Domestic wastewater treatment by real-scale electrocoagulation process

Serdar Koyuncu and Sema Arıman

ABSTRACT

In this study, domestic wastewaters originating from a settlement with a population of 17,500 were treated by electrocoagulation process in a real-scale EC plant and the economic applicability of the process was investigated. The removal efficiencies of control parameters in the influent and effluent of the real-scale treatment plant such as suspended solids (SS), biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and changes of pH and conductivity parameters were monitored for 12 months. The obtained data were evaluated according to European Urban Wastewater Treatment Directive, Turkish Water Pollution Control Regulation and Turkish Urban Wastewater Treatment Regulation. According to the results obtained, the removal efficiencies of the pollutant parameters were achieved in the range of 72–83% for SS, 67–80% for COD, 69–81% for BOD, 21–47% for TN and 27–46% for TP. Considering the Turkish wastewater discharge regulations, it can be concluded that the discharge standards for SS, COD and BOD parameters were achieved while they were not achieved in certain periods for TN and TP. In addition, the energy consumption and the operating cost of this real-scale plant were determined to be 0.49–0.54 kWh/m^3 and 0.24–0.28 EUR/m^3, respectively.

Key words | cost evaluation, electrocoagulation, wastewater treatment

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INTRODUCTION

One of the most important factors constituting environmental pollution is the discharge of wastewater to receiving environments without any treatment. The industrial and domestic wastewaters that need treatment in terms of human and environmental health are treated by means of various processes. Some of these processes are physical, chemical, biological, physicochemical, or electrochemical methods. The most important parts of the operating expenses of wastewater treatment plants are energy and chemicals. There is an increasing tendency to consider alternative processes where the same treatment efficiency will be achieved but with low operating costs such as energy, chemicals and personnel (Vepsalainen 2012).

The electrocoagulation (EC) process is one of the alternative treatment methods which is gaining importance for domestic wastewater treatment. In the last decades, different wastewaters were effectively treated by EC process. Such methods have been found to be successful in removing many contaminants from water such as lignin, phenol, heavy metal ions and anionic dyes (Aoudj *et al.* 2010; Butler *et al.* 2011; Valero *et al.* 2011; Vasudevan & Lakshmi 2011; Al-Shannag *et al.* 2013; El-Naas *et al.* 2014; Mohora *et al.* 2014; Pulkka *et al.* 2014; Esfandyari *et al.* 2015; Kobya & Demirbaş 2015; Bibi *et al.* 2017; Naji *et al.* 2017). Especially the high efficiency, environmental friendliness and versatility properties of the process have led to great progress in the removal of the bio-refractory materials in wastewater treatment (Juttner *et al.* 2000; Brillas *et al.* 2009). In addition, the EC processes have great contributions to reduction of the suspended solids (SS), total dissolved solids, chemical oxygen demand (COD), and biological oxygen demand (BOD) in the wastewater. Especially, many previous researches have shown that the EC method is an alternative approach for the removal of heavy metal ions such as chromium, copper, nickel, arsenic, zinc, manganese, mercury, cadmium, lead, silver, iron and boron from industrial wastewater (Zaroual *et al.* 2006; Nanseu-Njiki *et al.* 2009; Akbal & Camcı 2011; Sridhar *et al.* 2011; Wan *et al.* 2011; Al Aji *et al.* 2012; Varank *et al.* 2014; Al-Shannag *et al.* 2015; Bazrafshan *et al.* 2015;

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Mahmad *et al.* 2015; Bazrafshan *et al.* 2016; Hashim *et al.* 2017).

One of the main advantages of EC is avoiding the use of chemical additives (except possible NaCl addition), which makes the EC process a 'green technology'. Indeed, 'electron' can be considered as the only 'chemical' and this can prevent secondary pollution (Kuokkanen 2016). The EC process has also been used for the improvement of the ground water and surface water at different locations, because of its wide applicability (Joffe & Knieper 2000). This means ease of application, reduced sludge production, and no need of chemicals. The EC process has been applied effectively in different water treatment problems (Rajeshwar & Ibanez 1997; Aswathy *et al.* 2016; Ensanoa *et al.* 2019; Maitlo *et al.* 2019).

