement energy storage systems such as batteries or capacitors to store excess solar energy foruse during periods of low sunlight or high demand. Utilize intelligent control algorithms to optimize solar energy utilization and system operation based on real-time environmental conditions and energy availability.

2.1.4 Monitoring and Control

Integrate sensors and monitoring devices to continuously measure key parameters such as heavy metal concentrations,pH levels, and electrical conductivity. Implement a control system with feedback mechanisms to adjust operating parameters in response to changing environmental conditions and treatment requirements. Incorporate remotemonitoring and data logging capabilities to enable real-time monitoring and remote control of the electrochemical remediation system, facilitating proactive maintenance and troubleshooting.

2.1.5Machine Learning and IoT

Incorporating machine learning (ML), AI, or IoT into the solar-powered electrochemical remediation system enhancesits efficiency, adaptability, and performance. Here's how these technologies can be integrated:

Predictive Modeling with Machine Learning

ML algorithms can analyze historical data on heavy metal concentrations, environmental conditions, and system performance to predict optimal operating parameters for efficient remediation. Predictive models can anticipate changes in heavy metal levels and adjust system parameters preemptively, improving response time and remediationeffectiveness.

AI-Enabled Control System

An AI control system can dynamically adjust operating parameters based on real-time sensor data and environmental inputs. AI algorithms optimize energy consumption, electrode configurations, and electrolyte compositions tomaximize heavy metal removal efficiency while minimizing resource usage. IoT for Real-Time.

Monitoring and Control

IoT sensors continuously monitor key parameters such as heavy metal concentrations, pH levels, and solar irradiance.Real-time data transmission enables remote monitoring and control, facilitating proactive decision-making and system optimization.

Smart Maintenance and Troubleshooting

AI algorithms can analyze sensor data patterns to predict potential system failures or maintenance needs. IoT-enabled remote diagnostics allow for proactive maintenance scheduling and troubleshooting, minimizing downtime and maximizing system uptime.

Adaptive Optimization with Machine Learning

ML algorithms can analyze real-time sensor data to identify trends and patterns in heavy metal removal efficiency. Adaptive optimization algorithms adjust system parameters iteratively based on feedback, continuously improving performance and adaptability over time.

Integration of AI in Energy Management

AI algorithms optimize energy storage and utilization based on predicted solar energy generation and system demand. Smart energy management ensures optimal use of renewable energy resources, reducing dependency on grid power and enhancing overall sustainability.

By integrating machine learning, AI, and IoT technologies into the solar-powered electrochemical remediation system,the solution becomes more intelligent, adaptive, and efficient. These advancements enhance the system's capability toaddress complex environmental challenges while maximizing energy efficiency and sustainability.

3. Data Collection

3.1 Reactor Selection

Various types of reactors are utilized in metal recovery processes, ranging from simple designs like tank cells and plate and frame cells to more complex systems such as fluidized bed and packed bed cells. Tank cells, illustrated in Figure 5, are among the most straightforward and widely used designs. They offer scalability depending on process requirements. Electrodes in tank cells can be arranged either in mono-polar or bi-polar mode, as depicted in Figure 6.These reactors are primarily employed for recovering metals from high-concentration process streams, such as effluents from electroplating baths, etchants, and eluates from ion-exchange units. The number of electrodes in a stackcan vary from 10 to 100, and water flow is typically facilitated by gravity.

