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Application of Sequential Combination of Electro-Coagulation/Electro-Oxidation and Adsorption for the Treatment of Hemodialysis Wastewater for Possible Reuse

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Abstract: Reusing hemodialysis wastewater (HWW) is more difficult due to its higher conductivity (salinity) and the need for an iterative RO or adsorption process. It can therefore be challenging and technologically laborious. In this context, this study aimed to investigate the possibility of treating HWW by combining electro-coagulation (EC) and electro-oxidation (EO) processes and adsorption as the best technologies to achieve efficient removal of dissolved micropollutants. In this work, the application of electro-coagulation/electro-oxidation processes using, respectively, aluminum and platinum electrodes combined with adsorption onto active carbon to treat HWW was studied. In the EC process, high removal of phosphate ions and chemical oxygen demand (COD) was observed. In the EO process, the COD removal performance, total nitrogen, and Mg were significant and reached 100, 83, and 89%, respectively, after 100 min of treatment. The estimated energies required to treat HWW by EC and/or EO were approximately 0.7 kWh/m^3 and 0.05 kWh/m^3, respectively. While the EO and EC processes used for COD removal from HWW showed almost similar performances, the EO process seems to consume less energy. Therefore, electrochemical removal of HWW can be successfully performed using the EO process and activated carbon (AC) for the complete removal of COD and the mineralization of pharmaceutical residues. The experimental results showed that the coupling of the three processes (EC–EO–AC) provides treated water that can be reused in agriculture due to its less sodium absorption ratio (SAR) value and might be an alternative method of wastewater treatment responding to the concept of green dialysis.

Keywords: electro-coagulation/electro-oxidation; activated carbon adsorption; hemodialysis wastewater; energy consumption; COD; conductivity

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1. Introduction

Population density growth, climate changes, and progressive industrial activities have led to numerous efforts and more attention to the quantity and quality of human consumption and the wastewater reuse approach. The biggest challenges in providing water quality and quantity to ensure the sustainability of water resources have now begun in the twenty-first century [1]. Depending on specific conditions, technologies, and water shortage priority, several countries use treated industrial, domestic, and agricultural wastewater for many purposes [2]. Since hospital wastewater may contain various minerals and organic nutrients, it can be considered as another source of pollution. Hence, it is paramount that hospital wastewater is treated or reused before being drained to sewers or water bodies because of the homogeneity of wastewater within different units/services. In a general hospital, wastewaters are similar to domestic one, but with a large variety of substances used for medical purposes and in laboratories, and also excreta from patients [3]. This

waste contains insoluble/soluble organic/inorganic pollutants that can harm the ecological balance and public health. It may lead to outbreaks of transmissible diseases, diarrhea epidemics, water contamination, and radioactive pollution, thereby threatening potential toxic effects to the aquatic biota [4]. According to the diversity of contaminants, the intrinsic toxicity of hospital effluent is 15 times higher compared to urban effluent, and it carries multiple pathogenic microorganisms, contributing to the spread of antibiotic-resistant bacteria into the environment [5].

Conventional wastewater treatment plants are not suitable for treating the combined hospital wastewater of all types of chemical and biological contaminants. As a consequence, the first step is to separate all hospital sections. HWW is one of the sections of the hospital that could be appropriate for sanitation and irrigation purposes. HWW contains various mineral/organic matters. In addition, it may be contaminated with the COVID-19 virus and bio-hazardous agents because SARS-CoV-2 RNA was detected in hemodialysis effluent from a patient with COVID-19 pneumonia and prolonged inflammation [6]. Additionally, authors isolated SARS-CoV-2 RNA in sewage samples collected from 14 wastewater treatment plants (WWTPs) in Tunisia [7]. Thus, one of the challenges faced by healthcare facilities dealing with hemodialysis and healthcare waste in a way that can minimize potential risks is to take steps toward green hospital management.

According to Machado et al. [8], hemodialysis contains a higher concentration of phosphates, sulfates, salinity, ammonia, nitrites, turbidity, and total nitrogen and an elevated chemical oxygen demand (COD), conductivity, and biochemical oxygen demand (BOD) that exceed the thresholds defined [9]. In addition, Dehghani et al. [10] from the Hormozgan province educational hospital in Iran characterized HWW and demonstrated some parameters, such as the COD of this waste showed a higher removal by EC from 32.3% to 87.1%. Moreover, Abarkan et al. [11] treated hemodialysis effluent by electrodialysis. They showed effective removal of excess ions, such as sodium, chloride, sulphate, and nitrate, which meets the standards for several reuse applications such as rehabilitation pools or pre-sterilization cleaning.

Compared with the other magrebian countries [12], it is relevant to mention that Tunisia has the highest prevalence of hemodialysis patients. According to the Tunisian Ministry of Health, that prevalence accounted for 1080 patients per million in 2021, about 12,000 hemodialyzed patients. Moreover, it is also relevant to notice that 936.000 m^3 per year is the national water burden for hemodialysis therapy. For a dialysis session of 4 h, with a usual dialysate flow of 500 mL/min (120 L per session), to produce the dialysate, the total water consumption with standard reverse osmosis can be over 300 L and, according to the Australian study, when pre-treatment priming, rinsing, and sterilization of the system are added in, a single hemodialysis session can consume up to 500 L (0.5 m^3) of water per patient. The amount of dialysate (spent water brought to the sewer) represents approximately 20 to 35 m^3/year/patient because each patient is dialyzed three times a week [13]. The expense of hemodialysis in Tunisia represents up to 5.5% of the health budget while the same in France is up to 2.5% [14,15].

