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ORIGINAL ARTICLE

Predesign Cost Estimation of a Potential Wastewater Treatment Plant for Jordan Petroleum Refinery-Electrocoagulation

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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 min, Al/SS electrodes, and inter-electrode distance 10 mm. Overall treatment costs for the simulated wastewater was found to be 10.75 \$/m^3 (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 it for cut flower irrigation but could be treated to conform to the norms for using it 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.

Highlights
- An affordable overall treatment cost for Jordan refinery wastewater was found.
- Optimal pollutant removal efficiencies were achieved in electrocoagulation tests.
- During wastewater treatment the most stringent Jordanian norms were not reached.

Keywords Fixed capital investment · Working capital · Total capital investment · Electrocoagulation (EC) · Annual operating cost · Middle East and North Africa

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1 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 (e.g., 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 and environmental degradation, and reducing water withdrawal from either surface or ground waters (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 km^3/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 m^3 (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 among the most hazardous compounds released into the environment (Diyauddeen 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 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 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 is 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; Srivastav 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 $/m^3 (6.4 US $/kg $COD_{removed}$) and 1.45 US $/m^3 (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 €/m^3 (5.8 €/kg $COD_{removed}$) and 1.56 €/m^3 (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 $/m^3 (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 €/m^3 (1.6 €/kg $COD_{removed}$) and 4.732 €/m^3 (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/RuO_2) to be 189.1 US $/m^3 (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 aluminum electrodes under optimal conditions to be 2.7 US $/m^3 (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 aluminum electrodes under optimal conditions to be 6.22 US $/m^3 (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 aluminum electrodes to be 0.026 US $/m^3 (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 aluminum and iron electrodes under optimal conditions to be 1.54 US $/m^3 (0.82 US $/kg $COD_{removed}$) and 0.51 US $/m^3 (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 $/m^3 (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; Gaied et al. 2019) present capital and operating costs for plants that have a capacity ranging from 1 to 28 m^3/d; none of them present 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 undertaking 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 author's knowledge, there is no research available that talks about the treatment of Jordan refinery wastewater (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, such 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 (3840 m^3/d) 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 our 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?

Our paper is organized as follows: in "Definition of Important Terms", we define important terms; in "Methods and Materials", we describe the experimental set-up, synthetic petroleum refinery wastewater, measurement methods, and sludge characteristics; in "Estimation of Fixed and Operating Costs of EC Treatment Plant", we summarize the methodology used for the cost calculations; in "Results and Interpretations", we present our results; in "Discussion", we discuss them; and in "Conclusions", we end with conclusions.

2 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 Methods and Materials

3.1 Experimental Set-up

The treatment of synthetic JRWW 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 aluminum/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.

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 was 10 mm in the trials. A reaction batch of 4 L 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 finally rinsed with tap water to remove oxide and passivation layers. The consumption of energy was calculated using the following equation:

$$\text{Energy consumption}\left(\frac{\text{kWh}}{\text{m}^3}\right) = \frac{\text{V I t}}{\text{Treated Volume}} \tag{1}$$

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

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

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

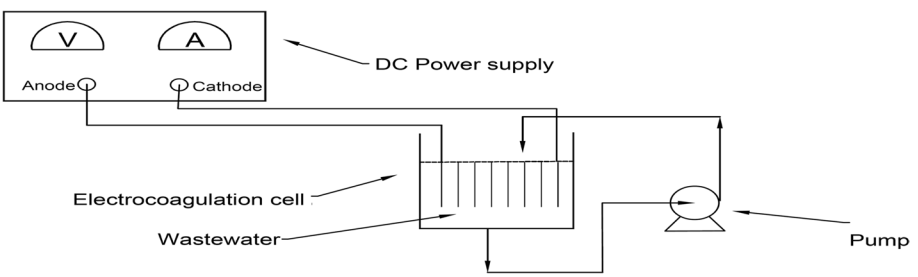

Fig. 1 Schematic diagram of the electrocoagulation cell in a bipolar connection mode

3.2 Synthetic Petroleum Refinery Wastewater

Synthetic petroleum refinery wastewater was prepared according to the concentrations of actual Jordanian refinery wastewater which was used as a reference. The different concentrations of real Jordan refinery wastewater that was only mechanically treated is shown in Table 1 along with the concentrations of the different parameters that were 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 (C_6H_5OH) was added, Na_2SO_4 was used to form total dissolved solids (TDS), sand was used to form total suspended solids (TSS), Potassium Hydrogen Phthalate ($C_8H_5KO_4$) 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 were of analytical grade.