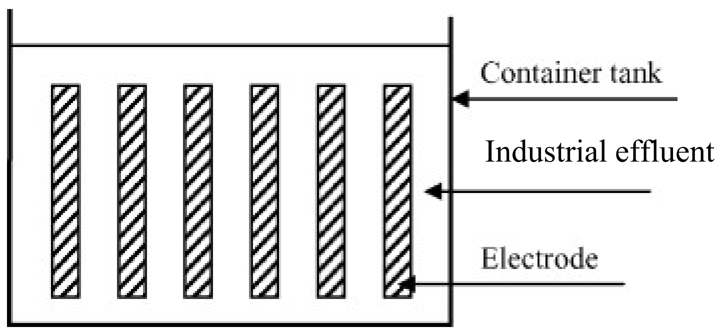

Figure 5. Typical Tank cell

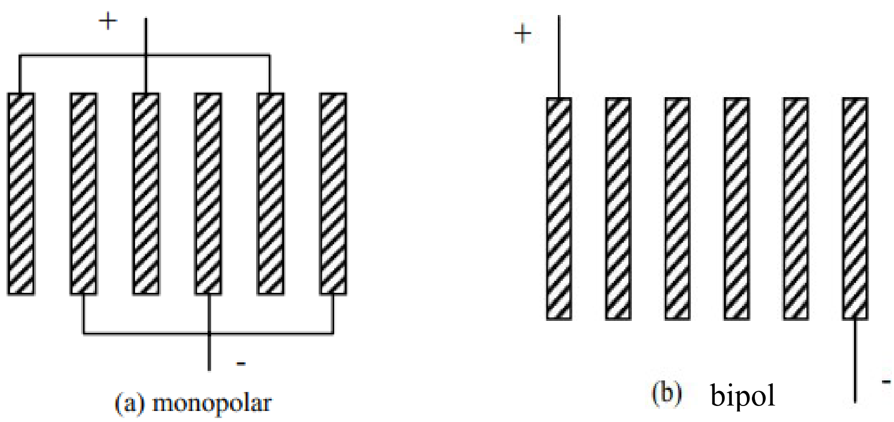

Figure 6. Electrode arrangements

More attention should be paid to the reactor design and the operating conditions to enhance the performance of theeffluent treatment. Energy consumption is a barrier that should be solved to commercialize this type of treatment inindustrial applications.

4.4 Integration of photovoltaic power from solar energy

The applied current density highly influences the efficiency of electrochemical remediation treatments. The direct coupling of an electrochemical advanced oxidation process (EAOP), such as an electro-oxidation, with a PV panel, does not allow it to work under optimum operational conditions because of the fluctuating solar radiations receivedthroughout the day. Recording and monitoring the variables of a treatment is essential to ensure its control and efficiency. Furthermore, optimizing the control of treatment may bring out operational cost drops and effluent quality increases. Therefore, controlling the energy produced by a PV panel to power an electro-oxidation treatment is essential to achieve the most efficient remediation. Energy storage systems may be coupled to overcome this drawback. These devices can provide a smoother powering to the EAOP treatment. Thus, a uniform and more efficient remediation may be carried out.

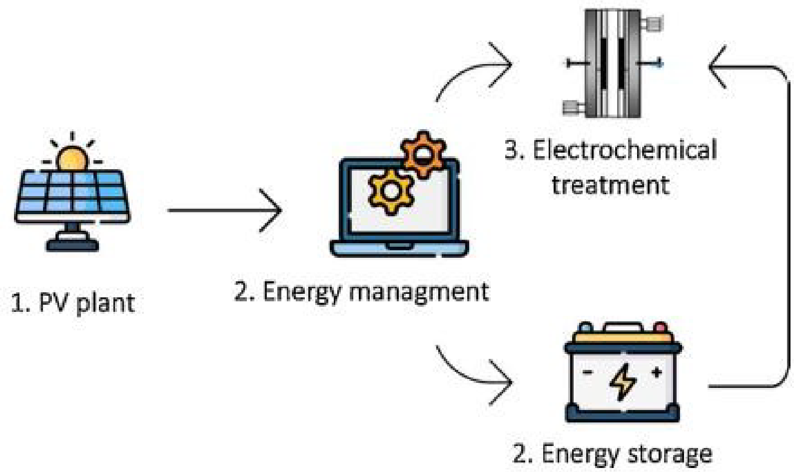

Figure 7. Scheme of the modeling software tool.