The EC process is composed of a power source, an anode and a cathode immersed in an electrolyte. When power is applied from an external source, the anode undergoes oxidation and the cathode undergoes reduction. In this case, the anode will be electrochemically dissolved and the cathode will be passivated. For the adequate dissolution of the metal electrodes, the electrodes must have large surface area and there must be enough distance between the electrodes. In EC process, iron, stainless steel, and aluminium electrodes are the most commonly used. These electrodes are preferred because of their low cost, easy availability, and proven efficiencies (Chen *et al.* 2000). The parameters affecting the process efficiency in EC application are listed as follows: current density, the presence of NaCl in the solution as electrolyte, conductivity electrodes, reaction period pH, and ambient temperature.

The general mechanism of electrochemical treatment processes includes coagulation, adsorption, absorption, precipitation, and flotation processes (Ihara *et al.* 2004). The EC process is based on the treatment of wastewater pollutants with physicochemical processes. Treatment process is by the integration of the oxidation, flocculation, and flotation processes. In addition, because of the use of chloride salt (NaCl) as an electrolyte, chlorine gas (Cl_2) is formed at the anode by the oxidation of chloride, and therefore if the pH value is stabilised between 6 and 8, disinfection effect is also observed with hypochlorous acid (HOCl) in the treated water (Chen 2004; Mollah *et al.* 2004).

The EC process is extensively used for the treatment of different waters and wastewaters and for the removal of inorganic contaminants and pathogens. There are a number of studies in the literature regarding the applications of EC process for wastewater treatment either at laboratory or in pilot scale in batch/continuous conditions (Zolotukhin 1989; Calvo *et al.* 2003; Fenga *et al.* 2003; Holt *et al.* 2005; Den & Huang 2006; Bukhari 2008; Rodrigo *et al.* 2010; Attour *et al.* 2014; Moussa *et al.* 2017). Applications of electroflocculation/EC methods which are used in the treatment of industrial wastewaters are also increasing in the treatment of domestic wastewaters (Lacasa *et al.* 2019). There are many laboratory- and pilot-scale studies on this area. However, in the wastewater treatment plants (WWTPs), it is important to determine the effects of operational parameters on treatment performance at real scale, in order to evaluate the applicability of the process. The purpose of this study is to determine the treatment efficiency, the energy consumption and operation cost of the EC process when the process is applied for a real-scale domestic WWTP.

MATERIALS AND METHOD

Real-scale EC treatment plant

This study was carried out in a real-scale WWTP with a capacity of 2,400 m^3/day, which includes the EC process for the treatment of domestic wastewater from a settlement with a population of 17,500. The wastewater plant consists of screens, equalization tank, EC reactors, filtration unit, treated wastewater tank, and filter press. The flow diagram of the wastewater treatment process is given in Figure 1. The process was monitored by a full

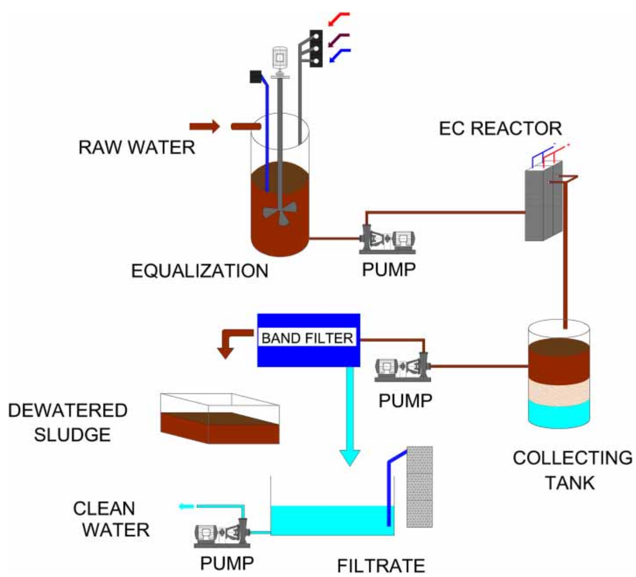

Figure 1 | Wastewater treatment plant with EC process.

automation supervisory control and data acquisition system. The system has instruments for measuring pH, conductivity, ambient temperature, water levels, flows, and pressure.