Treatment of HWW is not easy, considering the vast quantities of HWW generated with high COD, nitrogen, and other content. Furthermore, the onset of the COVID-19 pandemic has shifted the focus to COD, sulfate, and other inorganic contents removal in HWW. Previously, no one substantially addressed this area in Tunisia. Electrochemical technologies, such as electro-coagulation (EC), electro-oxidation (EO), and activated carbon adsorption (AC), have increased the attention of researchers, media, and the public. Open literature authors have investigated coagulation, flocculation, sedimentation (CFS), and ultrafiltration (UF) processes [16]. Mahdavi et al. reported that removal efficiencies of HWW by a coagulation and ultrafiltration combination led to 96%, 95%, and 54 % turbidity, color, and COD, respectively [2]. Despite these promises, EC, EO, and AC have not yet been proposed for implementation in HWW, whereas environmental consideration of these techniques is relevant.

The present research purpose was to determine the efficiency of electrochemical technologies (EC + EO) combined with AC to treat the wastewater from hemodialysis and evaluate the feasibility of reusing this treated water as an alternative source for other purposes. Various treated wastewater parameters were investigated, including COD, pH, electrical conductivity (EC), salinity, sulfates, phosphates, Na^+(%), Mg^{2+}(%), Ca^{2+}(%), NH_4^+(%), and total nitrogen. We also tested the treated HWW for seed germination and root elongation. The ultimate goal was to reduce pollutant loads and to assess the effluent used for irrigation.

2. Materials and Methods

2.1. Experimental Procedure

In this study, the wastewater samples were collected from the dialysis facility of Hédi Chaker University Hospital in Sfax, Tunisia. Wastewater sampling performed using the grabbing technique from the inlet of the hemodialysis discharged wastewater. Clean plastic bottles (polyethylene tetraphthalate (PET)) were used for the sample collection. Before sampling, each bottle was cleaned with detergent, rinsed with tap water, soaked in 10% of concentrate nitric acid, rinsed with deionized water, and rinsed again at the time of sample collection with a portion of HWW. Finally, the collected samples were transported to the laboratory and stored at 4 °C until use.

2.1.1. Electro-Chemical Reactors

In this study, we performed HWW treatment with a sequential combination of electro-coagulation/electro-oxidation and adsorption. HWW was treated first by EC, then by EO, and finally by the AC process according to the following procedure.

Electro-Coagulation Reactor

The electro-coagulation experiment was conducted in an EC reactor of capacity 500 mL fabricated of glass material. The contents in the reactor were kept under the agitation process using a magnetic stirrer. Agitation and stirring processes are used during electrolysis time. We used aluminum electrode rods measuring 3.2 cm in width and 12 cm in length and estimated the cathode and anode surface area to be 38.4 cm^2. The anode and cathode were immersed in wastewater vertically and maintained between the two electrodes, a 1 cm gap. Electrodes were connected to the respective terminals of the DC rectifier and energized for a required duration at a known current density of 2.8 V. Power supply (Model- A TM 501-2 DC) with digital indicators were used as a DC source (Figure 1).

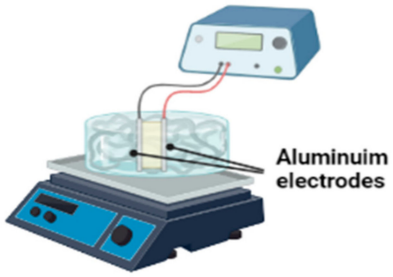


Figure 1. Schematic diagram of the experimental setup used for the electrocoagulation study.

Electro-Oxidation Reactor

The experimental design of the EO was performed in a batch type reactor with a working volume of 350 mL. The reactor (Figure 2) of the EO system was realized by an array platinum sheet, which was used as an anode and cathode for electrooxidation. Specific areas for the platinum electrodes were 5 cm^2 and the distance between them was established at 1 cm.

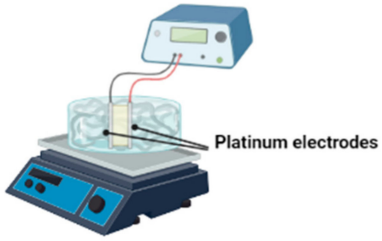


Figure 2. A schematic diagram of the electro-oxidation reactor.

2.1.2. Activated Carbon (AC) Process

In this experiment, different amounts of AC (0.5 g and 1 g) were added to 100 mL of wastewater samples (under optimum conditions), and the system was continuously stirred at 250 rpm for at which time adsorption equilibrium was achieved. The experimental setup of the AC process is illustrated in Figure 3.

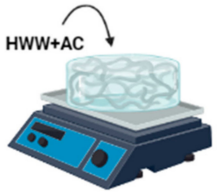


Figure 3. Schematic of HWW treatment by AC adsorption.