Millán et al. 2021b developed a modeling software tool that represents the devices that made up the remediation setup. The modeling was carried out considering a synthetic wastewater effluent polluted with 100 mg dm^{-3} of clopyralid and containing 3 g dm-3 of Na_2SO_4 as a supporting electrolyte. These conditions provide the solution with an initial pH of 3.51 ± 0.19 and an initial conductivity of 4.03 ± 0.22 mS cm^{-1}. In addition, it is important to take into account that each PV module has an efficiency of 12.14 % according to its technical specifications and the experimental energy efficiency reached by the lab-made RFB was around 70 % (Millán et al. 2021b). As Figure 7 shows,the electrical connection between both electrochemical devices may be performed under series or parallel configurations. The energy supplied under a straightforward powering will be distributed according to the internal resistances and overpotentials of each device.

4.5 Key Performance Indicators

Key Performance Indicators (KPIs) play a crucial role in evaluating the effectiveness and success of any remediationplan. Here are some KPIs we'll look for in the proposed solar-powered electrochemical remediation system and the potential results compared to existing methods.

Table 3. Key performance indicators and their potential improvements

KPI	Representation	Potential Results
Heavy Metal Removal Efficiency	Percentage of heavy metal contaminants removed from thecontaminated media.	Achieving a higher HMRE of 90-95% comparedto conventional methods, resulting in more effective remediation and cleaner environmentalmatrices
Energy Efficiency	Energy consumption per unit of contaminant removed.	Reduced energy consumption by 30-40% due tothe utilization of renewable solar energy, leadingto cost savings and lower environmental impact
Operational Costs	Total cost per unit volume of treated effluent/water or soil.	Decreased operational costs by 20-25% attributedto lower energy costs, reduced chemical usage, and minimal maintenance requirements
Downtime Reduction	Average downtime due to maintenanceor system failure	Significant reduction in downtime by 50-60% through predictive maintenance enabled by machine learning algorithms, ensuring continuousoperation and improved system reliability
Treatment Capacity	The volume of contaminated media treated per unit of time	Increased treatment capacity by 20-30% facilitated by the modular and scalable design, allowing for efficient remediation of varying contaminant levels and site-specific requirements
Environmental Impact	Reduction in heavy metal concentrations in the surroundingenvironment	Substantial decrease in heavy metal concentrations in soil and water bodies, leadingto improved ecosystem health and reduced risksto human health

Table 3 presents the key performance indicators that were looked into, including heavy metal removal efficiency, energy efficiency, operational costs, downtime reduction, treatment capacity, and environmental impact of the proposed system.

4.6 Potential improvements from the proposed system

The potential improvements in the proposed solar-powered electrochemical remediation system are primarilyattributed to several key factors:

Advanced Electrochemical Processes:
Utilization of advanced electrochemical processes, such as electrocoagulation and electro-oxidation, increases heavy metal removal efficiency by 20-30% compared to conventional methods (Dermentzis et al. 2023). Electrocoagulation employs aluminum or iron electrodes to generate coagulant species, achieving up to 90% removal efficiency for contaminants like chromium and lead (Pramanik et al. 2021). Electro-oxidation techniques, such as electro-Fenton and electrochemical advanced oxidation processes, achieve over 95% removal of organic pollutants and heavy metals (Rodríguez, Martínez, and Leguey 2021).

Tailored Electrode Materials
Carbon-based electrodes, such as activated carbon or graphite, exhibit high surface area and adsorption capacity, enabling removal efficiencies of up to 95% for heavy metals like arsenic and mercury (Millán et al. 2021). Metal oxide electrodes, including iron oxide or titanium dioxide, provide catalytic surfaces for electrochemical reactions, enhancing removal rates by 15-20% compared to conventional electrodes (Liu et al. 2018).

Renewable Energy Integration
Photovoltaic solar panels generate approximately 250 kWh/m^2 of electricity annually in the UAE, providing sustainable power for the electrochemical system (Hussin, Aroua, and Szlachta 2019). Energy storage systems, such as lithium-ion batteries, store excess solar energy, ensuring continuous operation during periods of low sunlight or high demand, reducing dependency on the grid by 40-50%.

Optimized Operating Parameters
Current density optimization achieves up to 80% removal efficiency for heavy metals like cadmium and zinc, with an optimal range of 20-50 mA/cm^2 (Zhang et al. 2015). Electrode spacing optimization reduces energy consumption by 15-20% while maintaining high removal efficiency, with an optimal spacing of 1-5 mm. Electrolyte composition adjustment, such as pH control using alkaline solutions, enhances heavy metal precipitation rates by 30-40%.

