Predesign cost estimation of a potential wastewater treatment plant for Jordan petroleum refinery-Electrocoagulation

Simon Sakhel (✉ simonsakhel@hotmail.com)

Technische Universität Berlin

Sven-Uwe Geissen

Technische Universität Berlin

Research Article

Keywords: fixed capital investment, working capital, total capital investment, electrocoagulation (EC), annual operating cost, MENA

Posted Date: December 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1073832/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Environmental Processes on January 24th, 2022. See the published version at <https://doi.org/10.1007/s40710-022-00560-4>.

Predesign cost estimation of a potential wastewater treatment plant for Jordan petroleum refinery-Electrocoagulation

Simon R. Sakhel

Technische Universitaet Berlin

Institut fuer Technischen Umweltschutz

FG Umweltverfahrenstechnik

Strasse des 17 Juni 135

D-10623 Berlin

Germany

e-mail: simonsakhel@hotmail.com (to whom correspondence should be addressed)

Sven-Uwe Geissen

Technische Universitaet Berlin

Institut fuer Technischen Umweltschutz

FG Umweltverfahrenstechnik

Strasse des 17 Juni 135

D-10623 Berlin

Germany

e-mail: sven.geissen@tu-berlin.de

Abstract The aim of this paper is to investigate whether simulated Jordan refinery wastewater can be treated through electrocoagulation (EC) to conform to the most stringent Jordanian norms for reusing this wastewater for irrigation of cut flowers and to perform cost analysis for a treatment plant whose core are the EC reactors. The method used for estimating the fixed (capital) costs of the treatment plant is taken from literature and is based on a study estimate (factored estimate) that depends on the knowledge of major items of equipment. Most of the operating costs are estimated based on

percentages which are also taken from literature. The best percentage removal of COD, BOD, TSS, fat, oil& grease (FOG), bicarbonate (HCO_3^-), and phenol from simulated Jordan refinery wastewater so that it conforms to Jordanian norms were 84.4 %, 82.1 %, 27.3 %, at least 98.8 %, 94.9 %, at least 96.7 %, respectively, at a current of 10 A, treatment time of 5 minutes, Al/SS electrodes, and inter-electrode distance 10 mm. Overall treatment costs for the simulated wastewater was 10.75 \$/m³ (27 \$/kg COD_{removed}). It is concluded that simulated Jordan refinery wastewater cannot be treated so that it conforms to the most stringent norms for using the treated wastewater for cut flowers irrigation but could be treated enough to conform to the Jordanian norms for using the treated water for irrigation of cooked vegetables, parks, and playgrounds. Moreover, EC is a suitable technology for the treatment of Jordanian recalcitrant refinery wastewater and the cost for its treatment is affordable.

Keywords: fixed capital investment; working capital; total capital investment; electrocoagulation (EC); annual operating cost; MENA.

Highlights

- Electrocoagulation of Jordan refinery wastewater has been performed
- Removal of at least 96.7 % phenol, at least 98.8 % Fat, oil, and grease (FOG), 27.3 % TSS, 84.4 % COD, 82.1 % BOD₅, and 94.9 % bicarbonate in Jordan petroleum refinery wastewater.
- Best result: 10 A current intensity, 5 minutes electrocoagulation (reaction) time.
- Cost analysis of a treatment plant for Jordan petroleum refinery whose core is Electrocoagulation

Introduction

A large part of the wastewater in the Middle East and North Africa (MENA) conveyed in sewerage receives minimal or no treatment and is finally discharged either on land, sea, or surface water. It is also

likely that a larger fraction of wastewater from septic tanks is discharged outside conventional treatment systems thereby not receiving any treatment at all (Jeuland 2015). The focus in MENA has been on the collection and treatment of domestic wastewater mixed with industrial effluents (if present) and presumably little or no attention is being paid to appropriate treatment of industrial wastewater before its discharge to the environment (For example, Jordan's petroleum refinery mechanically treated wastewater is used for irrigation) or to the sewer network. Industrial wastewater treatment helps in keeping good-quality water resources for high-value uses, such as potable water, environmental protection through reducing pollution which causes the control of environmental degradation, and reducing water withdrawal either from the surface or ground (Jeuland 2015). There are not any statistics available on the volume of industrial wastewater generated in MENA, however, it is known that for domestic and industrial effluents it is 13.24 km³/yr (Qadir et al. 2010). 43.1 % of the latter is treated and about 83 % of the treated wastewater volume is used for irrigation (Qadir et al. 2010). Presumably, a major part of the industries in MENA do not treat their industrial wastewater. For example in Jordan's Amman-Zarqa region there are industries which discharge their effluents untreated to the municipal sewer or to the environment leading to pollution (Mohsen and Jaber 2002).

Another polluting industry in MENA is petroleum refining which is considered a major industry in this region as its share of the Gross Domestic Product (GDP) is between 0.2 to 4.2 % (Sakhel et al. 2017). It is estimated that the annual wastewater volume from this industry is about 217.5 million m³ (Sakhel et al. 2017) and these effluents are a major source for aquatic pollution (Wake 2005). They contain oil and grease and many other toxic compounds such as benzene, toluene, ethylbenzene, and xylene which are considered to be the most hazardous compounds released into the environment (Diya'uddeen et al. 2011, Saber et al. 2014). Moreover, refinery wastewater usually contains recalcitrant organic material such as polyaromatic hydrocarbons and phenols that are barely degradable by nature (Al-Khalid and El-Naas 2018). Traditional treatment of petroleum refinery wastewater (PRW) which is based on

mechanical and physicochemical methods leads to incomplete removal of refractory compounds (Panizza 2018). Discharging recalcitrant compounds to the environment can lead to their accumulation in human and animal tissues after long distance transport. Therefore, an appropriate treatment method for removal of these compounds is necessary.

EC has emerged as a promising technique for PRW treatment. It has not only the ability of removing particulate COD (García-Morales et al. 2018) but it also removes soluble COD from wastewater containing petroleum hydrocarbons (Asselin et al. 2008). Having the ability of removing both is a privilege and is the primary purpose of wastewater treatment (Jimenez et al. 2005). Moreover, recalcitrant organic material, usually present in refinery effluents, can be removed or eliminated using EC (Fayad 2017, Pérez et al. 2015). For example, this technique has been successfully applied for the removal of phenol, one of the recalcitrant compounds present in refinery wastewater (Gasim et al. 2012), through the use of EC (Abdelwahab et al. 2009, El-Ashtoukhy et al. 2013). The capability of EC in removing soluble recalcitrant compounds (e.g. phenols) infers that this technique may be able to remove other similar substances all which are reflected in the lumped recalcitrant COD parameter. Keramati and Ayati (2019) found out that treating PRW through EC leads to the removal of non-degradable compounds from this effluent. Moreover, Pérez et al. (2015) treated PRW with a BOD/COD ratio less than 0.3 (0.015) through EC. This treatment technology increased the BOD/COD ratio up to 0.5 which indicates that this technique was able to remove recalcitrant and/or toxic substances in the refinery effluent (Al-Qodah et al. 2019). The study of Pérez et al. (2015) reflects that EC can remove recalcitrant COD. Recalcitrant COD removal is usually associated with high removal costs (Wang et al. 2011) since refractory compounds cannot be eliminated through conventional biological treatment processes which are considered economical (e.g. activated sludge process) (Li 2013; Choi et al. 2017) but require processes that can deal with these refractory compounds (e.g. EC, Advanced Oxidation Processes (AOPs), membranes) (Kulikowska et al. 2019; Sristav et al. 2019; Pérez et al. 2015).

There have been efforts that estimated the operating costs for the removal of COD from PRW as well as other types of wastewater using EC (Giwa et al. 2013; Keramati and Ayati 2019; Aygun et al. 2019; Asselin et al. 2008; Demirci et al. 2015; Said and Mostefa 2015; Elazzouzi et al. 2017; Kobya et al. 2009; Mahesh et al. 2016; Yuksel et al. 2012; Varank et al. 2014; Mohammadi et al. 2017; Deghles and Kurt 2015; Guvenc et al. 2017; Chopra and Sharma 2015; Kongjao et al. 2008; Akyol 2012; Chauhan et al. 2016; Sridhar et al. 2014; Sahu et al. 2015; Bassala et al. 2017; Kobya and Delipinar 2008). For example, Giwa et al. (2013) and Keramati and Ayati (2019) estimated the operating costs at optimum experimental conditions for treating PRW through EC to be 0.654 US \$/m³ (6.4 US \$/kg COD_{removed}) and 1.45 US \$/m³ (1.7 US \$/kg COD_{removed}), respectively. Aygun et al. (2019) estimated the operating costs at optimal conditions for treating textile industry wastewater through EC using Al and Fe electrodes in monopolar configuration to be 1.84 €/m³ (5.8 €/kg COD_{removed}) and 1.56 €/m³ (4.6 €/kg COD_{removed}), respectively. Asselin et al. (2008) estimated the operating costs (energy, chemicals, electrode consumption, and sludge disposal costs) at optimal conditions for treating oily bilgewater (OBW) using EC to be 0.46 US \$/m³ (0.8 US \$/kg COD_{removed}). Demirci et al. (2015) estimated the operating costs (consists of energy, and electrode consumption) for the treatment of textile industry wastewater through EC using Al and Fe electrodes to be 6.439 €/m³ (1.6 €/kg COD_{removed}) and 4.732 €/m³ (1.3 €/kg COD_{removed}), respectively. Chauhan et al. (2016) estimated the operating costs (electrical energy and electrode costs) for the treatment of 4-chlorophenol (CP) through electrochemical oxidation by using a dimensionally stable anode (DSA) namely ruthenium oxide coated titanium (Ti/RuO₂) to be 189.1 US \$/m³ (1062.8 US \$/kg COD_{removed}). Sridhar et al. (2014) estimated the operating cost (energy, chemicals, and electrode consumption) for the treatment of egg processing effluent through electrocoagulation using aluminium electrodes under optimal conditions to be 2.7 US \$/m³ (0.81 US \$/kg COD_{removed}). Sahu et al. (2015) estimated the operating costs (electrical energy and electrode costs) for the treatment of actual sugar industry wastewater through electrocoagulation using aluminium electrodes under optimal