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 was extracted from water with chloroform and the absorbance was 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 was used to determine the total alkalinity while the phenolphthalein indicator was used to determine the phenolphthalein alkalinity. TDS and TSS were determined by gravimetric methods, FOG were determined by acidifying the synthetic wastewater sample to a 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 was distilled from the extract and the residue was desiccated and weighed. COD was determined by the open reflux method, the dissolved oxygen (DO) was determined by titrimetric procedure (iodometric test), and consequently, BOD was calculated from

Table 1 Characteristics of actual and synthetic Jordan refinery wastewater

Parameter	Actual Jordan 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

[a]The Hashemite Kingdom of Jordan Environment Statistics 2014-2015 (2018); [b]This work

determined DOs, while pH was determined using a digital pH meter (Ultratech). Sludge production (metal hydroxide flocs and removed pollutants) were 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. It was then allowed to settle and the volume of compacted sludge was reported at 0, 10, 20, and 30 min in the presence and absence of a flocculating agent. SSV30 and Sludge Volume Index (SVI) have been determined as follows: (1) the sludge was allowed to settle for a period of 30 min and the volume of sludge recorded at this time is the SSV30; (2) the SVI was calculated using the following formula:

$$\mathrm{SVI}\left(\frac{\mathrm{mL}}{\mathrm{g}}\right) = \frac{\mathrm{SSV30}\left(\frac{\mathrm{mL}}{\mathrm{L}}\right)}{\mathrm{TSS}\left(\frac{\mathrm{g}}{\mathrm{L}}\right)} \tag{3}$$

The TSS (Mixed Liquor Suspended Solids; MLSS) of the treated wastewater was determined gravimetrically and used in the SVI calculation.

4 Estimation of Fixed and Operating Costs of EC Treatment Plant

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

a) Selection of the major items of equipment:

1- *Selection of the sludge dewatering machine*: Capital, operation, and maintenance costs have been estimated for the most prominent techniques used in sludge dewatering by using appropriate cost equations taken from Sharma (2010). The decanter centrifuge was selected for dewatering the sludge generated from EC treatment of JRWW since it had the lowest capital, operation, and maintenance costs among all outstanding techniques considered.
2- *Selection of core of the JRWW TP*: EC reactors have been selected for the core of the JRWW Treatment Plant (TP) due to several reasons; some of them are:

- EC is most commonly used in the oil and gas industry to remove emulsified oil, total petroleum 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 the absence of 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 was also selected.

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

b) % dry solids content of sludge resulting from the treatment of JRWW through EC:

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

$$\text{Sludge flow}\left(\frac{\text{m}^3}{\text{day}}\right)=\frac{\text{dry solids load}\left(\frac{\text{kg}}{\text{day}}\right)}{\left(\frac{\text{dry solids\%}}{100}\right)\left(\text{Sludge density}\left(\frac{\text{kg}}{\text{m}^3}\right)\right)} \tag{4}$$

The volumetric sludge generation rate (sludge flow) has been determined based on sludge settling tests while the sludge/slurry density and the dry solids load (sludge production) have been determined experimentally to be 956 kg/m^3 and 2.9 kg dry solids/m^3 based on gravimetric methods.

iii) Hydraulic mixing pump capacity and mixing power:

The mixing pump capacity in the concrete slurry tank and UST as well as the mixing power in the aforementioned tanks was calculated according to Eqs. (5) and (6), respectively (US EPA 1985):

$$\text{Mixing pump capacity}\left(\text{m}^3\ \text{per}\ \text{min}\right)=\frac{(\text{MP})\ (6.1183)}{(\text{EF})\ (\text{TDH})\ (956)} \tag{5}$$

where MP is the mixing power (W); EF is the efficiency of mixing pump with default value = 0.7 (US EPA 1985) (dimensionless); TDH is the total dynamic head of the pump

Table 2 Major items of equipment selected for the electrocoagulation treatment plant

Number	Major equipment name
1	3 EC reactors
2	3 (53.3 m^3/h) feeding pumps to EC reactors
3	3 Tanks (each tank adjacent to an EC reactor)
4	3 (53.3 m^3/h) slurry pumps (plus 3 standby)
5	1 Concrete slurry tank
6	1 Hydraulic mixing pump for concrete slurry tank
7	2 (80 m^3/h) 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/h)
12	1 Polymer station
13	1 Decanter centrifuge

with default value = 7.62 m (US EPA 1985) (m); 956 is the density of sludge (kg/m^3); and 6.1183 is the conversion factor to convert Watts to kg-m/min.

MP is given by

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

where

ME is the mixing energy (W/m^3); and sludge volume is its volume (m^3).

iv) Decanter centrifuge cake volumetric flow rate estimation:

The estimation of this quantity from decanter centrifuge was based on Eqs. (7), (8) and (9) (Records and Sutherland 2001; Celenza 2000):

$$\text{Mass flow rate of solids to decanter} = \text{Mass flow rate of cake solids} + \text{Mass flow rate of centrate solids} \tag{7}$$

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

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

where Q_f is the volumetric flow rate of sludge to decanter (m^3/d); x_f is the solids fraction in sludge in influent to decanter (dimensionless); ρ_f is the density of sludge (kg/m^3); Q_p is the volumetric flow rate of flocculant (m^3/d); x_p is the solids fraction in flocculant in influent to decanter (dimensionless); ρ_p is the density of flocculant (kg/m^3); Q_{ca} is the volumetric flow rate of cake (m^3/d); x_{ca} is the solids fraction in cake (dimensionless); ρ_{ca} is the density of cake (kg/m^3); Q_c is the volumetric flow rate of centrate (m^3/d); x_c is the solids fraction in centrate (dimensionless), and ρ_c is the density of centrate (kg/m^3). Recovery of solids is the % of feed solids captured in the cake.

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

These have been estimated using respectively Eqs. (10) and (11) (McFarland 2000):

$$\Delta P = \frac{2\, f\, \rho\, L\, V^2}{D} \tag{10}$$

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

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

f) Net positive suction head (NPSH):

The net positive suction head available (NPSHa) has been calculated using Eq. (12):

$$\mathrm{NPSHa} = Z + \frac{P_a}{\rho g} - \frac{P_{vp}}{\rho g} - h_f \tag{12}$$

where NPSHa (m); Z the difference between the pump impeller eye level and the suction water level (m); P_a the absolute atmospheric pressure (N/m^2); P_{vp} the absolute vapor pressure of the fluid at pumping temperature (N/m^2); ρ the density of fluid (kg/m^3); g the acceleration of gravity (m/s^2); and h_f is the head lost in the suction pipework (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 to keep the pump from cavitating (NPSHr). However, in practice there should be an additional head added to NPSHr which acts as a buffer against uncertainties of pumping. Thus, to avoid pump cavitation the following should apply:

$$\mathrm{NPSHa} \geq \mathrm{NPSHr} + \text{additional head} \tag{13}$$

where

NPSHa, NPSHr, and the additional head are all (m).

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 ±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 pieces of equipment only.