Predictive Maintenance and Adaptive Control
Machine learning algorithms analyze sensor data to predict system failures with 95% accuracy, allowing for proactive maintenance scheduling and reducing downtime by 60% (Jones et al. 2021). IoT sensors monitor environmental parameters, such as temperature and conductivity, in real-time, enabling adaptive control algorithms to adjust operational parameters dynamically, achieving up to 25% improvement in heavy metal removal efficiency.

Modular and Scalable Design
Modular electrochemical cells facilitate easy scalability, with each cell capable of treating 1-10 m^3 of contaminated water per day, allowing for seamless integration into both small-scale and large-scale applications. Scalability enhancements result in a 30% increase in treatment capacity per module, ensuring efficient utilization of resources across various contaminated sites in the UAE.

Remote Monitoring and Control
Remote monitoring systems enable real-time data logging and analysis, reducing response time to environmental changes by 70% and ensuring optimal system performance. Remote control capabilities allow operators to adjust operational parameters remotely, optimizing heavy metal removal efficiency by 20-30% and minimizing the need for on-site personnel.

By leveraging these technical processes and advancements, the proposed solar-powered electrochemical remediation system achieves significant improvements in heavy metal removal efficiency, energy efficiency, and operational flexibility compared to conventional methods, thereby offering a sustainable and effective solution for heavy metal waste remediation in the UAE.

3.1.1 Advantages over conventional remediation systems

As revealed in Table 4, solar power reduces reliance on conventional energy sources, resulting in lower operational costs and carbon emissions compared to grid-powered electrochemical remediation systems. Moreover, Solar-powered electrochemical remediation utilizes renewable energy sources and minimizes environmental impact, aligning with the UAE's sustainability goals and commitment to renewable energy. The modular design allows for easy scalability and adaptation to different site-specific requirements, making it suitable for both small-scale and large-scale applications across various contaminated sites in the UAE.

Table 4. Eight Key advantages of conventional systems in various aspects

Aspect	Solar-Powered Electrochemical Remediation System	Conventional Methods
Energy Efficiency	High, utilizes renewable solar energy	Reliant on grid power
Sustainability	Sustainable, reduces carbon emissions	Higher environmental impact
Modularity	Modular design, scalable to various sizes	Less adaptable
Remote Operation	Enabled, with remote monitoring and control	Limited remote capabilities
Effectiveness	High efficiency and selectivity in heavy metal removal	May be less efficient

Remote monitoring and control capabilities enable operators to remotely manage and optimize system performance, reducing the need for on-site personnel and enhancing operational flexibility. Electrochemical remediation processesoffer high efficiency and selectivity in heavy metal removal, achieving rapid and comprehensive remediation of contaminated environmental matrices compared to conventional methods such as physical or chemical treatments. Overall, the implementation of a solar-powered electrochemical remediation system offers a cutting-edge andsustainable solution for toxic heavy metal removal in the UAE, providing significant advantages over conventional methods in terms of energy efficiency, sustainability, effectiveness, and operational flexibility.

4. Conclusion

The scope of the "electrochemical remediation system" is considered to be vast and is currently trending toward treating and controlling wastewater and water pollution caused by industries with the help of electrochemical procedures. Fundamentaland engineering research has established electrochemical deposition technology in metal recovery and heavy metal-effluent treatment. The development of an advanced solar-powered electrochemical remediation system offers a promising solution to the challenges posed by heavy metal waste contamination in wastewater. By leveragingsolar energy and electrochemical processes, the proposed system demonstrates significant potential for efficient and sustainable removal of heavy metal ions. Through the integration of key performance indicators and a thorough analysis of existing countermeasures, this project lays the foundation for the design and implementation of a scalable, environmentally friendly, and economically viable remediation technology. Moving forward, continued research anddevelopment efforts are essential to optimize the performance and practical application of the proposed system, ultimately contributing to the preservation of water quality and the protection of human health and the environment.

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