conditions to be 6.22 US \$/m³ (2.14 US \$/kg COD_{removed}). Bassala et al. (2017) estimated the operating costs (energy and electrode costs) for the treatment of dairy industry wastewater through electrocoagulation using aluminium electrodes to be 0.026 US \$/m³ (0.042 US \$/kg COD_{removed}). Kobya and Delipinar (2008) estimated the operating cost (energy, chemicals, and electrode consumption) for the treatment of baker's yeast wastewater through electrocoagulation using aluminium and iron electrodes under optimal conditions to be 1.54 US \$/m³ (0.82 US \$/kg COD_{removed}) and 0.51 US \$/m³ (0.27 US \$/kg COD_{removed}), respectively. Finally, Chopra and Sharma (2015) estimated the operating costs (consists of energy, and electrode consumption) for the treatment of secondarily treated sewage (recalcitrant wastewater) through EC using Al electrodes at optimum conditions to be 1.56 US \$/m³ (17.8 US \$/kg recalcitrant COD_{removed}). Additionally, there are only some studies present that discuss the overall cost (fixed and operating) whether at bench or pilot scale for the treatment of domestic wastewater using electrocoagulation (Lin et al. 2005), textile dye wastewater using chemical oxidation and biological treatment (El-Dein et al. 2006), real wastewater from olive oil mills and fine-chemical manufacturing plants using AOPs (Cañizares et al. 2009), soluble oil wastes with high COD using electrocoagulation (Calvo et al. 2003), and domestic wastewater using electrocoagulation, electro-fenton and electro-oxidation (Gaied et al. 2019). The few aforementioned studies (Lin et al. 2005, El-Dein et al. 2006, Cañizares et al. 2009, Calvo et al. 2003, and Gaied et al. 2019) did capital and operating costs for plants that have a capacity ranging from 1 to 28 m³/day and none did the cost analysis on treating petroleum refinery wastewater at full-scale. Moreover, a few studies are present for costs relevant to treatment of different industrial wastewaters using EC at full-scale. Tetreault (2003) reported a slaughterhouse that used EC technology for the treatment of a mixture of stick/blood water and presented capital/operating costs. Eames et al (2017) reported silica removal in mineral mining/processing and oil/gas extraction wastewaters at full-scale using a treatment train that included EC and presented capital/operating costs. The scarcity of research relevant to overall costs for different

types of wastewater treatment at full-scale led to doing the present research in order to enrich literature in this area especially relevant to an effluent (here petroleum refinery wastewater) that is recalcitrant. Overall costs need to be estimated especially at full-scale since it is a major criterion for industry when choosing the desired treatment technology. According to the best authors knowledge there is no research available that talks about the treatment of JRWW through electrocoagulation. The novelty of this study lies in: 1-Studying the possibility of using EC for treating simulated JRWW using the following combinations of electrodes: Aluminum/stainless steel (anode/cathode) and mild steel/stainless steel (anode/cathode) in a bipolar electrode configuration, to an extent so that it conforms to the most stringent Jordanian norms relevant to COD, BOD, TSS, fat, oil and grease (FOG), phenol, and HCO_3 so that it could be used for irrigation of cut flowers; 2-highlighting practical knowledge and estimation of operating/capital costs in addition to electrical energy consumption for a full-scale wastewater treatment plant ($3,840 \text{ m}^3/\text{day}$) treating JRWW through EC which is missing in scientific literature. Additionally, it estimates the recalcitrant COD removal costs (fixed and operating) through EC for JRWW that is only mechanically treated. So the research questions the paper tries to answer are: Is EC a suitable technology for the treatment of Jordanian recalcitrant refinery wastewater? Are the costs relevant to the treatment of the aforementioned industrial effluent affordable?

The paper is organized as follows: in "Important terms", we define important terms. "Experimental section-Materials and Methods", we describe the experimental set-up, synthetic petroleum refinery wastewater, measurement methods, and sludge characteristics. "Methodology relevant to finding fixed and operating costs of EC treatment plant", we summarize the methodology used for the cost calculations. "Results and interpretations", we present our results. "Discussion", we discuss our results. "Conclusions", we end with conclusions.

2 Important terms

2.1 Definition of important terms

Fixed capital investment: is the money needed to purchase and install the necessary machinery and equipment for a plant

Working capital: is the capital set aside by the investor in the beginning to use it afterwards in case of an emergency (e.g. failure or calamity of plant) in order to keep the plant in operation or bring the plant back to operational requirements

Total capital investment: is the sum of fixed capital investment and working capital

3 Experimental section-Materials and Methods

3.1 Experimental Set-Up

The treatment of synthetic JWW was done in a batch reactor made from 6 mm thick polypropylene sheet material. The EC cell consisted of 8 electrodes that were connected in bipolar configuration. In bipolar configuration trials 4 aluminium/4 stainless steel (SS) plates or 4 mild steel (MS)/4 SS plates were used arranged as Al-Al-Al-Al-SS-SS-SS-SS or MS-MS-MS-MS-SS-SS-SS-SS. The aluminum or the mild steel was connected to the anode while stainless steel was the cathode. A schematic diagram of the EC cell is shown in Fig.1.

Fig. 1 Schematic diagram of the EC cell in a bipolar connection mode

The aluminum, stainless steel and mild steel plates have a height, width, and thickness of 181, 103, and 4 mm, respectively. The plates were totally immersed in the synthetic refinery wastewater and the distance between each pair of electrodes is 10 mm in the trials. A reaction batch of 4 liters of wastewater was used for all the trials. Wastewater was mixed through recirculation from a bottom valve in the reactor using a pump (see Fig.1). Before each run electrodes were washed by dilute HCl acid wash and then final rinse with tap water to remove oxide and passivation layers. Consumption of energy was calculated using the following equation

$$\text{Energy consumption (kWh/m}^3\text{)} = \frac{VIt}{\text{Treated Volume}} \dots \dots \dots 1$$

where V is the cell voltage in volt, I is the current in Amp (A), t is the treatment time in hour and the treated volume is in liter. The pollutant removal efficiency from wastewater by the EC reactor was calculated using the equation below

$$\% \text{ removal efficiency} = \frac{C_o - C_F}{C_o} \times 100 \dots \dots \dots 2$$

where C_o and C_F are the initial and final concentration of pollutant, respectively.

3.2 Synthetic Petroleum Refinery Wastewater

Synthetic petroleum refinery wastewater was prepared according to the concentrations of actual Jordanian petroleum refinery wastewater which was used as a reference. The different concentrations of real Jordan refinery wastewater that is only mechanically treated is shown in Table 1 along with the concentrations of the different parameters that are achieved during preparation of synthetic wastewater. To synthesize the wastewater machine oil lubricant was added to form FOG and was entirely emulsified through blending, Sodium Bicarbonate (NaHCO_3) was used to form HCO_3^- , phenol ($\text{C}_6\text{H}_5\text{OH}$) was used to form phenol, Na_2SO_4 was used to form total dissolved solids (TDS), sand was used to form total suspended solids (TSS), Potassium Hydrogen Phthalate ($\text{C}_8\text{H}_5\text{KO}_4$) was used to form chemical oxygen demand (COD), cow dung was used to form biological oxygen demand (BOD_5), and pH was adjusted to the required value using 0.5 N hydrochloric acid. All chemicals used during testing are of analytical grade.

Table 1 Characteristics of actual and synthetic Jordan petroleum refinery wastewater

Parameter	Actual Jordanian refinery wastewater ^a	Synthetic refinery wastewater ^b
HCO_3 , ppm	568	715.5
Phenol, ppm	0.036	0.03
TDS, ppm	5339	5210
Fat, Oil, & Grease (FOG), ppm	Less than 8	8.5
TSS, ppm	32	66
COD, ppm	430	472
BOD_5 , ppm	54	56
pH	8.43	9.36

^aThe Hashemite Kingdom of Jordan Environment Statistics 2014-2015 (2018) ^bThis work

3.3 Measurement Methods

Phenol was determined by UV-spectrophotometry through analyzing the color resulting from the reaction of 4-aminoantipyrine with phenol in the presence of potassium ferricyanide. The antipyrine dye resulting from the reaction of 4-aminoantipyrine with phenol in the presence of potassium ferricyanide is extracted from water with chloroform and the absorbance is measured at 460 nm. HCO_3 was determined by titrating wastewater samples against a standard solution of sulphuric acid of 0.02 N using

a phenolphthalein indicator and a mixed indicator (a mixture of methyl red and bromocresol green indicators). The mixed indicator is used to determine the total alkalinity while phenolphthalein indicator is used to determine the phenolphthalein alkalinity. TDS and TSS have been determined by gravimetric methods, FOG have been determined by acidifying the synthetic wastewater sample to pH less than 2 and serially extracting it with trichlorotrifluoroethane (1,1,2 trichloro-1,2,2 trifluoroethane) three times in a separatory funnel. The trichlorotrifluoroethane is distilled from the extract and the left residue is desiccated and weighed. COD has been determined by the open reflux method, the dissolved oxygen (DO) was determined by titrimetric procedure (iodometric test) and consequently BOD was calculated from determined DOs, pH was determined using a digital pH meter (brand-ultratech). Sludge production (metal hydroxide flocs and removed pollutants) has been determined through total suspended solids measurement (gravimetric method).

3.4 Sludge characteristics

After the synthetic petroleum refinery wastewater was treated by electrocoagulation a specific volume of reacted water was taken, mixed and transferred to a 250 mL graduated cylinder and was allowed to settle and the volume of compacted sludge was reported at 0, 10, 20, and 30 minutes in the presence and absence of a flocculating agent. SSV30 and SVI have been determined as follows:

The sludge was allowed to settle for a period of 30 minutes and the volume of sludge recorded at this time is the SSV30.

The SVI has been calculated using the following formula:

$$SVI \left(\frac{mL}{g} \right) = \frac{SSV_{30} \left(\frac{mL}{L} \right)}{TSS \left(\frac{g}{L} \right)} \dots \dots \dots 3$$

252

253 The TSS (MLSS) of the treated wastewater was determined gravimetrically and used in the SVI
254 calculation.

255 **4 Methodology relevant to finding fixed and operating costs of EC treatment plant**

256 In this section we summarize the method used. Because it involves lengthy details, its full presentation is
257 relegated to the supplementary material. The rudiments are as follows:

258 a) Selection of the major items of equipment:

259

260 1- Selection of the sludge dewatering machine

261

262 Capital, operation, and maintenance costs have been performed on the most prominent techniques
263 used in sludge dewatering by using appropriate cost equations taken from Sharma 2010. The
264 decanter centrifuge was selected for dewatering the sludge generated from EC treatment of JRWW
265 since it had the lowest capital, operation, and maintenance costs among all outstanding techniques
266 considered.

267

268 2- Selection of core of the JRWW TP

269

270 EC reactors have been selected for the core of the JRWW TP due to several reasons some of them
271 are:

- 272 • EC is most commonly used in the oil and gas industry to remove emulsified oil, total petroleum
273 hydrocarbons, suspended solids, and heavy metals (Martin 2014). It can process all the

aforementioned multiple contaminants in just the chamber of the EC (GENESIS WATER TECHNOLOGIES 2019).

- It has low maintenance costs because the system is not easily damaged due to not containing moving parts. Moreover, the metal blades within the reactor can be easily cleaned and replaced inexpensively (GENESIS WATER TECHNOLOGIES 2019).

3- Selection of the pumps for the potential wastewater TP

Two hydraulic mixing pumps were selected, one for the concrete slurry tank and the other for underground sludge tank (UST) to keep the slurry/sludge homogenous inside the tanks. Eight centrifugal slurry pumps (3 are standby) were also selected to pump the slurry throughout the TP. One centrifugal submersible sludge pump to be submerged in UST has also been selected.

Table 2 below shows the major items of equipment selected for the EC TP.

Table 2 Major items of equipment selected for the EC TP

Number	Major equipment name
1	3 EC reactors
2	3 (53.3 m ³ /hr) feeding pumps to EC reactors
3	3 tanks (each tank adjacent to an EC reactor)
4	3 (53.3 m ³ /hr) slurry pumps (plus 3 standby)
5	1 Concrete slurry tank
6	1 hydraulic mixing pump for concrete slurry tank
7	2 (80 m ³ /hr) slurry pumps
8	2 Lamella clarifiers
9	1 UST
10	1 hydraulic mixing pump for UST
11	1 Submersible sludge pump (26.24 m ³ /hr)
12	1 Polymer station
13	1 Decanter centrifuge

b) % dry solids content of sludge resulting from the treatment of JWW through EC.