2.2. Analytical Techniques

Physicochemical parameters were determined using standard analytical procedures. Conventional quality parameters associated with wastewater treatment including pH, conductivity, ammonium, chemical oxygen demand (COD), chloride and trace metals measurements were determined according to the previous methods carried out on real wastewater tannery [17]. A simple spectrophotometric (Jenway 7315 spectrophotometer) method was used to determine the phosphate and sulfate contents in the samples in accordance with Aniyikaiye et al. [18]. Hardness concentration was determined according to the procedure reported by Qasim et Mane [19].

2.3. Energy Consumption Calculation

The cost of energy consumption for the HWW treatments process has been detected as the factor with the highest priority. Energy consumption normalized with respect to the volume of wastewater treated, for electro-coagulation (EC) and electro-oxidation processes (EO), can be calculated with the following Equations (1) and (2), respectively:

$$E_{EC} = \frac{VIt}{v_R} \quad (1)$$

$$E_{EO} = \frac{VIt}{(COD_{\circ} - COD_{t)}v_R} \quad (2)$$

where V is voltage (V), I is applied current (A), t is electrolysis time (h), v_R is the volume of HWW (L), and COD is chemical oxygen demand (mg/L).

2.4. Phytotoxicity Test

Germination test in petri dishes

With seed germination of alfalfa and maize, the phytotoxicity test was assessed with untreated and treated HWW, salty water, and reverse osmosis reject water, previously mentioned above. The above method follows the previous research determined in [17]. In plastic Petri dishes, we placed ten seeds on filter papers and added 5 mL of HWW samples

uniformly to each one. Then, in a dark incubator at a 25 °C temperature, we capped and kept every dish for seven days.

Germination test in pots

We performed tensile and compressive strength tests on the formulated seedling pots and the commercial pot. Samples were named, numbered, and labeled by the process operation and the replicates number. To keep climatic conditions uniform, we changed the positions of the pot every week. Seeds were washed, dried, and stored in each commercial pot. Seed biomass (fresh and dried) and length were measured at harvest using electric balance and a measuring rod. All samples, including the control, were run in triplicate. We calculated a germination index (GI) by counting the number of germinated seeds and the average sum of the seeds' root elongation in a sample relative to the control [20]. Results were finally expressed as a percentage following this equation:

$$NGS = \frac{\text{Number of germinated seeds in sample}}{\text{Number of germinated seed in deionized water (Control)}} \quad (3)$$

$$LMR = \frac{Average\ root\ length\ of\ seeds\ in\ sample}{Average\ root\ length\ of\ seeds\ in\ deionized\ water\ (control)} \quad (4)$$

$$GI(\%) = NGS \times LMR \times 100 \quad (5)$$

3. Results and Discussions

3.1. Characteristics of HWW

The physiochemical characteristics of the HWW compared with other wastewaters as well as with the standard values are listed in Table 1.

Table 1. Comparison of hemodialysis wastewater composition at the dialysis facility of Hédi Chaker University Hospital Sfax in Tunisia with other wastewaters, and quality standards for agriculture.

Parameters	*Current Study*	*HWW from Brazil [8]*	*HWW from Iran [21]*	*HWW from Morocco [22]*	*FAO/WHO Standards for Irrigation Water [23,24]*
pH	7.46	7.49	7.84	7.84	6–8.5
Conductivity (mS/cm)	13.53	4.08	0.854	13.2	0.3–0.7
Salinity (g/L)	9.113	9.42	-	-	-
COD (mg/L)	262.033	832	16.10	-	5–45
Cl^- (mg/L)	3976	-	25.93	289	30
Total nitrogen (mg N/L)	143	126.7	-	-	-
PO_4^{3-} (mg/L)	6.472	53.95	-	-	-
SO_4^{2-} (mg/L)	110.67	23	133.86	80.4	0–20
Mg^{2+} (mg/L)	13.88	-	-	-	-
Ca^{2+} (mg/L)	21.091	-	-	-	-
Na^+(mg/L)	3757	-	-	-	-

The HWW does not meet the FAO/WHO Standards of Water for Irrigation. The results of the physicochemical characterization showed that the HWW had 20 times higher conductivity and salinity as defined by FAO/WHO Standards for Irrigation Water. Thus, the HWW samples were brackish water. Likewise, the chloride was 132 times higher than the maximum recommended. Sulfate and COD were approximately six times the defined

limit. A few studies have shown the presence and harm of helminthes egg and other biologically active poisons on humans in HWW. Consequently, before its use for irrigation, HWW must be treated to be within acceptable standards. Machado et al. [8] evaluated the degree of acute and chronic environmental toxicity of HWW and showed that HWW's immediate release into the environment, especially in urban cities with untreated sewage, may cause significant environmental hazards.