In the treatment plant, removal of solid material and the physical treatment of wastewater were performed by means of screens. In order to prevent the changes of flow and to provide steady flow to the system, the wastewater was stored in an equalization tank. NaCl was added to the wastewater before the EC reactor to achieve optimum conductivity; then wastewater was transferred to the EC reactor. The operating conditions of the EC reactor are given Table 1. Iron was used as electrode material in the EC reactor. The residence time of wastewater in the EC reactor was 5–6 minutes. The current was between 90 and 120 A and the voltage was around 400 V. In the EC reactor, the iron hydroxides formed as a result of the dissolution of the iron anode cause flocculation, and the hydrogen gas bubbles formed in the cathode float the flocculated sludge. This slurry was removed from the surface and the sludge–liquid mixture was filtered through a band filter. The filtered water was passed through sand filter and transferred to the treated wastewater tank. The sludge cake was disposed of.

ANALYTICAL METHODS

The treatment efficiency of the WWTP with a real-scale EC process has been investigated. In order to determine the seasonal changes of the treatment efficiency, the treatment plant was monitored for 12 months. During this period, composite samples were taken every 10 days and the basic control parameters were analysed in order to determine the raw and treated wastewater characterization (Ministry of Environment and Forestry 2010). The collected data have been evaluated for minimum, maximum, and monthly average values and the efficiency of the process was determined. During this research, the analysis methods of the basic parameters are as follows; wastewater flow rate: flowmeter with area velocity method, pH: SM 4500-H B method, temperature: SM 2550 B method, conductivity: SM 2510 B method, SS: SM 2510 B method, COD: SM 5250 C closed reflux method, BOD: SM 5210 B method, TN: SM 4500 NB method, TP: SM 4500 PB method (Rice & Baird 2017). The analysis was repeated at least twice and the average values were used.

Table 1 | The operating conditions of the EC reactor

Total reactor volume	7.5 m^3
Retention time	5–6 min
Electrode material	Iron
Electrode number	80
Electrode area	1.15 m^2
Current density	80–102 A/m^2
Applied current	90–120 A
Voltage	400 V

RESULTS AND DISCUSSION

Evaluation of treatment efficiency of EC process

In this study, the changes in basic parameters such as raw wastewater flow rate, SS, BOD, COD, TN, TP, conductivity and pH which affect the efficiency of the real-scale EC plant treating domestic wastewater were monitored and efficiency of EC process was determined. Analysis results of domestic wastewater quality parameters and receiving environment discharge limit values (Urban Wastewater Treatment Regulation 2006; Water Pollution Control Regulation 2008) are given in Table 2. According to monthly average values, it was determined that raw wastewater was generally dilute wastewater having domestic properties. The temperature of raw wastewater was around 15–24 °C, which can be accepted as the ideal values.

The raw wastewater flow rate was in the range of 1,803–2,075 m^3/day with an average of 1,907 m^3/day. Due to the operation of the existing sewerage system as a combined system, an increase in the flow rate was observed in rainy periods and in the summer months when the mobile population was the highest (Figure S1, Supplementary Material). Because of the modular structure of the treatment plant, the number of reactors operated also varied according to flow changes and the efficiency of the process was not affected even in excess flow conditions.

The pH value of raw wastewater was measured in the range of 7.5–7.9 with an average of 7.7. Since the influent pH values were neutral, the system was operated without any pH adjustment. In this study no significant pH change was observed in the influent and effluent of the EC reactor. The pH, which is an important parameter in terms of efficiency in the EC process, should be in the range of 6–9 (Figure 2). Ferrous ions are only oxidized to ferric ions if the pH is above 5 even though complete oxidation only occurs at pH around 8–9 (Malakootian *et al.* 2010; Vepsalainen 2012; Gatsios *et al.* 2015). At highly alkaline

Table 2 | Analysis results of some parameters and process efficiency

Parameter	Raw wastewater			Treated wastewater			Removal efficiency %			Turkish discharge limits
	Average	Min	Max	Average	Min	Max	Average	Min	Max	
Flow (m^3/day)	1,907	1,803	2,075	–	–	–	–	–	–	–
T (°C)	20	15	24	–	–	–	–	–	–	–
pH	7.7	7.5	7.9	7.6	7.4	7.8	–	–	–	6–9[a]
Conductivity (μS/cm)	2,284	1,799	2,679	2,267	1,784	2,544	–	–	–	–
SS (mg/l)	158	138	244	35	29	42	78	72	83	45[a]
COD (mg/l)	277	194	401	74	62	123	73	67	80	140[a]
BOD (mg/l)	163	120	250	36	24	48	77	69	81	50[a]
TN (mg/l)	38.8	30.5	47.7	24.2	17.4	29.6	37	21	47	15[b]
TP (mg/l)	3.8	3	5.5	2.3	1.5	3.1	38	27	46	2[b]

[a]Water Pollution Control Regulation (2008).
[b]Urban Wastewater Treatment Regulation (2006).