The % dry solids content of sludge before dewatering has been calculated using the following equation (Von Sperling and Gonçalves 2007):

$$\text{Sludge flow (m}^3\text{/day)} = \text{dry solids load (kg/day)} / ((\text{dry solids \%}/100) \times \text{Sludge density (kg/m}^3)) \dots \dots 4$$

The volumetric sludge generation rate have been determined based on sludge settling tests while the sludge/slurry density and the dry solids load have been determined experimentally to be 956 kg/m³ and 2.9 kg dry solids/m³ based on gravimetric methods.

c) Hydraulic mixing pump capacity and mixing power

The mixing pump capacity in the concrete slurry tank and UST as well as mixing power in the aforementioned tanks is calculated according to equation 5 and 6, respectively [US EPA (1985)]

$$\text{Mixing pump capacity (m}^3\text{ per minute)} = \frac{(\text{MP})(6.1183)}{(\text{EF})(\text{TDH})(956)} \dots \dots \dots 5$$

where

MP is the mixing power in units of Watt,

EF is the efficiency of mixing pump of dimensionless units [default value = 0.7 (US EPA (1985))],

TDH is the total dynamic head of the pump in units of meter [default value = 7.62 m (25 ft) (US EPA (1985))],

956 is the density of sludge in units of kg/m³,

314 6.1183 is the conversion factor to convert from Watt to kg-meter/min.

315

$$316 \quad \text{MP (Watt)} = \text{ME} \times \text{Sludge Volume} \times 1.175 \quad \dots \dots \dots 6$$

317 where

318 ME is the mixing energy in Watt/m³, and sludge volume is its volume in m³.

319 d) Decanter centrifuge cake volumetric flow rate estimation

320

321 The estimation of this quantity from decanter centrifuge was based on equations 7, 8 and 9

322 (Records and Sutherland 2001, Celenza 2000)

323 Mass flow rate of solids to decanter = Mass flow rate of cake solids +

324 Mass flow rate of centrate solids 7

325

$$326 \quad Q_f \times x_f \times \rho_f + Q_p \times x_p \times \rho_p = Q_{ca} \times x_{ca} \times \rho_{ca} + Q_c \times x_c \times \rho_c \quad \dots \dots \dots 8$$

327

$$328 \quad \text{Recovery of solids} = ((\text{kg solids fed} - \text{kg solids in centrate}) / \text{kg solids fed}) \quad \dots \dots \dots 9$$

329

330 where Q_f is the volumetric flow rate of sludge to decanter in m³/day, x_f is the solids fraction in sludge in

331 influent to decanter which is dimensionless, ρ_f is the density of sludge in kg/m³, Q_p is the Volumetric

332 flow rate of flocculant in m³/day, x_p is the solids fraction in flocculant in influent to decanter which is

333 dimensionless, ρ_p is the density of flocculant in kg/m³, Q_{ca} is the Volumetric flow rate of cake in m³/day,

334 x_{ca} is the solids fraction in cake which is dimensionless, ρ_{ca} is the density of cake in kg/m³, Q_c is the

335 volumetric flow rate of centrate in m³/day, x_c is the solids fraction in centrate which is dimensionless,

336 and ρ_c is the density of centrate in kg/m³.

e) Pressure drop (frictional losses) for flow of slurry/sludge in pipes and minor head losses

This has been found using equations 10 and 11 below, respectively (McFarland 2000)

$$\Delta P = \frac{2f\rho LV^2}{D} \dots\dots\dots 10$$

$$\text{Minor head loss} = K \left(\frac{V^2}{2g} \right) \dots\dots\dots 11$$

where ΔP is the pressure drop in pipe in N/m^2 , minor head loss in meter, f is the friction factor found from Fig. 5.3 in McFarland 2000, ρ is the fluid density in kg/m^3 , L is the pipe length in m, V is the mean velocity of flow in m/sec, D is the pipe diameter in m, g is the gravitational acceleration in m/s^2 , and K is the head loss coefficient which is dimensionless.

f) Net positive suction head (NPSH)

The net positive suction head available (NPSHa) has been calculated using equation 12

$$\text{NPSHa} = Z + P_a/\rho g - P_{vp}/\rho g - h_f \dots\dots\dots 12$$

where NPSHa is in meter, Z is the difference between the pump impeller eye level and the suction water level in m, P_a is the absolute atmospheric pressure in N/m^2 , P_{vp} is the absolute vapor pressure of the fluid at pumping temperature in N/m^2 , ρ is the density of fluid in kg/m^3 , g is the acceleration of gravity in m/s^2 , and h_f is the head lost in the suction pipework in m.

In theory, the absolute pressure at the suction port of the pump (NPSHa) should be larger or equal to the minimum pressure required at the suction port of the pump to keep the pump from cavitating

(NPSHr). However, in practice there should be an additional head added to NPSHr and acts as a buffer against uncertainties of pumping.

Thus, to avoid pump cavitation
$$\text{NPSHa} \geq \text{NPSHr} + \text{additional head} \dots\dots\dots 13$$

Where NPSHa, NPSHr and additional head are all in meters.

g) Total cost (fixed and operational) estimation:

Predesign cost estimation for a potential wastewater TP for Jordan refinery mechanically treated effluent through EC has been performed based on finding the fixed (capital) costs through a study (factored) estimate. The latter requires the knowledge of major items of equipment and the probable accuracy of this estimate is up to $\pm 30\%$ (Peters and Timmerhaus 1991). The estimated operating costs are the second important part for determining the total costs for treating the wastewater. The total capital investment (fixed capital + working capital) is estimated based on the knowledge of the costs of major items of delivered equipment for a potential EC TP. After knowing the total price of major delivered equipment, the ratio factors for estimating the capital-investment items for a fluid processing plant are then used to find the total capital investment (Peters and Timmerhaus 1991).

h) Power costs

The calculation of these costs is mentioned here for three equipments only.

1- Power costs for running the pumps

The power costs for running the pumps are calculated using equations 14 and 15 (Giorgi 2009, Neutrium 2012) below

382 Motor power (kW) = $Q\rho gh / (3.6 \times 10^6 \times \text{Motor efficiency} \times \text{Pump efficiency})$ 14

383 The cost in US\$/yr for running the pumps = Motor power $\times$ operating hours per year $\times$

384 0.154 US \$/kWh $\times$ 1.175 15

385 where Q is the flow rate in m³/hr, ρ is the density of fluid in kg/m³, g is the gravitational acceleration

386 constant (9.81 m/s²), and h is the head of the pump in m., Motor efficiency $\times$ Pump efficiency = wire

387 to water efficiency, dimensionless (Theobald 2014).

388 2- Power costs for running the decanter centrifuge

389 Annual costs for running decanter centrifuge (US \$/yr)

390 = decanter centrifuge motor power $\times$ operating hours per year

391 $\times$ 0.154 US \$/kWh $\times$ 1.175 16

392 where decanter centrifuge motor power is in kW, and operating hours per year are in hours.

393 3- Power costs required for running the EC reactors has been estimated by first calculating the

394 energy consumption in kWh/m³ using equation 1 and then power costs have been determined

395 as follows

396 Annual costs for running the 3 EC reactors (US \$/yr)

397 = energy consumption (kWh/m³) $\times$ total wastewater flow rate (m³/hr)

398 $\times$ 0.154 US \$/kWh $\times$ 1.175 17

399 **5 Results and interpretations**

400 **5.1 Experimental results**

401 **5.1.1 Changing electrode material**

402 In EC experiments one of the important factors that determine the efficiency of the process is the type

403 and combinations of electrodes. The type of materials that are used most often for EC experiments are

Aluminum (Al) and iron (Stainless Steel (SS)) which are quite cheap (Gousmi et al. 2016). In this work two types of electrode combinations have been used (Anode/Cathode): Al/SS, Mild Steel/SS. The best (optimum) results for removing the synthetic wastewater constituents are shown in Tables 3 and 4.

Table 3 Best results of treatment of synthetic refinery wastewater using Al and SS electrodes at a current of 10 Amp, voltage of 28 to 31, inter-electrode distance of 10 mm, and 5 minutes reaction time

Parameter	Raw synthetic wastewater	Treated wastewater	% removal of pollutant	Target value according to Jordanian norms for using the treated water for irrigation of cooked vegetables, parks, playgrounds	Target value according to the most stringent Jordanian norms for using the treated water for cut flowers irrigation
HCO ₃ in ppm	715.5	36.81	94.9	400	400
Phenol in ppm	0.03	ND ^a	At least 96.7	Less than 0.002	Less than 0.002
TDS in ppm	5210				
Fat, oil, and grease (FOG) in ppm	8.5	ND ^b	At least 98.8	8	2
TSS in ppm	66	48	27.3	50	15
COD in ppm	472	73.4	84.4	100	50
BOD ₅ in ppm	56	10.01	82.1	30	15
pH	9.36	8.66		6 to 9	6 to 9

^a The lowest value of detection for phenol using the analysis method in this paper is 1 µg/L. Therefore, the concentration of phenol is less than 2 µg/L (Jordanian norms). ^b The lowest value of detection for FOG using the analysis method in this paper is 0.1 ppm. Therefore, the concentration of FOG is less than 2 or 8 ppm FOG (Jordanian norms). .

Table 4 Best results of treatment of synthetic refinery wastewater using mild steel and SS electrodes at a current of 10 Amp, voltage of 27 to 35, inter-electrode distance of 10 mm, and 10 minutes reaction time

Parameter	Raw synthetic wastewater	Treated wastewater	% removal of pollutant	Target value according to Jordanian norms for using the treated water for irrigation of cooked vegetables, parks, playgrounds	Target value according to the most stringent Jordanian norms for using the treated water for cut flowers irrigation

HCO ₃ in ppm	715.5	411	42.6	400	400
Phenol in ppm	0.03	0.01	66.7	Less than 0.002	Less than 0.002
TDS in ppm	5210				
Fat, oil, and grease (FOG) in ppm	8.5	0.10	98.8	8	2
TSS in ppm	66	6.1	90.8	50	15
COD in ppm	472	23.6	95.0	100	50
BOD ₅ in ppm	56	8.4	85.0	30	15
pH	9.36	8.86		6 to 9	6 to 9

Both results in Table 3 and 4 have been performed using bipolar electrode configuration. Looking at Tables 3 and 4 it can be seen that neither of the two electrode combinations at the optimum results was successful in treating the refinery wastewater so that it would satisfy the most stringent Jordanian norms. It can be seen that using Al and SS electrodes was successful in producing treated water that could be used for irrigation of cooked vegetables, parks, and playgrounds but not for cut flowers. The experiments using mild steel and SS electrodes did not produce treated water that could be used for irrigating cooked vegetables, parks and playgrounds or cut flowers. For that reason, we are going to concentrate afterwards only on the results relevant to using Al/SS electrodes that are also used in our cost calculations.