1- *Power costs for running the pumps*: The power costs for running the pumps have been calculated using Eqs. (14) and (15) (Giorgi 2009; Neutrium 2012):

$$\text{Motor power (kW)} = \frac{Q\,\rho\,g\,h}{\left(3.6 \times 10^6 \times \text{Motor efficiency} \times \text{Pump efficiency}\right)} \tag{14}$$

$$\text{The cost in } \frac{\text{US\$}}{\text{yr}} \text{ for running the pumps} = \text{Motor power} \times \text{operating hours per year} \times 0.154\ \frac{\text{US \$}}{\text{kWh}} \times 1.175 \tag{15}$$

where Q is the flow rate (m^3/h); ρ the density of fluid (kg/m^3); g the gravitational acceleration constant (9.81 m/s^2); and h is the head of the pump (m). Further, Motor efficiency × Pump efficiency = wire to water efficiency (dimensionless) (Theobald 2014).

2- *Power costs for running the decanter centrifuge*:

For calculating the power costs we used Eq. (16):

$$\text{Annual costs for running decanter centrifuge}\left(\frac{\text{US \$}}{\text{yr}}\right) = \text{decanter centrifuge motor power} \times \text{operating hours per year} \times 0.154\frac{\text{US \$}}{\text{kWh}} \times 1.175 \tag{16}$$

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

3- Power costs required for running the EC reactors was estimated by first calculating the energy consumption in kWh/m^3 using Eq. (1) and then power costs were determined as follows:

$$\begin{aligned}&\text{Annual costs for running the 3 EC reactors}\left(\frac{\text{US \$}}{\text{yr}}\right)\\&= \text{energy consumption}\left(\frac{\text{kWh}}{\text{m}^3}\right) \times \text{total wastewater flow rate}\left(\frac{\text{m}^3}{\text{yr}}\right)\\&\times 0.154\,\frac{\text{US \$}}{\text{kWh}} \times 1.175\end{aligned} \tag{17}$$

5 Results and Interpretations

5.1 Experimental Results

5.1.1 Changing Electrode Material

In EC experiments, one of the important factors that determine the efficiency of the process is the type 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 inexpensive (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.

The results in Tables 3 and 4 have been developed 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 this reason, we are concentrating in the following sections only on the results relevant to using Al/SS electrodes that are also used in our cost calculations.

Table 3 Best results of treatment of synthetic refinery wastewater using aluminum and stainless steel electrodes at a current of 10 Amp, voltage of 28 to 31, inter-electrode distance of 10 mm, and 5 min 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 (ppm)	715.5	36.81	94.9	400	400
Phenol (ppm)	0.03	ND[a]	At least 96.7	Less than 0.002	Less than 0.002
TDS (ppm)	5210				
Fat, oil, and grease (FOG) (ppm)	8.5	ND[b]	At least 98.8	8	2
TSS (ppm)	66	48	27.3	50	15
COD (ppm)	472	73.4	84.4	100	50
BOD_5 (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 stainless steel electrodes at a current of 10 Amp, voltage of 27 to 35, inter-electrode distance of 10 mm, and 10 min 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 (ppm)	715.5	411	42.6	400	400
Phenol (ppm)	0.03	0.01	66.7	Less than 0.002	Less than 0.002
TDS (ppm)	5210				
Fat, oil, and grease (FOG) (ppm)	8.5	0.10	98.8	8	2
TSS (ppm)	66	6.1	90.8	50	15
COD (ppm)	472	23.6	95.0	100	50
BOD_5 (ppm)	56	8.4	85.0	30	15
pH	9.36	8.86		6 to 9	6 to 9

Table 5 Settling tests of the electrocoagulated water using aluminum/stainless steel electrodes in the absence of ANAFLOC

Time (min)	Settled sludge volume (mL/L)
0	1000
10	148
20	128
30	120

Table 6 Settling tests of the electrocoagulated water using aluminum/stainless steel electrodes in the presence of ANAFLOC

Time (min)	Settled sludge volume (mL/L)
0	1000
10	168
20	160
30	152

Table 7 Annual power costs for Jordan refinery wastewater electrocoagulation treatment plant 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	6468	193.51	$kWh/(m^3.yr)$	0.39
Two Lamella clarifiers flash mixers	592	96.75		0.036
Polymer station	3173	2.94	kWh/m^3	0.19
Decanter centrifuge	47,303	1.34		2.87
Total	1,647,296			

5.1.2 Sludge Settling Tests and Production

The settling tests of the electrocoagulated water (using Al/SS electrodes, a current of 10 Amp, 28 to 31 Volt, and 5 min reaction time) have 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 min in the absence and presence of the flocculating agent, respectively.