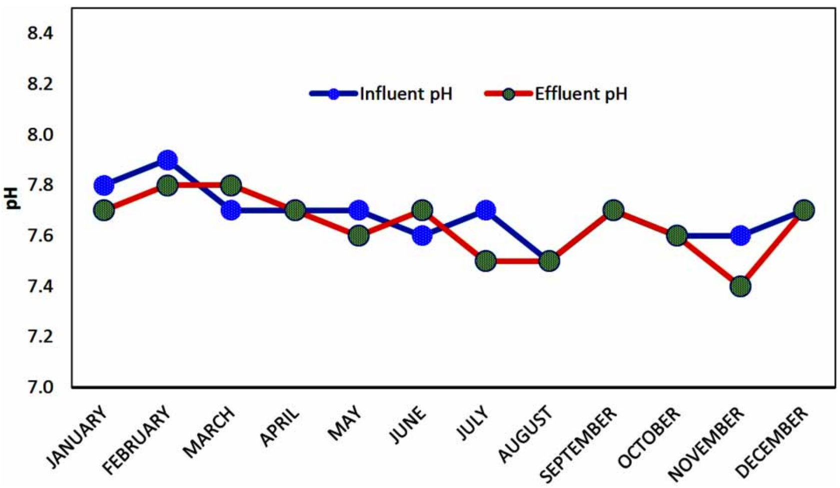

Figure 2 | Variation of influent and effluent pH values.

pH, undesired $Fe(OH)_4^-$ forms, which is a weak coagulant and deteriorates EC performance (Lakshmanan *et al.* 2009; Vepsalainen 2012). It is therefore concluded that the optimum operating pH range of iron EC is 5–9. In electrochemical treatment systems, the wastewater should have a certain conductivity value. In some cases, supporting electrolyte was added in order to increase the electrical conductivity. For domestic wastewaters NaCl is generally used as an electrolyte (Yang & Dluhy 2002). The electrical conductivity was increased by adding 0.05 kg NaCl/m^3 to the wastewater. In order to provide better flocculation, 0.002 kg/m^3 cationic polyelectrolyte was also added to the wastewater. During the research period, raw wastewater conductivity was measured between 1,799 and 2,679 μS/cm with an average of 2,284 μS/cm, and treated wastewater conductivity was between 1,784 and 2,544 μS/cm with an average of 2,267 μS/cm (Figure S2, Supplementary Material).

The influent SS concentration was 158 mg/l and the effluent SS concentration was 35 mg/l on average. It is seen that the SS value in March increased considerably (approximately 100 mg/l) unlike the rest of the year. This is related to the high amount of precipitation in March 2017. An increase in SS value was observed as a result of the sweeping of SS into the sewer network. The SS removal efficiency of the process was determined in the range of 72–83% with an average of 78%. The treatment plant effluent

SS concentration was found to achieve the receiving environment discharge standard (≤45 mg/l) specified in the Turkish Water Pollution Control Regulation (2008) (Figure 3).

Influent COD concentration varied between 194 and 401 mg/l and effluent COD concentration varied between 62 and 123 mg/l. The COD removal efficiency of the process was between 67–80% and 73% on average. COD concentration was found to achieve the receiving environment discharge standard (≤140 mg/l) (Water Pollution Control Regulation 2008) (Figure 4). Yang *et al.* (2008) studied EC/electroflotation processes and reported that COD removal can be achieved. Ilhan *et al.* (2008), in their research in Istanbul Yenikapi domestic WWTP, stated that 60% COD and 70% SS were removed from domestic wastewater by EC process with iron–iron electrodes. In EC process, the responsible mechanism for COD removal is adsorption of organic compounds in wastewater by colloidal $(Fe(OH)_3)_m$ or $(Fe(OH)_2)_p$ adsorbents (Smoczynski *et al.* 2014). Influent BOD concentration varied between 120 and 250 mg/l and effluent BOD concentration varied between 24 and 48 mg/l as shown in Figure 5. The BOD removal efficiency was in the range of 69–81% with an average of 77%. The BOD concentration was also determined to achieve the receiving environment discharge standard (≤50 mg/l) according to the Turkish Water Pollution Control Regulation.