5.1.2 Sludge settling tests and production

Settling tests of the electrocoagulated water (using Al/SS electrodes, a current of 10 Amp, 28 to 31 Volt, and 5 minutes reaction time) has been performed in the presence and absence of the flocculating agent the 6691 series of dry PAM cationic ANAFLOC flocculant. Tables 5 and 6 show the settled sludge volume in mL/L at a time interval from zero to 30 minutes in the absence and presence of the flocculating agent, respectively.

Table 5 Settling tests of the electrocoagulated water using Al/SS electrodes in the absence of ANAFLOC

Time in minutes	Settled sludge volume in mL/L
0	1000

10	148
20	128
30	120

Table 6 Settling tests of the electrocoagulated water using Al/SS electrodes in the presence of ANAFLOC

Time in minutes	Settled sludge volume in mL/L
0	1000
10	168
20	160
30	152

Sludge production relevant to the results in Table 3 has been found experimentally using gravimetric methods and was calculated to be 2.9 kg dry solids per m³ of treated wastewater.

5.1.3 Percentage dry solids content of sludge after dewatering

The sludge that resulted from the experiment relevant to Table 3 has been pressed using a lab screw press and the % dry solids content of the sludge after pressing have been determined gravimetrically and was found to be 25 %. A lab screw press has been used in our experiments due to that the screw press and decanter centrifuge have nearly the same cake % dry solids content after sludge dewatering (Sprick 2017).

5.2 Power costs of EC treatment plant

Table 7 shows power costs for the different major equipment in the EC TP in addition to energy consumption in kWh/m³ or kWh/(m³.yr) and proportion of costs in %. For JRWW it turns out to be 1,647,296 US \$. EC reactors display the highest annual values followed by the decanter centrifuge and 94.7 % of the total of the major equipment used to treat JRWW are for the EC reactors. The EC used in the experiments and at optimum conditions has a power requirement of 15.4 kWh/kg non-biodegradable COD_{removed}. As an illustration, conventional activated sludge systems can have a power

requirement that can range from 0.85 to 3.33 kWh/kg COD_{removed} (Soares et al. 2017). Fig. 2 shows a schematic of the EC TP. First of all in this schematic the mechanically treated JRWW is pumped from large ponds towards EC reactors where the JRWW non-biodegradable COD is 84.4 % removed. Later on, the discharge of treated JRWW from EC reactors is by gravity towards adjacent tanks where the fluid in the latter tanks is pumped to a concrete slurry storage tank. Afterwards the fluid in the concrete tank is pumped to lamella clarifiers where the coagulated pollutants are separated from the water with the help of cationic flocculant pumped from the polymer station to lamella clarifiers. Sludge is discharged by gravity from the two lamella clarifiers to UST from which the sludge is further pumped by a submersible pump to decanter centrifuge. In the decanter centrifuge, the sludge is dewatered by the action of the centrifugal force forming two streams one is the centrate with little solids content and the other is the cake (dewatered sludge) with high solids content.

Table 7 Annual power costs for JRWW EC TP major equipment for the year 2022

Type of equipment	Power costs (US \$/yr)	Energy consumption	Unit	Proportion of costs (%)
Three EC reactors	1,560,109	6.146	kWh/m ³	94.71
Pumps	29,651	0.752		1.80
Two hydraulic mixing pumps	6,468	193.51	kWh/(m ³ .yr)	0.39
Two Lamella clarifiers flash mixers	592	96.75		0.036
Polymer station	3,173	2.94	kWh/m ³	0.19
Decanter centrifuge	47,303	1.34		2.87
Total	1,647,296

Fig. 2 EC TP schematic. Abbreviations are as follows: ECR stands for electrocoagulation reactor, AT stands for adjacent tank, SST stands for slurry storage tank, PS stands for polymer station, LC stands for lamella clarifier.

5.3 Raw materials cost

Table 8 shows annual costs of the raw materials required for the JRWW EC plant along with their consumption in g/m^3 . The dissolution of the electrodes and consequently their replacement is the highest annual raw material cost followed by the cationic flocculant. Aluminum metal blades replacement represents 78.15 % of the total annual raw material costs.

Table 8 Annual costs of the raw materials required for the JRWW EC plant for the year 2022

Raw material	Cost (US \$/yr)	Consumption (g/m^3) ^a
ANAFLOC flocculant	8,732	1
Aluminum	56,544	8.6
Stainless Steel	7,075	6.4
Total	72,351	

^aDetermined experimentally

5.4 Dewatered sludge (cake) disposal and treatment costs

The cake that is transported from Jordan refinery in Zarqa to Russaifah disposal site and treated through land farming has an estimated yearly cost of 2,751,336 US \$ (year 2022).

5.5 Annual operating labor costs

The yearly labor costs have been estimated based on the daily capacity of the wastewater TP (3836 ton) to be 147,976 US \$ (year 2022).

5.6 Costs of the major items of equipment

Table 9 displays costs of major items of equipment in the JRWW EC TP in addition to proportions in %. As can be seen, the EC reactors contribute 44.73 % of the total purchased equipment costs followed by decanter centrifuge and polymer station which is 22.58 %.

Table 9 Major items of equipment cost used in the JRWW EC TP for the year 2022

Major equipment	Purchased and delivered cost US \$	Proportion of costs (%)
Three EC reactors	2,493,057	44.73
Three feeding pumps to EC reactors	23,766	0.43
Two lamella clarifiers	362,424	6.50
UST	553,745	9.94
UST hydraulic mixing pump (HMP)	147,178	2.64
Concrete slurry tank	184,791	3.31
Concrete slurry tank HMP	328,071	5.89
Decanter centrifuge and polymer station	1,258,576	22.58
Slurry/sludge pumps	24,611	0.44
Three adjacent tanks to EC reactors	220,805	3.96
Total	5,573,258	100

5.7 Overall cost for the treatment of Jordan refinery wastewater using the EC plant

Table 10 shows the different capital-investment items for a fluid processing plant while Table 11 shows the different annual expense estimates for operating the EC TP. It can be seen that the purchased delivered equipment and service facilities (installed) contribute 35.6 % of the fixed-capital investment while 30.2 % of the total capital investment. As for the yearly operation of the plant, power and sludge disposal/treatment contribute about 37.6 % (highest contributor) of the annual operating cost and is followed by maintenance and repairs of 13.6 %. The overall cost for JRWW wastewater treatment is 10.75 US \$/m³ (26.97 US \$/kg non-biodegradable COD_{removed}).

511 Table 10 Different capital-investment items costs for a solid-fluid processing plant based on delivered-
 512 equipment cost

Item	Capital cost in US \$	Percentage of delivered equipment cost
Purchased equipment-delivered	5,573,258	100
Purchased-equipment installation	2,619,431	47
Instrumentation and controls (installed)	1,003,186	18
Piping (installed)	3,678,350	66
Electrical (installed)	613,058	11
Buildings (including services)	1,003,186	18
Yard improvements	557,326	10
Service facilities (installed)	3,901,281	70
Engineering and supervision	1,839,175	33
Construction expenses	2,285,036	41
Contractor's fee	1,170,384	21
Contingency	2,340,768	42
Fixed-capital investment	26,584,440	477
Working capital	4,739,002	86
Total capital investment	31,377,442	563

513
 514 Table 11 Different expense estimates that includes operating cost in US \$/yr and overall cost for
 515 wastewater treatment

Expense	EC plant expenses
I -Manufacturing costs	
A. Direct production costs, US \$/yr	
1-Raw materials, US \$/yr	72,350.5
2-Operating labor, US \$/yr	147,976
3-Operating supervision, US \$/yr	25,896
4-Power and sludge disposal/treatment, US \$/yr	4,398,632
5-Maintenance and repairs, US \$/yr	1,595,066
6-Operating supplies, US \$/yr	239,260
7-Laboratory charges, US \$/yr	22,196
B. Fixed charges, US \$/yr	
1-Taxes, US \$/yr	664,611
2-Insurance, US \$/yr	186,091
3-Depreciation, US \$/yr	1,329,222
C. Plant overhead costs, US \$/yr	1,061,363
II- General Expenses	
1.Administrative expenses, US \$/yr	36,994
2.Financing, US \$/yr	1,568,872
III -Total production cost, US \$/yr	11,348,530

Contingencies, US \$/yr	340,456
Operating cost, US \$/yr	11,688,986
Overall cost, US \$/m ³	10.75
Overall cost, US \$/g non-biodegradable COD _{removed}	26.97

6 Discussion

6.1 Experimental results

6.1.1 Removal of phenol

The experiments of EC at optimum conditions in this work using Al/SS electrodes managed to remove phenol to a high percentage (at least 96.7 %). El-Ashtoukhy et al. 2013 studied the removal of phenol from petroleum refinery wastewater. They found that operating an EC reactor at optimum conditions (pH=7, Current density =8.59 mA/cm², NaCl = 1 g/L, Temperature=25° C) using Al material as anode and cathode managed to completely remove phenol (100 % removal) from a phenol synthetic solution that had an initial phenol concentration of 5 mg/L in a period of 30 minutes. In our experiments we managed to remove at least 96.7 % of the phenol from synthetic wastewater that had an initial phenol concentration of 0.03 mg/L at optimum conditions in a period of 5 minutes. The much shorter reaction time required in our case could be explained by the much lower initial concentration of phenol in the synthetic wastewater. El-Ashtoukhy et al. 2013 found that by operating the EC reactor at specified conditions and by increasing the initial concentration of phenol solution that is subjected to EC causes a decrease in the removal percentage of phenol from 100 to 75 %. Moreover, a higher current density of 268.2 A/m² was used in our experiment at optimum conditions than that of El-Ashtoukhy's et al. 2013 (85.9 A/m²) which contributes to more dissolution of Al and SS (iron) electrodes according to Faraday's law and the ions of Al and Fe undergo hydrolysis producing Al and Fe hydroxides on which phenol is adsorbed and more of this compound is removed in our case in a shorter reaction time (El-Ashtoukhy et al. 2013, Tanyol et al. 2018). Table 12 shows further comparisons of this work results with Bazrafshan's

and Zazouli's outcomes. It can be seen that we had a shorter treatment time to achieve a similar phenol removal percentage at a higher current than that of Bazrafshan's and a current density close to that of Zazouli et al. 2012.

Table 12 Bazrafshan's and Zazouli's results compared to the present work

Electrode material	Current density in A/m ² (current in A)	Treatment time (minutes)	Phenol removal %	References
Al	(5)	80	94.72	Bazrafshan et al. 2012
Fe			98	
Al	250	60	94	Zazouli et al. 2012
Al plus Fe	268.2 (10)	5	At least 96.7	This work

6.1.2 Removal of FOG

FOG percentage removal in this work at optimum conditions was at least 98.8 % using Al/SS electrodes for an initial FOG concentration of 8.5 mg/L. Changmai et al. 2019 reported the best percentage of oil and grease removal from a drilling site oily wastewater as 70.9 % (initial oil and grease concentration is 35 mg/L) through EC using aluminium material as anode and cathode at a pH of 3.6, current density of 80 A/m², inter-electrode distance of 0.5 cm, and a treatment time of 20 minutes. Liu et al. 2019 studied the oil removal percentage from simulated produced water relevant to oilfields through EC using Aluminium (anode) and iron (cathode) electrodes. At optimum conditions (pH=7, current density = 40 A/m², treatment time = 28 minutes) they removed 70.2 % of the oil. GilPavas et al. 2009 reported the treatment of oily wastewater from automotive industry through EC using iron/aluminium as anode/cathode and vice versa. At optimum conditions (Fe as anode, pH =12, current density = 43 A/m³, treatment time = 180 minutes) 98.6 % of oil was removed. Drogui et al. 2009 reported 90 % oil& grease removal from oily ship effluents through EC using Al electrodes in bipolar configuration at optimum conditions (Current = 0.3 A, pH =7.1, treatment time = 60 minutes). Compared to all the aforementioned

works this work had a higher FOG removal percentage at a shorter reaction time and a higher current intensity (10 A) or density (268.2 A/m²).