The 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 m^3 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 and the % dry solids content of the sludge after pressing has been determined gravimetrically to be 25%. A lab screw press has been used in our experiments because this 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/m^3 or kWh/(m^3.yr) and proportion of costs in %. For JRWW, it turns out to be 1,647,296 US $ per year. 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). Figure 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 a decanter centrifuge. In the latter, 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.

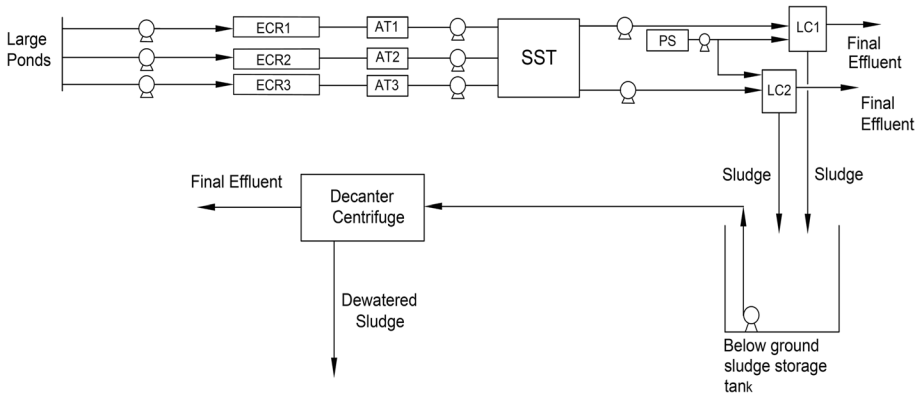

Fig. 2 Electrocoagulation treatment plant schematic. Abbreviations are as follows: ECR stands for electrocoagulation reactor, AT stands for adjacent tank, SST stands for slurry storage tank, PS stands for polymer station, LC stands for lamella clarifier

Table 8 Annual costs of the raw materials required for the Jordan refinery wastewater electrocoagulation plant for the year 2022

Raw material	Cost (US $/yr)	Consumption (g/m^3)[a]
ANAFLOC flocculant	8732	1
Aluminum	56,544	8.6
Stainless Steel	7075	6.4
Total	72,351	

[a]Determined experimentally

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.

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).

Table 9 Major items of equipment cost used in the Jordan refinery wastewater electrocoagulation treatment plant 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

Table 10 Different capital-investment item costs for a fluid processing plant based on delivered-equipment cost

Item	Capital cost (US $)	Percent 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

Table 11 Different expense estimates that includes operating cost in US $/yr and overall cost for 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

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%.

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 and 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 \$/m^3 (26.97 US \$/kg non-biodegradable $COD_{removed}$).

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/cm^2, NaCl = 1 g/L, Temperature = 25 °C) using Al material as anode and cathode managed to completely remove phenol from a synthetic solution with an initial phenol concentration of 5 mg/L in a period of 30 min. In our experiments, we managed to remove at least 96.7% of phenol from synthetic wastewater that had an initial phenol concentration of

Table 12 Comparison of the results of Bazrafshan et al. (2012) and Zazouli et al. (2012) to the present work

Electrode material	Current density (A/m^2)	Current (A)	Treatment time (min)	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

0.03 mg/L at optimum conditions in a period of 5 min. 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 its removal percentage from 100 to 75%. Moreover, a higher current density of 268.2 A/m^2 was used in our experiment at optimum conditions than that of El-Ashtoukhy et al. (2013) (85.9 A/m^2). This contributes to more dissolution of Al and SS (iron) electrodes according to Faraday's law such that the ions of Al and Fe undergo hydrolysis producing Al and Fe hydroxides on which phenol is adsorbed. As a result 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 our results with those of Bazrafshan's and Zazouli's. It can be seen that we needed 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.