3.2. Effect of Electrolysis Time on Contaminants Removal

Electrolysis time is a crucial operational parameter in the EC process as it indicates the length of the water treatment to meet the required criteria. In this study, the reaction time for the HWW treatment by electro-coagulation was 20, 40, 60, and 10 min. At 20 min, COD removal achievement was up to 100%. The operation cost is usually a concern in the EC process. We strive for the highest removal amount and the lowest charge. In the current study, we demonstrated total COD removal, achieved with low energy consumption equal to 0.74 KWH/m^3 after 20 min treatment. The present study showed that it is possible to remove micro-pollutants from HHW by EC with low energy consumption than the study conducted on hospital wastewater by Dehghani et al. [10]. In fact, they reported that COD removal efficiency up to 87% was obtained at an initial COD of 398 mg/L using four iron electrodes with an energy consumption equal to 30.6 V/h/L [10].

In addition, Figure 4 shows the removal of PO_4^{3-}, Mg^{2+}, Na^+, Ca^{2+}, and SO_4^{2-} using the electro-coagulation process, as a function of electrolysis time.

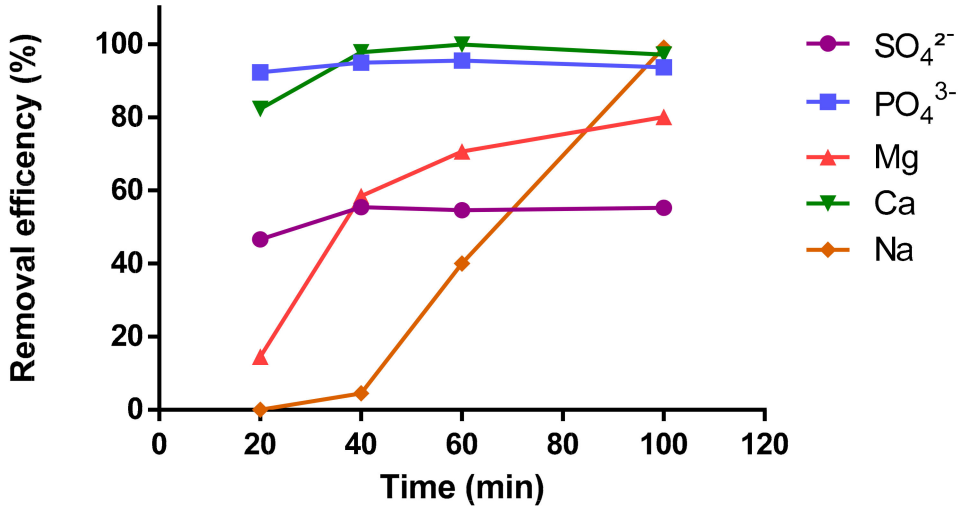


Figure 4. Effect of electrolysis time on inorganic ions.

Figure 4 discloses that the removal of calcium and phosphate is not influenced significantly by electrolysis time (Table S1 in the Supplementary Data, SD). Removal efficiencies achieved after 40 min were 97% and 94% for Ca^{2+} and PO_4^{3-}, respectively. According to Khandegar et al. [25], if the electrolysis time exceeds the optimal value, the elimination effectiveness of the contaminant does not change. We need enough flocs provided for the removal of such residues. In addition, Helmy et al. [26] found a calcium removal rate improvement with the electrolysis time until 60 min. Then, continuing the electrolysis has no significance. The decrease in phosphate concentration is attributed to the particular at a higher concentration level, the dissolution of the anode to Al^{3+} ions increases according to Faraday's law. Al^{3+} ions undergo hydrolysis, and the resulting aluminum hydroxides produce more sludge with consequent significant removal of phosphorus due to phosphorus adsorption on $Al(OH)_3$ (Equation (6)) and its polymeric compounds [21,22].

$$Al^{3+} + H_nPO_4^{3-n} \rightarrow AlPO_4 + nH^+ \quad (6)$$

Djuricic et al. used the electro-coagulation Al and Fe electrodes. They, hence, investigated the effect of electrolysis duration, the initial phosphate concentrations, and the electrolyte concentration on the phosphate removal efficiency [27]. At pH 3, maximum removal efficiency was achieved, which amounts to 98.9% for Al electrodes and 93.5% for Fe electrodes after 40 min. At pH 3, the author found a highest removal efficiency at an initial phosphate concentration of 50 mg/L and a current density of 1 mA/cm^2 [27]. Hamada et al. used aluminum electrodes [28], and found a significant calcium removal from the Gaza wastewater treatment plant with effectiveness higher than 93.33% [28].

The electrolysis increasing time improved magnesium and sodium removal efficiency reaching 80% and 99%, respectively, after 100 min of reaction (Table S1, SD). Hamdan et al. Naas [29] reported that the magnesium removal from groundwater achieved just 44% at optimum conditions (initial pH 8; operation time 30 min; liquid flow rate 30 mL/min; and current density of 7.61 mA/cm^2).

During the first minutes of treatment, the removal efficiency of sulfate started strongly and achieved 46% after 20 min. However, the time increase in electrolysis showed no significant improvement in the removal rate. It remained relatively stable and reached 55% of the initial sulfate concentration after 40 min of electrolysis.

The electro-coagulation seems to be an efficient technique to improve the removal of the HWW COD and inorganic ions. The results showed that COD and inorganic ions removal are time-dependent processes, and the applied time increase favors the contaminant removal.