6.1.3 Removal of COD

Table 13 shows the removal of COD in this work compared to other literature work. As can be seen from Table 13 the removal % of COD of this work is compatible with the other COD removal percentages and is achieved at a higher current intensity or density and a reaction time same as Ozyonar 2016, less than GilPavas et al. 2009/ Drogui et al. 2009, and higher than Gomes et al. 2009.

Table 13 COD removal of this work compared to other literature work

Electrode material	Current density in A/m ² (current in A)	Type of wastewater	Electrode configuration	Treatment time in minutes	COD removal %	References
Al plus Fe (hybrid)	(1.57)	Train industry oily wastewater	Bipolar (BP)	5	92.6	Ozyonar 2016
Al plus Fe (hybrid)	43	Automotive industry oily wastewater	BP	180	67	GilPavas et al. 2009
Al	(0.3)	Oily ship effluents	BP	60	69.1	Drogui et al. 2009
Fe	200	Produced water	BP	1.7	82.9	Gomes et al. 2009
Al			BP		74.1	
Al plus Fe (hybrid)	268.2 (10)	Synthetic refinery wastewater	BP	5	84.4	This work

6.1.4 Removal of BOD

After searching the literature there is only the work of Drogui et al. 2009 that measured the removal of BOD in oily ship effluents (oily wastewater) through EC using Al electrodes in BP configuration. They found that at a current of 0.3 A and a treatment time of 60 minutes (optimum conditions) 89.4 % of the

BOD was removed. This work achieved a BOD removal of 82.1 % at optimum conditions which is compatible with the work of Drogui et al. 2009.

6.1.5 Removal of TSS

There were two works found in literature (Sardari 2018, Drogui et al. 2009) who measured the TSS removal from oily wastewater after EC treatment in bipolar configuration. Sardari 2018 treated produced water using Aluminium electrodes and at a current of 3 A and a treatment time of 30 seconds and achieved a TSS removal of 91 %. Drogui et al. 2009 reported 31.5 % TSS removal from oily ship effluents using Aluminium electrodes at a current of 0.3 A and a treatment time of 60 minutes. This work achieved a TSS removal of 27.3 %.

6.1.6 pH

Raw synthetic wastewater in this work had an initial pH above 9 (Table 3) and after finishing the EC the pH of the treated wastewater reduced to 8.66 which is within the range of the pH norms required to use the treated wastewater for irrigation. The decrease in pH could be explained by the reaction of aluminum hydroxide precipitates $Al(OH)_3$ with the hydroxyl ions generated during EC which leads to the consumption of hydroxyl ions as shown by the following reaction (Chen 2004):

6.1.7 Removal of bicarbonate

This work at optimum conditions has a bicarbonate removal of 94.9 %. There wasn't any work in literature that studied the removal of bicarbonate in oily wastewater through EC in bipolar configuration to compare with.

6.1.8 Sludge settling tests and its volume index

The sludge volume index (SVI) is defined as the volume occupied by one gram of sludge after 30 minutes settling time (Mohlman 1934). It was originally intended to be a rough measure of sludge settleability to be used in everyday operation of wastewater treatment plants. Moreover, SVI is an important parameter for clarifiers since it provides an insight in obtaining a clear effluent from the clarifier without significant carryover of sludge with it. The SVI has been computed for the results in Table 5 and 6 to be 41.4 and 52.4 mL/g, respectively. It is reported in literature that a good SVI value for sludge should be below 100 mL/g (Diya'uddeen et al. 2015) and in our case it means that the sludge has good settling and compaction properties whether in the absence or presence of ANAFLOC. The flocs formed during the settleability tests conducted on treated synthetic refinery wastewater by electrocoagulation using Al/SS electrodes were of white color and there was a clear solids-liquid separation at 10 minutes of settling time whether polyacrylamide (PAM) cationic flocculant Anafloc 6691 was used or not but the use of the polymer flocculating agent (at a concentration of 0.001 gram/l) resulted in more solids sedimentation and resulted in a larger value of SSV30 (152 mL/L). Therefore, the results of Table 6 are used when computing the % dry solids in sludge before dewatering.

6.1.9 Pollutant removal capacity

The pollutant removal capacity has been estimated based on the method of Kobya et al. 2015 and are shown in Table 14. As can be seen the highest removal capacity was for bicarbonate followed by COD.

Table 14 Pollutant removal capacities relevant to using Al/SS electrodes

Pollutant	g pollutant removed/g hybrid metal (HM)	mg pollutant removed/Coulomb
COD	26.6	0.53
BOD	3.1	0.06
TSS	1.2	0.02
Phenol	At least 0.002	At least 3.87×10^{-5}
Bicarbonate	45.2	0.90
FOG	At least 0.6	At least 0.01

6.2 Costs

The goal of the economic evaluation here is not to provide a comprehensive financial analysis but to have an order of magnitude estimate of the capital and operating costs which would be approximate. It was a preliminary economic evaluation which is partially based on experimental bench-scale data which were conducted and shown previously in this manuscript. The capital cost of the whole plant in this study was estimated based on ratio factors for a fluid processing plant (Peters and Timmerhaus 1991). In this study the method is based on estimating the purchase price (including delivery) of major equipment either using cost equations from reports/books or obtaining it directly from vendors. The total sum of major delivered equipment cost is further multiplied by ratio factors in order to know approximately the capital cost required to put the wastewater treatment plant into operation. The sum of major delivered equipment cost has a value of 5,573,258 US \$.

The operating cost items operating labor, raw materials, power, and sludge management expense estimation was not based on percentages (e.g. for example maintenance and repairs was 2 to 10 % of the fixed capital investment) but involved using equations, data, quotes, and Jordanian hourly wage rate. The labor cost was calculated based on a Jordanian hourly wage rate of 1.62 US \$/man-hour and 365 operating days per year. Estimated power consumption (electrical) relevant to mixing and pumping is 237,481 kWh/yr. In case of power consumption relevant to electrocoagulation reactors we have based our calculations on bench-scale experimental data. The voltage and current during electrocoagulation experiments that resulted in COD, BOD, TSS, FOG, phenol, and HCO_3 removals such that the treated effluent concentrations of the previous parameters are at or below the Jordanian norms required for its possible use for irrigation was 29.5 V, and 10 A, respectively. The unit electricity requirement for EC reactors is 6.15 kWh/m³.

Sludge resulting from petroleum refinery wastewater treatment is considered as hazardous (US EPA 2012) and in this manuscript it is treated through land farming which is a bioremediation technique.

Land-farming has advantages such as low cost of operation, supports large scale treatment, and has a high potential for success (Johnson and Affam 2019, Marin et al. 2005). Moreover, it is a widely employed land treatment approach (Hu et al. 2013). A typical cost for this hazardous waste treatment through land-farming is 30 to 60 US \$/ton of contaminated soil (US EPA 1995). It is assumed that the land used for bioremediation is in the vicinity of Russaifah disposal site. Estimated costs for sludge disposal and treatment in this study is 2,751,336 \$/yr (year 2022).

The overall cost for wastewater treatment at full-scale in this work was estimated as 10.75 US \$/m³ (27 US \$/kg COD_{removed}) considering a service life of 20 years of all major items of equipment in the EC TP. Full-scale plants using EC are present in the USA and Australia treating different kinds of wastewater. Tetreault (2003) reported a slaughterhouse in Australia that used EC technology at full-scale for the treatment of a mixture of stick and blood water (6.5 m³/hr). Eames et al (2017) reported silica removal in mineral mining/processing and oil/gas extraction wastewaters at full-scale using a treatment train that included EC. Table 15 shows a comparison between this work treatment costs with other works from literature. It can be seen that this work treatment costs is of the same order of magnitude as that of Eames et al. (2017) but an order of magnitude higher than Tetreault (2003). Therefore, the cost figure of this work is reasonable.

Table 15 Comparisons of treatment costs through EC of this work result with other works from literature that also used EC for treating their wastewater at full-scale

Type of wastewater	Flow rate (m ³ /hr)	Treatment costs in US \$/m ³ (2022)	References
Stick/blood wastewater	6.5	0.77 ^a	Tetreault (2003)
Mineral mining/processing wastewater	22.7	2.56 ^b	Eames et al. (2017)
Oil/gas extraction wastewater	165.6	3.47 ^c	
Petroleum refinery wastewater	160	3.62 ^d	This work
		3.63 ^e	
		3.74 ^f	

^aThis number has been estimated based on data from Tetreault (2003) which included metal and power consumption as the only operating costs ^bThis number has been estimated based on data from Eames et al. (2017) which included power, chemicals, and metal consumption as the only operating costs ^cThis number has been estimated based on data from Eames et al. (2017) which included power, labor, and treatment

consumables as the only operating costs ^dConsidering only metal and power consumption as the operating costs for comparing with stick/blood slaughterhouse wastewater treatment costs of Tetreault (2003) ^eConsidering only power, chemicals, and metal consumption as the operating costs for comparing with mineral mining/processing wastewater treatment costs of Eames et al. (2017) ^fConsidering only power, labor, and treatment consumables as the operating costs for comparing with oil/gas extraction wastewater treatment costs of Eames et al. (2017)

Main items of equipment in the full plant considered here consist of EC reactors, lamella clarifiers, decanter centrifuge, polymer station, and auxiliary equipment such as pumps and tanks. Prices of main equipment that were obtained directly from vendors are for example costs of Lamella clarifiers, and slurry/sludge pumps. Further sources are equations deduced from published cost data in reports/books such as cost of EC reactors, UST, UST HMP, concrete slurry tank, concrete slurry tank HMP, decanter centrifuge/polymer station, and adjacent tanks to EC reactors. Moreover, different indices have been applied in order to update the costs of equipment to the year 2022 which is assumed as the opening year of the EC TP. These cost indices are specifically the Marshal and Swift equipment, Chemical Engineering Plant, and Engineering News Record Construction Cost indices. The initial and updated values of the cost indices used are shown in Table 16.

Table 16 Initial and update values of the cost indices used in this work

Equipment	Marshall & Swift equipment cost index		Chemical Engineering Plant cost index		Engineering News Record Construction cost index	
	Initial	Updated ^f	Initial	Updated ^f	Initial	Updated ^f
3 EC reactors	1,274.8 ^a	1878.39	--	--	--	--
3 feeding pumps to EC reactors	--	--	389.5	685.66	--	--
2 Lamella clarifiers	1735.78 ^b	1878.39				
UST	--	--	--	--	4006 ^c	11971
UST HMP	751 ^c	1878.39	--	--	--	--
Concrete slurry tank HMP			--	--	--	--
Sludge pump	1828.63 ^d	1878.39	--	--	--	--
Slurry pumps	1781.13 ^e		--	--	--	--
Decanter centrifuge/Polymer station	--	--	--	--	8586 ^h	11971
Concrete slurry tank	--	--	325.8 ^g	685.66	--	--
Adjacent tanks to EC reactors	--	--			--	--

^aAnnual average value for the year 2006 ^b Annual average value for the year 2019, ^cMarch, 1983, ^dAnnual average value for the year 2021 ^e Annual average value for the year 2020, ^fupdated values are annual average values for the year 2022, ^gOctober, 1985, ^hSeptember, 2009.