6.1.2 Removal of FOG

The FOG percent 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 aluminum material as anode and cathode at a pH of 3.6, current density of 80 A/m^2, inter-electrode distance of 0.5 cm, and a treatment time of 20 min. Liu et al. (2019) studied the oil removal percentage from simulated produced water relevant to oilfields through EC using aluminum (anode) and iron (cathode) electrodes. At optimum conditions (pH = 7, current density = 40 A/m^2, treatment time = 28 min), 70.2% of the oil was removed. GilPavas et al. (2009) reported the treatment of oily wastewater from automotive industry through EC using iron/aluminum as anode/cathode and vice versa. At optimum conditions (Fe as anode, pH =12, current density = 43 A/m^2, treatment time = 180 min) 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 min). Compared to all the aforementioned investigations, the present work has a higher FOG removal percentage at a shorter reaction time and a higher current intensity (10 A) or density (268.2 A/m^2).

6.1.3 Removal of COD

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

Table 13 Chemical Oxygen Demand (COD) removal of this work compared to other literature work

Electrode material	Current density (A/m^2)	Current (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, only Drogui et al. (2009) 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 min (optimum conditions), 89.4% of the BOD was removed. We however, 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

Only two previous investigations (Sardari 2018; Drogui et al. 2009) measured the TSS removal from oily wastewater after EC treatment in bipolar configuration. Sardari (2018) treated produced water using aluminum electrodes at a current of 3 A and a treatment time of 30 s achieving a TSS removal of 91%. Drogui et al. (2009) reported a 31.5% TSS removal from oily ship effluents using aluminum electrodes at a current of 0.3 A and a treatment time of 60 min. In this work, we achieved a TSS removal of 27.3%.

6.1.6 pH

The 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 was reduced to 8.66. This 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):

$$\mathrm{Al\,(OH)_3 + OH^- \rightarrow \quad Al\,(OH)_4^-}$$

6.1.7 Removal of Bicarbonate

This work at optimum conditions demonstrates a bicarbonate removal of 94.9%. In the literature, there are no previous studies that mention 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 g of sludge after 30 min 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 Tables 5 and 6 to be 41.4 and 52.4 mL/g, respectively. It is reported in the 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

Table 14 Pollutant removal capacities relevant to using aluminum/stainless steel electrodes

Pollutant	g pollutant removed/g hybrid metal (HM)	mg pollutant removed/C
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

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 min of settling time, whether polyacrylamide (PAM) cationic flocculant ANAFLOC 6691 was used or not. However, the use of the polymer flocculating agent (at a concentration of 0.001 g/L) resulted in more solids sedimentation and in a larger value of SSV30 (152 mL/L). Therefore, the results of Table 6 were used in 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 is for bicarbonate followed by COD.

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 approximate capital and operating costs. It was a preliminary economic evaluation partially based on experimental bench-scale data previously shown 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). The method here 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 were not based on percentages (e.g., maintenance and repairs are 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. The estimated electrical power consumption relevant to mixing and pumping is 237,481 kWh/yr and for electrocoagulation reactors we have based our calculations on bench-scale experimental data. The voltage and current during electrocoagulation experiments resulting in COD, BOD, TSS, FOG, phenol, and HCO_3 removals such that the treated effluent concentrations of the previous

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

Type of wastewater	Flow rate (m^3/h)	2022 Treatment costs (US \$/m^3)	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]	

[a]Estimations based on data from Tetreault (2003) which included metal and power consumption as the only operating costs. [b]Based on data from Eames et al. (2017) which included power, chemicals, and metal consumption as the only operating costs. [c]Based on data from Eames et al. (2017) which included power, labor, and treatment consumables as the only operating costs. [d]Considering only metal and power consumption as the operating costs for comparing with stick/blood slaughterhouse wastewater treatment costs of Tetreault (2003). [e]Considering only power, chemicals, and metal consumption as the operating costs for comparing with mineral mining/processing wastewater treatment costs of Eames et al. (2017). [f]Considering only power, labor, and treatment consumables as the operating costs for comparing with oil/gas extraction wastewater treatment costs of Eames et al. (2017)

parameters are at or below the Jordanian norms required for its possible use for irrigation were 29.5 V and 10 A. The unit electricity requirement for EC reactors is 6.15 kWh/m^3.