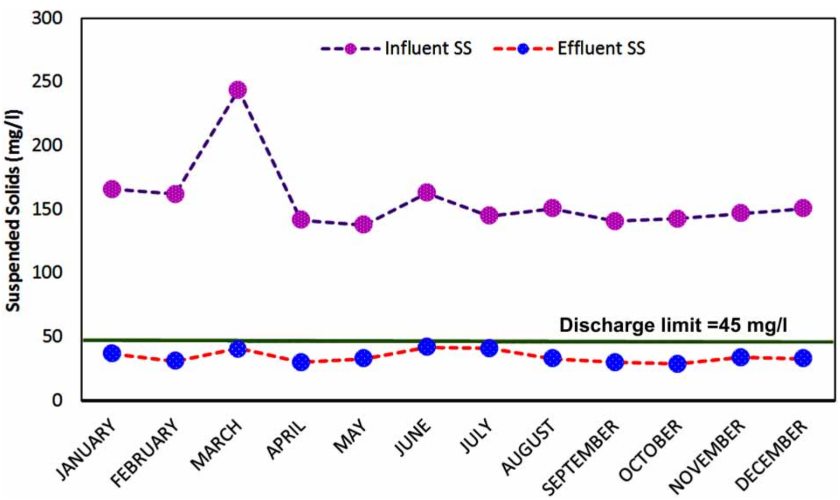

Figure 3 | Variation of influent and effluent SS values.

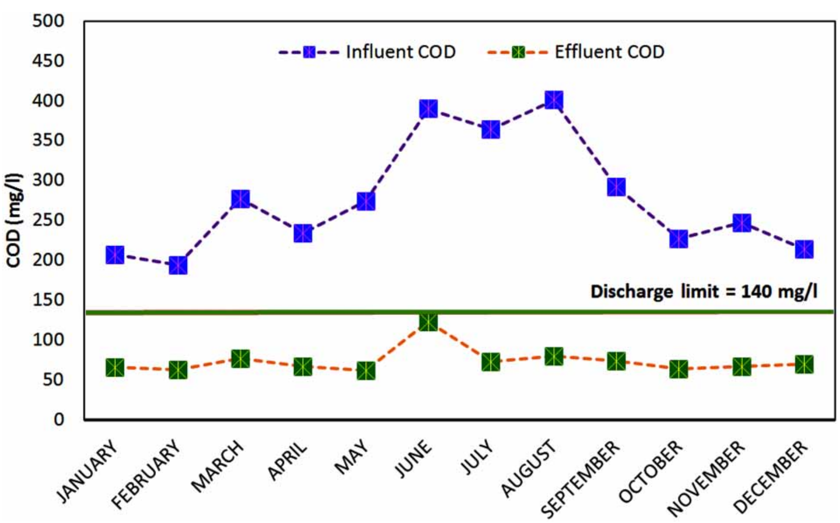

Figure 4 | Variation of influent and effluent COD values.

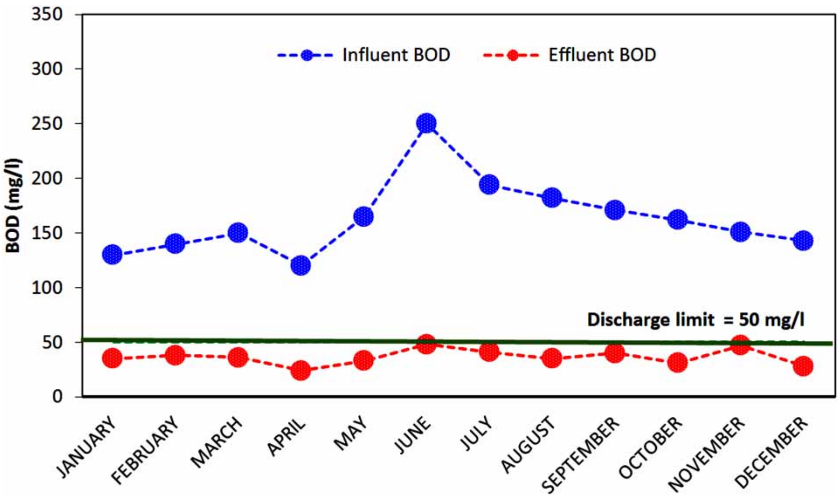

Figure 5 | Variation of influent and effluent BOD values.