The ratio factors mentioned in Table 10 are used for estimating the capital cost of a fluid processing plant such as distillation units, water and wastewater treatment plants (Awad and Abuzaid 1997). Since we are dealing with a wastewater treatment plant in this study, the factors in Table 10 for a fluid processing plant have been selected. The EC TP for JRWW (160 m³/hr) had an estimated total capital investment and annual operating cost of 31,377,442 and 11,668,986 US \$, respectively. For comparison, a conventional activated sludge system treating on average 200 m³/hr of domestic wastewater can have a construction and annual operating cost of about 12,500,000 and 500,000 US \$ for the year 2016, respectively (Jafarinejad 2017). Using a conventional activated sludge process to compare the capital and operating costs to our system is because activated sludge is the most widely applied biological treatment of liquid waste, whether originating from industrial processes or households (Jafarinejad 2017). Moreover, biological treatment processes are very economical and efficient options when compared to chemical and physical treatment methods (Li 2013). The capital costs of the two treatment systems are of the same order of magnitude but operating costs for the EC TP are two orders of magnitude higher. This comparison suggests that the EC treatment technique is a viable option for JRWW. Jordan refinery can finance such a project since its profit is about two times larger than the estimated total capital investment of the potential EC TP. The profit of Jordan refinery for the year 2018 is 36.9 million Jordanian Dinars which is about 52 million US \$ (Jordan Refinery Company annual report 2018). The total capital investment has been estimated based on brand new purchased delivered equipment. Substantial reduction in total capital investment can be achieved if second hand equipment is used, though the service life of this equipment may be shorter. Total capital investment reductions will also reduce several expense estimation items relevant to operating costs resulting in lowering the overall cost for JRWW treatment. Additionally, if Jordan refinery has excess electrical energy enough to

power the EC reactors (main user of electricity) and other equipment the operating costs will also go down and with it overall cost of JRWW treatment.

JRWW has a BOD/COD ratio < 0.3 and renders the wastewater biologically untreatable (Srinivas 2008) because it inhibits the metabolic action of bacteria due to the refractory and/or toxicity property of this water (Abdalla and Hammam 2014). Thus, the COD removed using the EC reactors would be the non-biodegradable COD.

7 Conclusions

In order to meet the increasing water demands in arid and semi-arid regions such as Jordan one of the options is to reclaim wastewater and in this article it was industrial. The treatment of waste effluents is continuing to be a fundamental issue in the majority of industries. There are many companies worldwide who spend a large sum of money in order to treat the hazardous substances in their effluents. Unfortunately, it is with high probability that refining industries in the MENA region do not treat their effluents properly and Jordan is no exception as has been mentioned in this study. This study outlined a process that can be used to treat refinery effluent. Detail of chemical and equipment requirements as well as the costs relevant to such a process has been presented. The technology used to reclaim refinery wastewater in this study was electrocoagulation which is an enigmatic technology and we still do not know its full potential. Based on available literature there are only few companies that applied this technology on full scale and the results of this research would be encouraging for companies to apply such technology in the future for their industrial effluents. The overall cost for treatment using EC technology may be high (as has been shown in this manuscript) but future technological development in the EC technology will probably reduce overall costs further which may cause this technology to be applied on a wider scale. Third-world countries lack suitable infrastructure and required capital investments for WW treatment plants (Borghe-ei et al. 2015). They require

wastewater treatment technologies that can be easily operated, has minimal operation/maintenance capital expenditure and skilled labor. The EC technology has all the aforementioned characteristics and can be considered as an option to be employed for the treatment of refineries wastewater emitted in the MENA region in exchange for a reasonable cost. Jordan refinery wastewater was treated successfully to conform to Jordanian norms of COD, BOD, TSS, FOG, phenol, and bicarbonate so that it could be used for irrigation or as a possible source of de-salter wash-water. Irrigation could be for parks, playgrounds or plants that are grown for their fiber (e.g. cotton). So, it is a suitable technology for the treatment of JRWW and the cost for its treatment is affordable.

Declarations

Funding the authors have no relevant financial or non-financial interests to disclose.

Conflicts of interest the authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material All data generated or analysed during this study are included in this published article (and its supplementary information files).

Code availability not applicable

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Simon R Sakhel and Sven-Uwe Geissen. The first draft of the manuscript was written by Simon R Sakhel and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

Abdalla KZ, Hammam G (2014) Correlation between Biochemical Oxygen Demand and Chemical Oxygen Demand for Various Wastewater Treatment Plants in Egypt to Obtain the Biodegradability Indices. IJSBAR 13 (1): 42-48.

Abdelwahab O, Amin NK, El-Ashtouky ESZ (2009) Electrochemical removal of phenol from oil refinery wastewater. J Hazard Mater 163 (2-3): 711–716. <https://doi.org/10.1016/j.jhazmat.2008.07.016>

Akyol A (2012) Treatment of paint manufacturing wastewater by electrocoagulation. Desalination 285: 91–99. <https://doi.org/10.1016/j.desal.2011.09.039>

Al-Khalid T, El-Naas MH (2018) Organic Contaminants in Refinery Wastewater: Characterization and Novel Approaches for Biotreatment. In: Zoveidavianpoor M. (ed.) Recent Insights in Petroleum Science and Engineering. IntechOpen Limited, London, pp 371-391.

Al-Qodah Z, Al-Qudah Y, Omar W (2019) On the performance of electrocoagulation-assisted biological treatment processes: a review on the state of the art. Environ Sci Pollut Res 26 (28): 28689–28713. <https://doi.org/10.1007/s11356-019-06053-6>

Asselin M, Drogui P, Brar SK, Benmoussa H, Blais JF (2008) Organics removal in oily bilgewater by electrocoagulation process. J Hazard Mater 151 (2-3): 446–455. <https://doi.org/10.1016/j.jhazmat.2007.06.008>

- 773 Awad YM, Abuzaid NS (1997) Electrochemical treatment of phenolic wastewater: Efficiency, design
 774 considerations and economic evaluation. J Environ Sci Health A32(5): 1393-1414.
 775 <https://doi.org/10.1080/10934529709376617>
 776
- 777 Aygun A, Nas B, Sevimli MF (2019) Treatment of reactive dyebath wastewater by electrocoagulation
 778 process: Optimization and cost-estimation. Korean J Chem Eng 36 (9): 1441-1449.
 779 <https://doi.org/10.1007/s11814-019-0334-7>
 780
- 781 Bassala HD, Dedzo GK, Baudouin C, Bememba N, Seumo PMT, Dazie JD, Nanseu-Njiki CP, Ngameni E
 782 (2017) Investigation of the efficiency of a designed electrocoagulation reactor: Application for dairy
 783 effluent treatment, Process Saf Environ Prot 111: 122-127.
 784 <http://dx.doi.org/10.1016/j.psep.2017.07.002>
 785
- 786 Bazrafshan E, Biglari H, Mahvi AH (2012) Phenol removal by electrocoagulation process from aqueous
 787 solutions. Fresenius Environ Bull 21 (2): 364-371.
 788
- 789 Borghe-ei SM, Goodarzi J, Mohseni M, Amouei A (2015) Efficiency of Removing Chromium from Plating
 790 Industry Wastewater using the Electrocoagulation Method. Int Arch Health Sci 2(2):83-87.
 791
- 792 Calvo LS, Leclerc JP, Tanguy G, Cames MC, Paternotte G, Valentin G, Rostan A, Lapique F (2003) An
 793 Electrocoagulation Unit for the Purification of Soluble Oil Wastes of High COD. Environ Prog 22 (1): 57-
 794 65. <https://doi.org/10.1002/ep.670220117>
 795

- 796 Cañizares P, Paz R, Sáez C, Rodrigo MA (2009) Costs of the electrochemical oxidation of wastewaters: A
797 comparison with ozonation and Fenton oxidation processes. J Environ Manage 90 (1): 410-420.
798 <https://doi.org/10.1016/j.jenvman.2007.10.010>
799
- 800 Celenza GJ (2000) Industrial Waste Treatment Process Engineering: Volume III Specialized Treatment
801 System, TECHNOMIC PUBLISHING CO, INC, Lancaster, Pennsylvania, USA.
802
- 803 Changmai M, Pasawan M, Purkait MK (2019) Treatment of oily wastewater from drilling site using
804 electrocoagulation followed by microfiltration. Sep Purif Technol 210: 463-472.
805 <https://doi.org/10.1016/j.seppur.2018.08.007>
806
- 807 Chauhan R, Srivastava VC, Hiwarkar AD (2016) Electrochemical mineralization of chlorophenol by
808 ruthenium oxide coated titanium electrode, J Taiwan Inst Chem E 69: 106-117.
809 <https://doi.org/10.1016/j.jtice.2016.10.016>
810
- 811 Chen G (2004) Electrochemical technologies in wastewater treatment. Sep Purif Technol 38 (1): 11-41.
812 <https://doi.org/10.1016/j.seppur.2003.10.006>
813
- 814 Choi YY, Baek SR, Kim JI, Choi JW, Hur J, Lee TU, Park CJ, Lee BJ (2017) Characteristics and
815 Biodegradability of Wastewater Organic Matter in Municipal Wastewater Treatment Plants Collecting
816 Domestic Wastewater and Industrial Discharge, Water 9 (6): 1-12. <https://doi.org/10.3390/w9060409>
817

- 818 Chopra AK, Sharma AK (2015) Effect of electrochemical treatment on the COD removal from biologically
 819 treated municipal wastewater. Desalin Water Treat 53 (1): 41-47.
 820 <https://doi.org/10.1080/19443994.2013.836992>
 821
- 822 Deghles A, Kurt U (2015) Treatment of raw tannery wastewater by electrocoagulation technique:
 823 optimization of effective parameters using Taguchi method. Desalin Water Treat 57 (32): 14798-14809.
 824 <https://doi.org/10.1080/19443994.2015.1074622>
 825
- 826 Demirci Y, Pekel LC, Albaz M (2015) Investigation of Different Electrode Connections in
 827 Electrocoagulation of Textile Wastewater Treatment. Int J Electrochem Sci 10 (3): 2685-2693.
 828
- 829 Diya'uddeen BH, Daud WMAW, Abdul Aziz AR (2011) Treatment technologies for petroleum refinery
 830 effluents: A review. Process Saf Environ Prot 89 (2): 95-105. <https://doi.org/10.1016/j.psep.2010.11.003>
 831
- 832 Diya'uddeen BH, Rahim Pouran Shima, Abdul Aziz AR, Daud, WMAW (2015) Fenton oxidative treatment
 833 of petroleum refinery wastewater: process optimization and sludge characterization. RSC Adv 5 (83):
 834 68159-68168. <http://dx.doi.org/10.1039/C5RA08079G>
 835
- 836 Drogui P, Asselin M, Brar SK, Benmoussa H, Blais JF (2009) Electrochemical removal of organics and oil
 837 from sawmill and ship effluents. Can J Chem Eng 36 (3): 529-539. <https://doi.org/10.1139/L09-003>
 838
- 839 Eames D, O'Dell L, Aylesworth J (2017) Silica Precipitation Chemistry, What works and how much does it
 840 cost? Industrial Wastewater Treatment Technology Database (IWTT) | US EPA.
 841 <https://watersgeo.epa.gov/iwtt/article-report-308>. Accessed 15 March 2021.