Sludge resulting from petroleum refinery wastewater treatment is considered as hazardous (US EPA 2012) and in this paper 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 the Russaifah disposal site. Estimated cost 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 to be 10.75 US \$/m^3 (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 m^3/h). 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 of our treatment costs with those of other works from the literature. It can be seen that our treatment cost is of the same order of magnitude as that of Eames et al. (2017), but an order of magnitude higher than that of Tetreault (2003). Therefore, the cost figures of this work are reasonable.

The 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 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 the cost of EC reactors, UST, UST HMP, concrete slurry tank, concrete slurry tank HMP, decanter centrifuge/polymer station, and

Table 16 Initial and updated values of the cost indices used in the present 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	1274.8[a]	1878.39	–	–	–	–
3 feeding pumps to EC reactors	–	–	389.5	685.66	–	–
2 Lamella clarifiers	1735.78[b]	1878.39				
UST	–	–	–	–	4006[c]	11,971
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]	11,971
Concrete slurry tank	–	–	325.8[g]	685.66	–	–
Adjacent tanks to EC reactors	–	–			–	–

[a]Annual average value for the year 2006 [b] Annual average value for the year 2019, [c]March, 1983, [d]Annual average value for the year 2021 [e] Annual average value for the year 2020, [f]Updated values are annual average values for the year 2022, [g]October, 1985, [h]September, 2009

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 indices are specifically the Marshal and Swift equipment, Chemical Engineering Plant, and Engineering News Record Construction Cost indices (Baasel 1990; Peters et al. 2003; Nouri A (personal communication, December 2019); Universidad De Los Andes, Lousada 2006; Jenkins 2018; Zevin 2019). The initial and updated values of the indices used are shown in Table 16.

The ratio factors mentioned in Table 10 are used for estimating the capital cost of a fluid processing plant such as distillation units as well as water and wastewater treatment plants (Awad and Abuzaid 1997). Since we are dealing with a wastewater treatment plant, the factors for a fluid processing plant have been selected as listed in Table 10. The EC TP for JRWW (160 m^3/h) had estimated total capital investment and annual operating costs of 31,377,442 and 11,668,986 US $, respectively. For comparison, a conventional activated sludge system treating on average 200 m^3/h of domestic wastewater can have construction and annual operating costs 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 aforementioned 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 both treatment systems are of the same order of magnitude, but operating costs for the EC TP are two orders of magnitude higher. Jordan refinery can finance such a project since its profit is about twice 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 lower several expense-estimation items that are relevant to operating costs. The latter results in the lowering of the overall cost for JRWW treatment. Additionally, if the 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 the 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 including 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 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. This study outlined a process that can be used to treat refinery effluent. Details of chemical and equipment requirements as well as the costs relevant to such a process have been presented. The technology used here to reclaim refinery wastewater was electrocoagulation, which is an enigmatic technology for which we still do not know its full potential. Based on the available literature, there are only a few companies that applied this technology at a full scale. Hence, the results of this research could encourage companies to apply such a technology in future treatment of their industrial effluents. It has been shown that the overall cost for treatment using EC technology may be high, but future development in this technology will probably reduce overall costs further which may lead to its application on a wider scale. Third-world countries lack suitable infrastructure and required capital investments for wastewater treatment plants. They require wastewater treatment technologies that can be easily operated, with minimal operation/maintenance capital expenditure and required skilled labor. The EC technology has all the aforementioned characteristics and can be considered as an option for the treatment of refinery 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). Hence, it is a suitable technology for the treatment of JRWW and the cost for its treatment is affordable.

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Declarations

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