3.3. Effect of Electro-Oxidation Treatment on HWW Characteristics

According to Figure 5, the EO process is efficient for the removed COD, total nitrogen, and Mg^{2+}. Removal rates were significant after 100 min of treatment and achieved 100, 83, and 89%, respectively (Table S1, SD). In contrast, the removal of sulfate and phosphate only reached 12 and 23%, respectively.

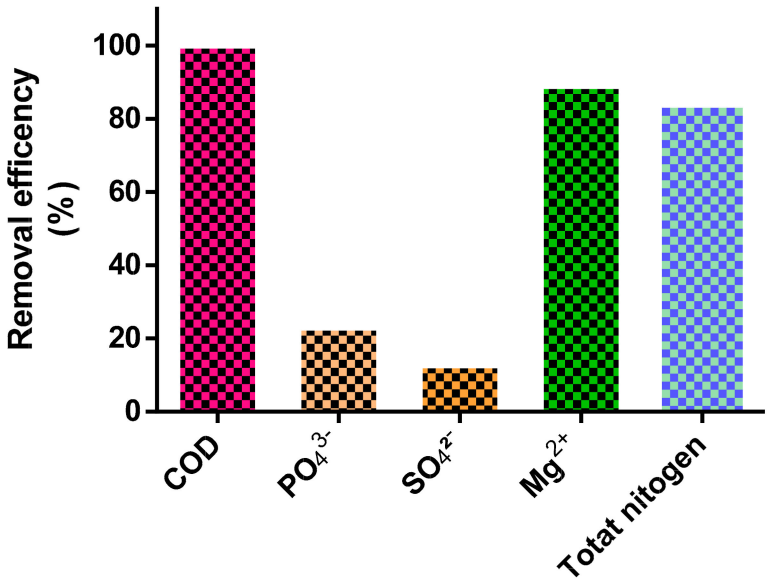


Figure 5. Effect of EO on HWW treatment after 100 min of electrolysis time.

Similar results were reported by Lan et al. [30] and showed that the COD removal efficiency reached 100% for the hospital wastewater treatment after 300 min of electrolysis time and 192 mg/L for the initial COD. In this study, the energy consumption for the total removal of COD in HWW was 0.05 kWh/Kg COD. Lan et al. [30] reported a complete purification of COD achieved by consuming up to 50 kWh/Kg of COD. Therefore, the value recorded in this study was significantly lower than that recorded in the study conducted by Lan et al. [30] for hospital wastewater treatment.

Ghimire et al. [31] reported that the removal efficiencies of NH_4^+–N from domestic wastewater are proportional to the electric voltage applied. The removal efficiencies of NH_4^+–N were 97.6%, 68%, 20% and 10% for the 5 V, 3 V, 1.2 V, and 0.6 V applications, respectively. In this study, the nitrogen removal might be due to its conversion to N2 gas. Several studies have stated that the mechanism of nitrogen removal from wastewater is complex by electro-oxidation, and many factors influence it, such as the number of electrolytes, type of electrode used, current density, and ionic species. However, ammonium is to be oxidized by several reactions, as follows. The electrochemical process can reduce generated nitrate to nitrogen, nitrogen oxides, and even ammonium, resulting in various nitrogen compounds [31].

Nevertheless, the removal efficiency for Mg was high and reached 83%. Lan et al. [30] found that the decay of the concentrations of Mg is significant. The concentration of Mg decreases from 8.8 mg L^{-1} to 2.7 mg L^{-1}.

Consistent with the effect of electrolysis time on inorganic ions, a decrease in the magnesium evolution rate was observed. This fluctuation was presumably caused by the intermittent formation of the hydroxide in the solution according to this equation [32].

$$Mg^{2+} + 2OH^- \rightarrow \xrightarrow{Mg(OH)_2} \quad (7)$$

3.4. Efficiency of HWW Treatment by Adsorption onto Activated Carbon

As illustrated in Figure 6, HWW adsorption treatment was found to be favorable to Ca^{2+} removal of up to 70% with the dose of 1 g. In addition, the removal efficiency of PO_4^{3-} was observed in the application of AC with the same dose. This study shows that activated carbon is capable of removing calcium. This study showed that activated carbon, capable of eliminating almost calcium, is explained by the availability of active sites and the occupation of a deep one, and the contribution of an increasing number of calcium ions that diffuse into the activated carbon, owing to its higher surface area, porosities, and surface functional groups used to eliminate a variety of contaminants, which include different heavy metals, pesticides, and organic compounds [33].