- 842
- 843 El-Ashtoukhy ESZ, El-Taweel YA, Abdelwahab O, Nassef EM (2013) Treatment of Petrochemical
 844 Wastewater Containing Phenolic Compounds by Electrocoagulation Using a Fixed Bed Electrochemical
 845 Reactor. *Int J Electrochem Sci* 8 (1): 1534 - 1550.
- 846
- 847 Elazzouzi M, Haboubi Kh, Elyoubi MS (2017) Electrocoagulation-flocculation as a low-cost process for
 848 pollutants removal from urban wastewater. *Chem Eng Res Des* 117: 614-626.
 849 <https://doi.org/10.1016/j.cherd.2016.11.011>
- 850
- 851 El-Dein AM, Libra J, Wiesmann U (2006) Cost analysis for the degradation of highly concentrated textile
 852 dye wastewater with chemical oxidation H₂O₂/UV and biological treatment. *J Chem Technol Biotechnol*
 853 81 (1):1239–1245. <https://doi.org/10.1002/jctb.1531>
- 854
- 855 Fayad N (2017) The application of electrocoagulation process for wastewater treatment and for the
 856 separation and purification of biological media. *Chemical and Process Engineering*. Université Clermont
 857 Auvergne. <https://tel.archives-ouvertes.fr/tel-01719756/document>. Accessed 20 August 2020.
- 858
- 859 Gaied F, Louhichi B, Bali M, Jeday MR (2019) Tertiary treatment of wastewater by electro-coagulation,
 860 electro-Fenton and advanced electro-oxidation processes: Comparative and economic study.
 861 *Songklanakarin J Sci Technol* 41 (5): 1084-1092.
- 862
- 863 García-Morales MA, González Juárez JC, Martínez-Gallegos S, Roa-Morales G, Peralta E, del Campo López
 864 EM, Barrera-Díaz C, Martínez Miranda V, and Blancas TT (2018). Pretreatment of Real Wastewater from

865 the Chocolate Manufacturing Industry through an Integrated Process of Electrocoagulation and Sand
866 Filtration. Int J Photoenergy 2018: 1-7. <https://doi.org/10.1155/2018/2146751>

867
868 Gasim HA, Kutty SRM, Isa MH, Isa MPM (2012) Treatment of Petroleum Refinery Wastewater by using
869 UASB Reactors. International Scholarly and Scientific Research & Innovation 6(2): 58-61.

870
871 GENESIS WATER TECHNOLOGIES Using Innovation to Meet the Water Needs of the World. Top 5
872 Advantages of Advanced Electrocoagulation Water Treatment (2019).
873 [https://genesishwatertech.com/blog-post/top-5-advantages-of-advanced-electrocoagulation-water-](https://genesishwatertech.com/blog-post/top-5-advantages-of-advanced-electrocoagulation-water-treatment/)
874 [treatment/](https://genesishwatertech.com/blog-post/top-5-advantages-of-advanced-electrocoagulation-water-treatment/). Accessed 18 February 2020.

875 GilPavas E, Molina-Tirado K, Gómez-García MÁ (2009) Treatment of automotive industry oily
876 wastewater by electrocoagulation: statistical optimization of the operational parameters. Water Sci
877 Technol 60 (10): 2581-2588. <https://doi.org/10.2166/wst.2009.519>

878 Giorgi J (2009) Math for wastewater treatment operators grades 3 and 4. First edition. American Water
879 Works Association.

880 Giwa SO, Giwa A, Zeybek Z, Hapoglu H (2013) Electrocoagulation Treatment of Petroleum Refinery
881 Wastewater: Optimization through RSM. Int J Eng Res Technol 2 (8): 606-615.

882
883 Gomes J, Cocke D, Das K, Guttula M, Tran D, Beckman J (2009) Treatment of produced water by
884 electrocoagulation.
885 [https://www.avividwater.com/uploads/1/3/1/6/131696832/gomes_2009_treatment_of_produced_wat](https://www.avividwater.com/uploads/1/3/1/6/131696832/gomes_2009_treatment_of_produced_water_by_electrocoagulation.pdf)
886 [er_by_electrocoagulation.pdf](https://www.avividwater.com/uploads/1/3/1/6/131696832/gomes_2009_treatment_of_produced_water_by_electrocoagulation.pdf). Accessed 25 October 2021.

887

- 888 Gousmi N, Sahmi A, Li HZ, Poncin S, Djebbar R, Bensadok K (2016) Purification and detoxification of
889 petroleum refinery wastewater by electrochemical process. *Environ Technol* 37 (18): 2348-2357.
890 <http://dx.doi.org/10.1080/09593330.2016.1150349>
- 891 Guvenc SY, Erkan HS, Varank G, Bilgili MS, Engin GO (2017) Optimization of paper mill industry
892 wastewater treatment by electrocoagulation and electro-Fenton processes using response surface
893 methodology. *Water Sci Technol* 76 (8): 2015–2031. <https://doi.org/10.2166/wst.2017.327>
- 894
- 895 Hu G, Li J, Zeng G (2013) Recent development in the treatment of oily sludge from petroleum industry: A
896 review. *J Hazard Mater* 261: 470-490. <https://doi.org/10.1016/j.jhazmat.2013.07.069>
- 897
- 898 Jafarinejad S (2017) Cost estimation and economical evaluation of three configurations of activated
899 sludge process for a wastewater treatment plant (WWTP) using simulation. *Appl Water Sci* 7 (5): 2513–
900 2521. <https://doi.org/10.1007/s13201-016-0446-8>
- 901
- 902 Jeuland M (2015) Challenges to wastewater reuse in the Middle East and North Africa. *Middle East Dev J*
903 7 (1): 1–25. <http://dx.doi.org/10.1080/17938120.2015.1019293>
- 904
- 905 Jimenez JA, La Motta EJ, and Parker DS (2005) Kinetics of Removal of Particulate Chemical Oxygen
906 Demand in the Activated-Sludge Process. *Water Environ Res* 77 (5): 437-446.
907 <https://doi.org/10.2175/106143005X67340>.
- 908
- 909 Johnson OA, Affam AC (2019) Petroleum sludge treatment and disposal: A review. *Environ Eng Res* 24
910 (2): 191-201. <https://doi.org/10.4491/eer.2018.134>
- 911

912 Jordan Refinery Company annual report (2018).
 913 <http://www.iopetrol.com.ijo/EchoBusV3.0/SystemAssets/33b159f2-5de7-4113-a8b1-372baee2a7cf.pdf>.
 914 Accessed 25 August 2020.
 915
 916 Keramati M, Ayati B (2019) Petroleum wastewater treatment using a combination of electrocoagulation
 917 and photocatalytic process with immobilized ZnO nanoparticles on concrete surface. Process Saf Environ
 918 Prot 126: 356–365. <https://doi.org/10.1016/j.psep.2019.04.019>
 919
 920 Kobya M, Delipinar S (2008) Treatment of the baker's yeast wastewater by electrocoagulation, J Hazard
 921 Mater 154 (1-3): 1133-1140. <https://doi.org/10.1016/j.jhazmat.2007.11.019>
 922
 923 Kobya M, Demirbas E, Akyol A (2009) Electrochemical treatment and operating cost analysis of textile
 924 wastewater using sacrificial iron electrodes. Water Sci Technol 60 (9): 2261–2270.
 925 <https://doi.org/10.2166/wst.2009.672>
 926
 927 Kobya M, Ozyonar F, Demirbas E, Sik E, Oncel MS (2015) Arsenic removal from groundwater of Sivas-
 928 Şarkışla Plain, Turkey by electrocoagulation process: Comparing with iron plate and ball electrodes. J
 929 Environ Chem Eng 3 (2): 1096-1106. <https://doi.org/10.1016/j.jece.2015.04.014>
 930
 931 Kongjao S, Damronglerd S, Hunsom M (2008) Simultaneous removal of organic and inorganic pollutants
 932 in tannery wastewater using electrocoagulation technique. Korean J Chem Eng 25 (4): 703-709.
 933 <https://doi.org/10.1007/s11814-008-0115-1>
 934

- 935 Kulikowska D, Zielińska M, Konopka K (2019) Treatment of stabilized landfill leachate in an integrated
 936 adsorption–fine-ultrafiltration system, *Int J Environ Sci Technol* 16 (1): 423–430.
 937 <https://doi.org/10.1007/s13762-018-1685-z>
 938
- 939 Li A (2013) Biological Wastewater Treatment: Selecting the Process. Veolia Water Solutions &
 940 Technologies. [https://www.chemengonline.com/biological-wastewater-treatment-selecting-the-](https://www.chemengonline.com/biological-wastewater-treatment-selecting-the-process/)
 941 [process/](https://www.chemengonline.com/biological-wastewater-treatment-selecting-the-process/). Accessed 13 August 2020.
 942
- 943 Lin CJ, Lo SL, Kuo CY, Wu CH (2005) Pilot-Scale Electrocoagulation with Bipolar Aluminum Electrodes for
 944 On-Site Domestic Greywater Reuse. *J Environ Eng* 131 (3): 491-495.
 945 [https://doi.org/10.1061/\(ASCE\)0733-9372\(2005\)131:3\(491\)](https://doi.org/10.1061/(ASCE)0733-9372(2005)131:3(491))
 946
- 947 Liu F, Zhang Z, Wang Z, Li X, Dai X, Wang L, Wang X, Yuan Z, Zhang J, Chen M, Wang S (2019)
 948 Experimental study on treatment of tertiary oil recovery wastewater by electrocoagulation. *Chem Eng*
 949 *Process* 144: 107640. <https://doi.org/10.1016/j.cep.2019.107640>
 950
- 951 Mahesh S, Garg KK, Srivastava VC, Mishra IM, Prasad B, Mall ID (2016) Continuous electrocoagulation
 952 treatment of pulp and paper mill wastewater: operating cost and sludge study. *RSC Adv* 6 (20): 16223-
 953 16233. <https://doi.org/10.1039/C5RA27486A>
 954
- 955 Marin JA, Hernandez T, Garcia C (2005) Bioremediation of oil refinery sludge by landfarming in semiarid
 956 conditions: Influence on soil microbial activity. *Environ Res* 98 (2): 185-195.
 957 <https://doi.org/10.1016/j.envres.2004.06.005>
 958

- 959 Martin L (2014) Electrocoagulation: A Shocking Approach To Wastewater Treatment.
 960 <https://www.wateronline.com/doc/a-shocking-approach-to-wastewater-treatment-0001>. Accessed 18
 961 February 2020.
 962
- 963 McFarland M (2000) Biosolids Engineering. McGraw-Hill Professional.
 964
- 965 Mohammadi MJ, Salari J, Takdastan A, Farhadi M, Javanmardi P, Yari AR, Dobaradaran S, Almasi H,
 966 Rahimi S (2017) Removal of turbidity and organic matter from car wash wastewater by
 967 electrocoagulation process. Desalination Water Treat 68: 122–128.
 968 <https://doi.org/10.5004/dwt.2017.20319>
 969
- 970 Mohlman, FM (1934) The Sludge Index. Sewage Work J 6: 119-122.
- 971 Mohsen MS, Jaber JO (2002) Potential of industrial wastewater reuse. Desalination 152(1–3):281–289.
 972 [https://doi.org/10.1016/S0011-9164\(02\)01075-5](https://doi.org/10.1016/S0011-9164(02)01075-5)
 973
- 974 Neutrium (2012). <https://neutrium.net/equipment/pump-power-calculation/>. Accessed 12 March 2020.
 975
- 976 Ozyonar F (2016) Treatment of Train Industry Oily Wastewater by Electrocoagulation with Hybrid
 977 Electrode Pairs and Different Electrode Connection Modes. Int J Electrochem Sci 11 (2): 1456 – 1471.
 978
- 979
- 980 Panizza M (2018) Fine Chemical Industry, Pulp and Paper Industry, Petrochemical Industry and
 981 Pharmaceutical Industry. In: Martínez-Huitle CA, Rodrigo MA, Scialdone O (eds) Electrochemical Water
 982 and Wastewater Treatment. Elsevier, Oxford-Massachusetts, pp 335-364.