Influent TP concentration was between 3 and 6 mg/l with an average of 3.8 mg/l and effluent TP concentration was between 1.5 and 3.1 mg/l with an average of 2.3 mg/l as shown in Figure 6. The TP removal efficiency varied between 27 and 46% with an average of 38%. It was found that TP concentration exceed the discharge limit (≤2 mg/l) specified in the Urban Wastewater Treatment Regulation (2006) according to the characteristics of the receiving environment (sensitive, less sensitive, etc.) and population and pollution load. As a result, discharge limit (TP ≤ 2 mg/l) was not generally achieved for TP during the operation period, but it was achieved when influent TP ≤ 3 mg/l. The phosphorus is found in raw wastewaters as organic phosphorus compounds and inorganic phosphate ions. The main mechanism of the EC process for organic phosphorus removal is the generation of metal and hydroxyl ions to form coagulant species that can absorb and/or precipitate organic phosphorus compounds which can then be separated. The phosphate ions can be removed from wastewater by co-precipitation with metal ions released from the electrodes and adsorption on metal hydroxides (Pulkka *et al.* 2014; Nguyen *et al.* 2016).

Influent TN concentration was between 31 and 48 mg/l with an average of 38.8 mg/l and effluent TN concentration was between 17.4 and 29.6 mg/l with an average of 24.2 mg/l as shown in Figure 7. The TN removal efficiency varied between 21 and 47% with an average of 37%. It

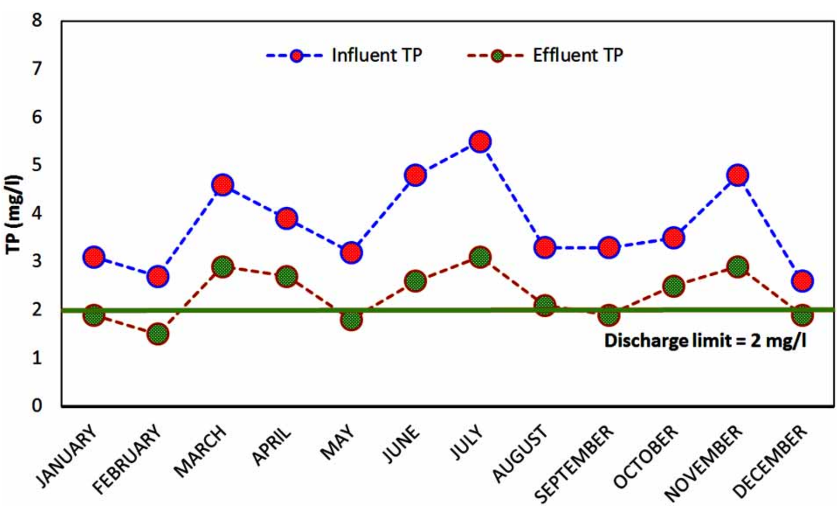

Figure 6 | Variation of influent and effluent TP values.

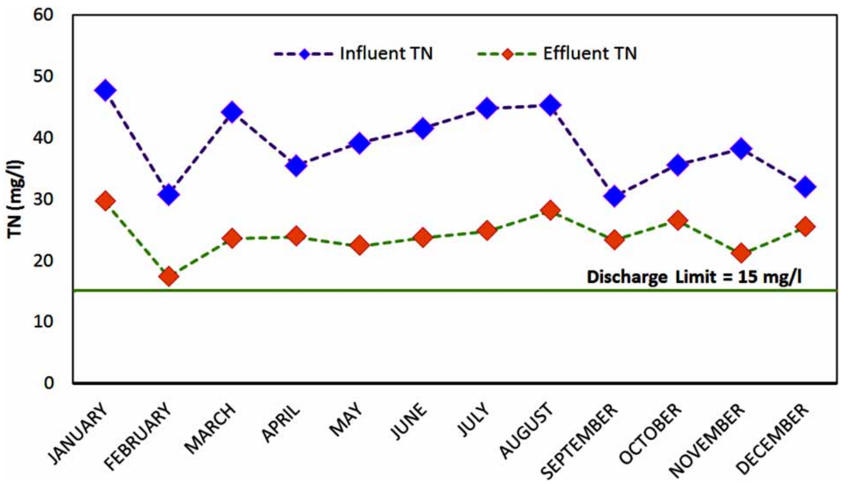

Figure 7 | Variation of influent and effluent TN values.