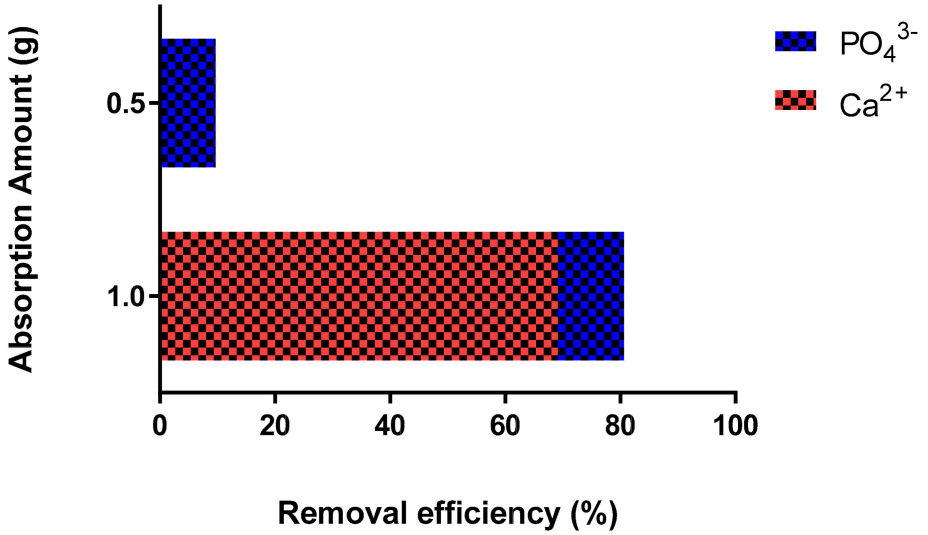


Figure 6. Effect of amount AC on HWW treatment.

Sepeher et al. and Rostamian et al. [32,33] reported that adsorption had the potential to remove Ca^{2+} and can be used as a suitable technique to eliminate hardness ions from drinking water due to the adequacy between the micropores of absorbent and the size of the cations Ca^{2+} and Mg^{2+}. Girgis et al. [34] reported that the sorption capacity of porous materials containing carbon is more than just linked to area and porosity.

It is related to the chemicals' ability to get inside the absorbent and depends on the ability dimensions of the molecules and the pore size distribution of the adsorbent. Pore diameter, larger than the size of the adsorbate, enhances the availability of the inner surface of the adsorbent materials.

3.5. SAR Hazard of HWW for Possible Reuse in Irrigation

SAR is an influential parameter in the evaluation of water for irrigation as it provides the value of the alkali/sodium risk to cultures. SAR also reflects the susceptibility of irrigation water to cation exchange reactions in the soil. According to the results, the treated TWW showed low soil sodium hazard due to the SAR index lower than 10 (Tables 2 and 3). It can be applied for irrigation on most varieties of soils with a slight risk of harmful levels of tradable sodium. Nevertheless, sodium-sensitive crops can accumulate unacceptable levels of sodium. Additionally, the calculated sodium content index was doubtful for both of them according to approved criteria for irrigation water by the Food and Agriculture Organization (FAO).

Table 2. Guidelines for interpretation of SAR index.

SAR Values (meq/L)	Sodium Hazard to Soil
0–10	Low
10–18	Medium
18–26	High
>26	Very high

Table 3. Calculated indices for raw and treated HWW, salty water, and RO reject.

Water Type	HWW	HWW Treated	Salty Water	RO Reject
SAR	157.13	1.78	1253	27
Na (%)	97	1.84	99	97

To determine the raw and treated HWW quality, salty water, and RO reject for irrigation purposes, sodium adsorption ratio, SAR [2], calculation of SAR and sodium content was performed using Equations (6) and (7):

$$\mathrm{SAR} = \frac{Na^{+}}{\left(\frac{Ca^{2+}+Mg^{2+}}{2}\right)^{0.5}} \tag{8}$$

$$\mathrm{Na} = \frac{Na^{+}}{Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}} \times 100 \tag{9}$$

where *Na*, *Ca*, and *Mg* concentrations are expressed in meq/L. The general guidelines for SAR index interpreting and evaluating sodium hazard to soil are summarized in Table 3

In this study, the SAR value of raw HWW salty water and rejected RO were very high, indicating that the HWW is unsuitable as it is for irrigation purposes (Tables 2 and 3). High SAR values indicate a hazard whereby sodium can displace adsorbed calcium and magnesium ions, which may damage the existing soil structure and plant roots. Irrigation water with high levels of SAR can accumulate high levels of Na in the soil with time and thus affect the soil porosity. Contrary, the treated HWW has a SAR between 0–10, which entrained that treated HWW is an excellent quality of irrigation (Tables 2 and 3). Research on the use of wastewater in agriculture in Portugal found that irrigation with wastewater can have two effects. The first can impact soil productivity and fertility, while the second can result in high risks to human and environmental health [34].

3.6. Evaluation of the Phytotoxicity of RO, Raw HWW and Salty Water on the Germination Test in Petri Dishes

The effect of raw and treated HWW, RO reject, and salty water taken as a reference on the germination of barley, alfalfa, maize, and tomato seed was investigated. The germination period was seven days. They estimated the germination rate by counting the number of germinated seeds (Figure 7).