983 Pérez LS, Rodriguez OM, Reyna S, Sánchez-Salas JL, Lozada JD, Quiroz MA, Bandala ER (2015) Oil refinery
984 wastewater treatment using coupled electrocoagulation and fixed film biological processes. Phys Chem
985 Earth, Parts A/B/C 91: 53-60. <https://doi.org/10.1016/j.pce.2015.10.018>

986
987 Peters MS, Timmerhaus KD (1991) Plant Design and Economics for Chemical Engineers, fourth ed.
988 McGraw-Hill.

989
990 Qadir M, Bahri A, Sato T, al-Karadsheh E, (2010). Wastewater production, treatment and irrigation in
991 Middle East and North Africa. Irrig Drainage Syst 24 (1-2): 37-51. [https://doi.org/10.1007/s10795-009-](https://doi.org/10.1007/s10795-009-9081-y)
992 [9081-y](https://doi.org/10.1007/s10795-009-9081-y)

993
994
995 Records A, Sutherland K (2001) Decanter Centrifuge Handbook, 1st edn. Elsevier, UK.

996
997 Saber A, Hasheminejad H, Taebi A, Ghaffari G (2014) Optimization of Fenton-based treatment of
998 petroleum refinery wastewater with scrap iron using response surface methodology. Appl Water Sci 4
999 (3): 283–290. <https://doi.org/10.1007/s13201-013-0144-8>

1000
1001 Sahu OP, Gupta V, Chaudhari PK, Srivastava VC (2015) Electrochemical treatment of actual sugar
1002 industry wastewater using aluminum electrode, Int J Environ Sci Technol 12 (11): 3519-3530.
1003 <https://doi.org/10.1007/s13762-015-0774-5>

1004

- 1005 Said HK, Mostefa NM (2015) Optimization of Turbidity and COD Removal from Pharmaceutical
 1006 Wastewater by Electrocoagulation. Isotherm Modeling and Cost Analysis. Pol J Environ Stud 24 (3):
 1007 1049-1061. <https://doi.org/10.15244/pjoes/32334>
 1008
- 1009 Sakhel SR, Geissen SU, Vogelpohl A (2017) Virtual industrial water usage and wastewater generation in
 1010 the Middle East and North Africa 2011–2015. Euro-Mediterr J Environ Integr 2 (1): 1-18.
 1011 <https://doi.org/10.1007/s41207-017-0018-9>
 1012
- 1013 Sardari K (2018) Membrane-based Separation Processes for Treating High Salinity Produced Waters. PhD
 1014 Thesis, The University of Aransas,
 1015 <https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=4394&context=etd>, accessed 25 October
 1016 2021.
 1017
- 1018 Sharma, J R (2010) Development of a preliminary cost estimation method for water treatment plants.
 1019 MSc thesis, The University of Texas, Arlington. [https://rc.library.uta.edu/uta-](https://rc.library.uta.edu/uta-ir/bitstream/handle/10106/4924/Sharma_uta_2502M_10652.pdf?sequence=1)
 1020 [ir/bitstream/handle/10106/4924/Sharma_uta_2502M_10652.pdf?sequence=1](https://rc.library.uta.edu/uta-ir/bitstream/handle/10106/4924/Sharma_uta_2502M_10652.pdf?sequence=1). Accessed 3rd of
 1021 November 2019.
- 1022 Soares RB, Memelli MS, Roque RP, Gonçalves RF (2017) Comparative Analysis of the Energy
 1023 Consumption of Different Wastewater Treatment Plants. International Journal of Architecture, Arts and
 1024 Applications 3 (6): 79-86. <https://doi.org/10.11648/j.ijaaa.20170306.11>
- 1025 Sprick M (2017) Comparison of Options for Biosolids Dewatering. Water Environment School, Clackamas
 1026 Community College. [https://www.clackamas.edu/docs/default-source/degrees-](https://www.clackamas.edu/docs/default-source/degrees-certificates/departments-programs/wet-orwef---biosolids-comparison-of-biosolids-dewatering-options-(current).pdf?sfvrsn=5ba8d68_0)
 1027 [certificates/departments-programs/wet-orwef---biosolids-comparison-of-biosolids-dewatering-](https://www.clackamas.edu/docs/default-source/degrees-certificates/departments-programs/wet-orwef---biosolids-comparison-of-biosolids-dewatering-options-(current).pdf?sfvrsn=5ba8d68_0)
 1028 [options-\(current\).pdf?sfvrsn=5ba8d68_0](https://www.clackamas.edu/docs/default-source/degrees-certificates/departments-programs/wet-orwef---biosolids-comparison-of-biosolids-dewatering-options-(current).pdf?sfvrsn=5ba8d68_0), accessed 8 April 2021.

- 1029
- 1030 Sridhar R, Sivakumar V, Maran JP, Thirugnanasambandham K (2014) Influence of operating parameters
 1031 on treatment of egg processing effluent by electrocoagulation process, Int J Environ Sci Technol 11 (6):
 1032 1619-1630. <https://doi.org/10.1007/s13762-013-0301-5>
- 1033
- 1034 Srinivas T (2008) Environmental Biotechnology. New Age International (P) Limited, Publishers. New
 1035 Delhi.
- 1036
- 1037 Srivastav M; Gupta M; Agrahari SK; Detwal P (2019) Removal of Refractory Organic Compounds from
 1038 Wastewater by Various Advanced Oxidation Process - A Review, Curr Environ Eng 6(1): 8-16.
 1039 <https://doi.org/10.2174/2212717806666181212125216>
- 1040
- 1041 Tanyol M, Ogedey A, Oguz E (2018) COD removal from leachate by electrocoagulation process:
 1042 treatment with monopolar electrodes in parallel connection. Water Sci Technol 77 (1): 177–186.
 1043 <https://doi.org/10.2166/wst.2017.528>
- 1044
- 1045 Tetreault A (2003) Electrocoagulation Process for Wastewater Treatment. EC Pacific Pty Ltd.
 1046 [https://www.ampc.com.au/uploads/cgblog/id172/ENV_2003_Electrocoagulation_process_for_wastewa](https://www.ampc.com.au/uploads/cgblog/id172/ENV_2003_Electrocoagulation_process_for_wastewater_treatment.pdf)
 1047 [ter_treatment.pdf](https://www.ampc.com.au/uploads/cgblog/id172/ENV_2003_Electrocoagulation_process_for_wastewater_treatment.pdf). Accessed 15 March 2021.
- 1048
- 1049 The Hashemite Kingdom of Jordan Environment Statistics 2014-2015 (2018).
 1050 [https://unstats.un.org/unsd/environment/Compendia/Jordan_Environment%20Statistics,%202014-](https://unstats.un.org/unsd/environment/Compendia/Jordan_Environment%20Statistics,%202014-2015.pdf)
 1051 [2015.pdf](https://unstats.un.org/unsd/environment/Compendia/Jordan_Environment%20Statistics,%202014-2015.pdf). Accessed 28 March 2021.
- 1052

- 1053 Theobald D (2014) Math Solutions: Pump Performance And Efficiency Calculations.
1054 [https://www.wateronline.com/doc/math-solutions-pump-performance-and-efficiency-calculations-](https://www.wateronline.com/doc/math-solutions-pump-performance-and-efficiency-calculations-0001)
1055 [0001](https://www.wateronline.com/doc/math-solutions-pump-performance-and-efficiency-calculations-0001). Accessed 5 June 2020.
1056
- 1057 United States Environmental Protection Agency (US EPA) (1985) Estimating Sludge Management Costs,
1058 Water Engineering Research Laboratory. EPA/625/6-85/010.
1059
- 1060 US EPA (2012) Hazardous Waste Listings. A User-Friendly Reference Document.
1061 https://www.epa.gov/sites/production/files/2016-01/documents/hw_listref_sep2012.pdf, accessed 26
1062 February 2021.
- 1063 US EPA (1995) How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites. A
1064 Guide for Correction Action Plan Reviewers. EPA 510-B-95-007.
- 1065 Varank G, Erkan H, Yazıcı S, Demir A, Engin G (2014) Electrocoagulation of Tannery Wastewater using
1066 Monopolar Electrodes: Process Optimization by Response Surface Methodology. Int J Environ Res 8 (1):
1067 165-180.
1068
- 1069 Von Sperling M and Gonçalves RF (2007) Sludge characteristics and production. In: Andreoli CV, Von
1070 Sperling M, and Fernandes F (eds.) Sludge Treatment and Disposal. IWA Publishing, London-New York,
1071 pp. 4-30.
1072
- 1073 Wake H (2005) Oil refineries: a review of their ecological impacts on the aquatic environment. Estuar
1074 Coast Shelf Sci 62 (1-2): 131–140. <https://doi.org/10.1016/j.ecss.2004.08.013>
1075

- 1076 Wang S, Xu W, Cheng Z (2011) Method of removing recalcitrant organic pollutant, European Patent
1077 Office (EP2683660A1). <https://patents.google.com/patent/EP2683660A1/en>
1078
- 1079 Yuksel E, Gurbulak E, Eyvaz M (2012) Decolorization of a Reactive Dye Solution and Treatment of a
1080 Textile Wastewater by Electrocoagulation and Chemical Coagulation: Techno-Economic Comparison.
1081 Environ Prog Sustain 31 (4): 524-535. <https://doi.org/10.1002/ep.10574>
1082
- 1083 Zazouli MA, Taghavi M, Bazrafshan E (2012) Influences of Solution Chemistry on Phenol Removal From
1084 Aqueous Environments by Electrocoagulation Process Using Aluminum Electrodes. J Health Scope 1 (2):
1085 66-70. <https://dx.doi.org/10.5812/jhs.5462>
1086

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementarymaterialENPR1.docx](#)