was determined that the TN concentration was above the discharge limit (≤15 mg/l) specified in the Urban Wastewater Treatment Regulation (2006) according to the characteristics of receiving environment (sensitive, less sensitive, etc.). Nitrogen is generally found in raw wastewaters in the form of organic nitrogen and ammonium nitrogen; oxidized forms of nitrogen such as nitrate and nitrite generally are in negligible concentrations. The principal mechanisms for ammonium removal are direct or indirect oxidation of ammonium. Indirect oxidation of ammonium requires the presence of chloride ions in wastewater, while direct oxidation of ammonium occurs at the anode–liquid interface (Mahvi *et al.* 2011). The removal of organic nitrogen compounds in wastewater is regarded to be the effect of sweep flocculation where excess micelles and sludge flocs sweep wastewater pollutants. This process appears to be a simple surface phenomenon where wastewater pollutants are adsorbed on the surface of colloidal micelles such as $(Fe(OH)_3)_m$ or $(Fe(OH)_2)_p$ (Chen 2004).

In this study, EC process yielded a removal efficiency of 72–83% for SS, 67–80% for COD, 69–81% for BOD, 21–47% for TN and 27–46% for TP (Figure 8). According to the Turkish wastewater discharge regulations (Urban Wastewater Treatment Regulation 2006; Water Pollution Control Regulation 2008), discharge limits for SS, COD, and BOD parameters were achieved but discharge limits for TN and TP parameters were not achieved. According to the European Urban Wastewater Treatment Directive (CEC 1991)

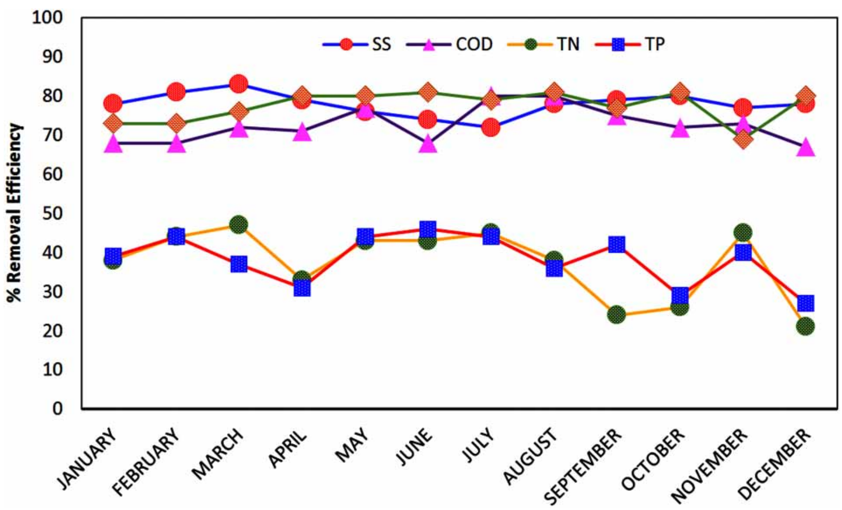

Figure 8 | Pollutant removal efficiencies of the EC process.

discharge requirements, the required percentage of reduction for BOD and COD parameters (BOD 70–90%; COD 75%) was achieved but the required percentage of reduction for SS (90%) was not achieved with EC process. It was also observed that the required percentage of reduction for TN (70–80%) and TP (80%) parameters for discharge to sensitive receiving environments could not be achieved.

The studies on the treatment of real domestic and urban wastewater by using EC method were generally carried out in batch system and in laboratory or pilot scale and COD, SS, TN, TP and turbidity removals were monitored during EC process. In this study, treatment of domestic wastewater by EC method was performed in real-scale conditions at Konya WWTP and removal efficiency of SS, COD, BOD, TN, TP parameters were determined. As can be seen from Table 3, COD removal efficiency was closer to that obtained in laboratory-scale studies but TP removal efficiency was lower than that obtained at laboratory-scale studies.