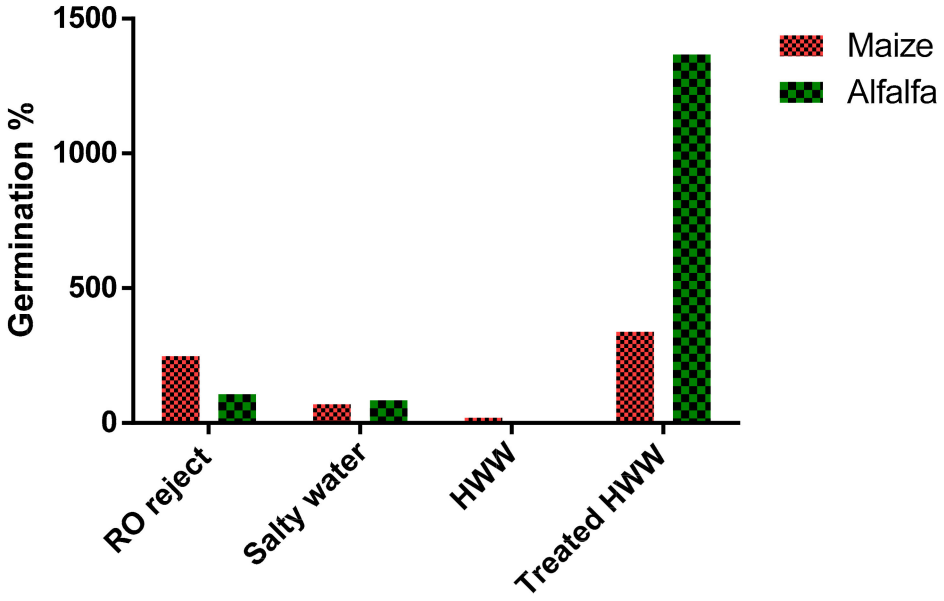


Figure 7. Germination rate for the two seeds watered with different samples.

The germination of alfalfa and maize seeds increased in the RO reject medium compared to that observed in the untreated HWW and salty water. The maize seeds had the highest germination index during the germination in Petri dishes. Likewise, the results showed that salinity negatively affects the seed's germination, as evidenced by the results obtained with a test carried out in salty water. This finding suggests an important role of salt concentration in the germination of barley, alfalfa, and maize seeds. High saline concentration indicated a less germination index. Thus, they observed low germination effects with symptoms of high salts water concentrations toxicity as previously reported by Jallouli et al. [17]. A negative effect of higher salt content on seed germination was also observed for pigeon pea, with a germination percentage of 53% stated by Salian et al. [35]. Similar inhibitory effects of higher salt concentrations were reported by Barazani and Golan-Goldhirsh [36] on germination of *Salsola inermis* and by Khan et al. [37] on rice germination. The high salinity can be due to the high concentrations of dissolved solid, leading to the reduction/inhibition of seed germination [38]. Abu-Dieyeh et al. [37] inferred higher salinity levels for organic and inorganic elements occurring in wastewater, which are harmful to seed germination. The present study of HWW contained high EC, turbidity, orthophosphates, sulfates, COD and salinity values and a reduction in the number of seeds germinated for all crops.

The germination % showed mighty higher growth with treated HWW. This observation revealed that TW significantly influenced plant growth. In this study, the combined treatment improved water properties for germination. These results are consistent with what came out of another study [39]. They studied the removal of organic impurities from dairy wastewater of a dairy plant by coagulation-flocculation with Alum and polymer at f 20 Mg/L $Al_2(SO_4)_3$ under a pH varying between 6.5 and 7.5.

3.7. Germination Tests on Pots

3.7.1. Germination Rate Index "GRI"

Because corn has the highest index germination in Petri dishes, maize seeds were selected for cultivation in pots irrigated by the RO, salty water, and HWW (diluted by 50%). The salinity of the media was estimated to be 2.6 g/L, 2.2 g/L, and 9.1 g/L, respectively.

The highest GRI for maize was with RO by 97.22%, and the lowest GRI was with the diluted HWW. These results can be attributed to high dissolved salts, as described with the dishes germination test. Berrada et al. [35] also encountered a similar impact of salinity on corn seeds GRI when using HWW. Salian et al. [36] evaluated the effects of raw and diluted brewery effluent on germination and growth parameters of selected crop species like chickpea, maize, and pigeon pea. The results showed that brewery wastewater was phytotoxic to all three crops, and the effect on root elongation became less when using the diluted wastewater.

3.7.2. Effect of Irrigation with Treated HWW on the Soil Salinity

Figure 8 shows the highest conductivity level observed in the soil irrigated with diluted HWW. The increase in conductivity in soils resulted from the accumulation of salt.

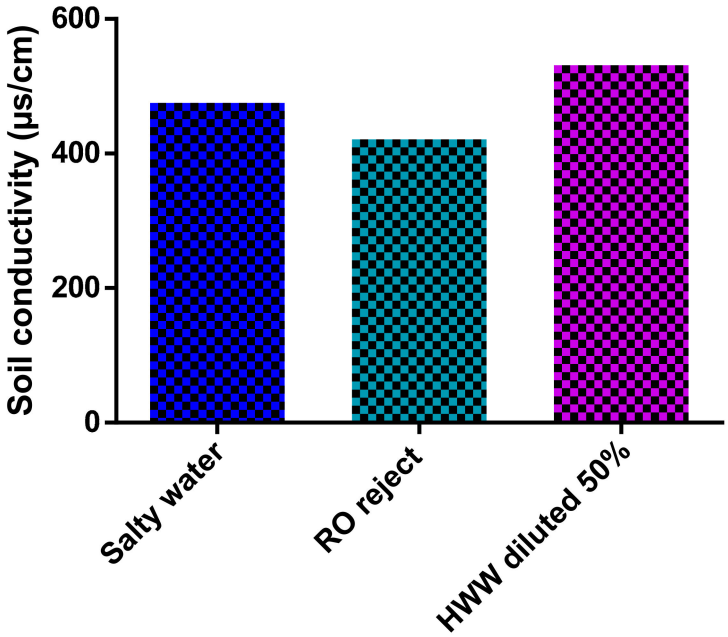


Figure 8. Effect of three effluents on the soil.

Several studies reported that using wastewater in irrigation could lead to soil pollution with heavy metals and increase soil salinity, adversely affecting the soil quality [37]. Qishlaqi et al. [40] noted that wastewater reuse in agriculture significantly impacts the soils and crops. This reuse may cause changing soil qualities (pH, OM, Ex-Ca), increasing the soil levels of heavy metals (especially Ni and Pb) and in the crops (Cd and Ni), and may present a hazard to health due to the use of contaminated vegetables [40].

3.7.3. Progress towards Zero Waste Fluid in Hemodialysis

Due to the HWW treatment, the number of wastes discarded in the environment decreased, enhancing its quality. The treatment of HWW samples needed the addition of chemicals. However, we can consider combination methods to avoid this step. Nowadays, a single treatment process may not be adequate for the wastewater recycling in general and HWW in particular. Hence, the researchers are attempting a combination of two or more treatment methods to get a complete and successful HWW contaminants removal. In this research, we investigated the treatment of HWW to reveal the importance of controlling

the quantity of water discharged from hemodialysis and the need for good planning of preventive maintenance of a combination of the three treatments (electro-coagulation, electro-oxidation, and adsorption). The mingling of EC +AC for indigo-polluted industrial textile wastewater treatment was reported to fulfill the legal requirements for discharge and was reported by Gilpavas et al. [39]. It allowed for the reduction of 96% of color, 72% of COD, and 60% of TOC. Moreover, no toxicity was observed, the biodegradability index (BOD_5/COD) improved from 0.13 to 0.29. Combining electro-coagulation and catalytic oxidation compilation, Wang et al. [41] studied polyvinyl alcohol (PVA) removal. It removes 71.29% of PVA under optimal conditions (cell voltage 9 V, natural pH 7, NaCl concentration 0.02 mol/L, and interelectrode distance 3.0 cm).

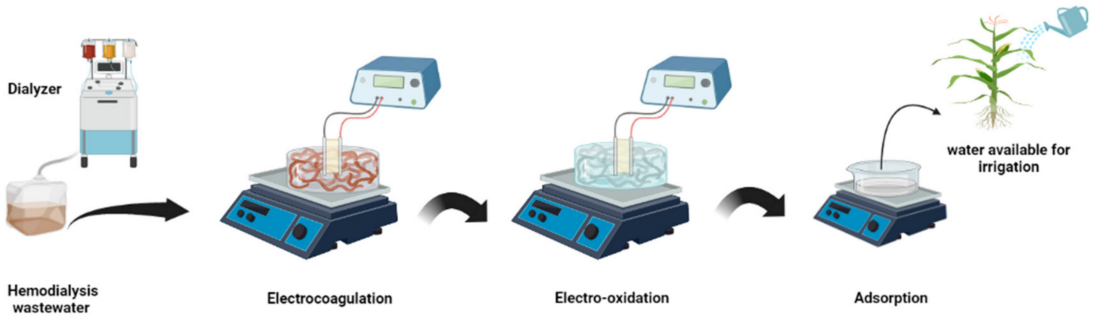
Over 31,000 patients were on hemodialysis in Iran in 2020, and for them, the global HWW amount produced for each dialysis session is at least 3720$m^{3.}$ [2]. Similarly, in our research, a combined EC + EO + AC is proposed for the HWW treatment as a prospective technique to reduce organic load and toxicity from HWW. By assessing the technical feasibility of reusing HWW, this study highlights this issue, which has been an overlooked aspect of hemodialysis treatment. This issue may offer a "green" or ecological approach to dialysis.

4. Conclusions

We applied electro-coagulation, electro-oxidation, and adsorption processes to remove numerous pollutants from HWW. We found the following results:

1. With the EO process, the removal performance of COD, total nitrogen, and Mg was significantly better and reached 100, 83, and 89%, respectively, after 100 min of treatment, compared to sulfate and phosphate being only 12 and 23%, respectively.
2. With the EC process, the removal efficiency of Mg and Na increased with increasing electrolysis time and achieved 80% and 99%, respectively, after 100 min. The optimal time was 40 min for the Ca, sulfate, and phosphate removal efficiency. A high-rate of performance reduction was after 20 min for COD.
3. The increased amount of activated carbon from 0.5 to 1 g increased the removal efficiency of calcium and a slight increase of phosphate.

Thus, as illustrated in Scheme 1, a coupled EC + EO + AC process can be considered an efficient alternative for the HWW treatment from hemodialysis units. The coupling efficiency allows for obtaining treated HWW with a lower SAR and using it for irrigation.



Scheme 1. A proposed strategy of hemodialysis wastewater treatment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14159597/s1.

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