Energy and electrode consumption of EC process

The energy consumptions per removed pollutant ($E_{pollutant}$) and electrical energy (C_{energy}) and electrode ($C_{electrode}$) consumptions were calculated according to Equations (1)–(3) using the following formulas:

$$E_{pollutant}\,(\mathrm{kWh/kg}) = \frac{E \times 1000}{(X_i - X_e) \times Q \times 30} \tag{1}$$

$$C_{energy}\,(\mathrm{kWh/m^3}) = \frac{i \times U \times 0.024}{Q} \tag{2}$$

$$C_{electrode}\,(\mathrm{g}) = \frac{i \times t_{EC} \times M_{Fe}}{Z \times F} \tag{3}$$

where $E_{pollutant}$ is the energy consumption per amount of pollutant removed (kWh/kg), E is the energy consumption (kWh/month), X_i is influent pollutant concentrations (mg/l), X_e is effluent pollutant concentration (mg/l), Q is

Table 3 | An overview of literature studies on domestic/municipality wastewaters by EC

Wastewater	Parameter	Concentration mg/L Initial	Final	Process	Removal efficiency %	Reference
Domestic wastewater	COD	260	75	EC laboratory-scale batch system (iron electrode)	70	Kurt *et al.* (2008)
	SS	95	10		90	
Real oxide-CMP wastewater	COD	571	57	EC laboratory-scale batch system (iron electrode-coagulant)	90	Chou *et al.* (2009)
	Turbidity	250	400		destabilized	
Domestic wastewater	COD	128	85	EC laboratory-scale batch system (aluminium electrode)	34	Rodrigo *et al.* (2010)
	TP	1.02	0.1		90	
Urban wastewater	COD	92	65		30	
	TP	2.08	0.1		95	
Municipal wastewater	COD	122	60	EC laboratory-scale (iron electrode)	60	Zaleschi *et al.* (2012)
	TP	0.8	0.1		87.5	
	TN	12	2		83	
Municipal wastewater	COD	85	15	EC laboratory-scale batch system (iron electrode)	83	Al-Shannag *et al.* (2013)
	TP	47.2	5		89	
Municipal wastewater	TP	3	0.12	EC laboratory-scale continuous system (iron electrode-coagulant)	95	Nguyen *et al.* (2016)
Natural municipal wastewater	COD	737	304	EC pilot scale (aluminium electrodes)	58.7	Smoczynski *et al.* (2017)
	TP	10.7	5.3		51	
Municipal wastewater	TP	5	2	EC small scale (iron electrode)	60	Mishima *et al.* (2018)
Domestic wastewater	COD	277	74	Real-scale EC process (iron electrode)	73	This study
	BOD	163	36		77	
	SS	158	35		78	
	TN	38.8	24.2		37	
	TP	3.8	2.3		38	

CMP: chemical mechanical polishing.

the treated effluent flow rate (m^3/day), 30 is the number of days in a month, 1,000 is a unit conversion factor to obtain pollutant concentration in kg/m^3, i is the current intensity (A), U is the voltage (V), 0.024 is a unit conversion factor to obtain electric energy in kWh/m^3, t_{EC} is the operating time (s), Z is the number of electrons transferred ($Z_{Fe} = 2$), M_{Fe} is the molecular weight of iron (g/mol) and F is Faraday's constant (9.65×10^4 C/mol). The price of electricity in the Turkish market was 0.110 Euro/kWh in August 2017. Energy consumption of this real-scale plant is 0.49–0.54 kWh/m^3. Electrode consumption was calculated as 9.40–10.44 g. Table 4 shows the energy consumption per amount of pollutant removed. The total operating costs of the plant include energy (0.049–0.056 EUR/m^3), personnel (0.068–0.079 EUR/m^3), chemicals (0.066–0.076 EUR/m^3), service/maintenance (0.024–0.028 EUR/m^3) and other expenses (0.034–0.039 EUR/m^3). The operating cost is 0.24–0.28 EUR/m^3.

Sludge formation in EC process

In the treatment plant where this study was carried out, the wastewater was passed to the pre-treatment unit and then to the EC. By the application of the high current, decomposition starts in the electrolytic water and hydrogen, oxygen, and hydroxyl radicals are formed. The ions formed by oxidation of the anode material pass into the water in the reactor, and the cations formed as a result of oxidation coupled with hydroxyl groups begin to flocculate with the addition of polymer. With the separation of the liquid phase, stable organic and inorganic compounds are formed. The toxic substances and heavy metals in wastewater transfer to the solid phase and become stable after the process. EC produces much less sludge volume than chemical coagulation and the sludge formed is more stable and non-toxic. EC sludge is reported to be of a better quality in terms of floc size, acid-resistance of flocs and dewatering potential than conventional chemical coagulation sludge, making it easy to handle and process (Moussa *et al.* 2016). It was determined that 0.6–1.2 kg sludge was produced per cubic metre of treated wastewater with iron electrodes. After dewatering in the band filter, sludge with solid matter of 20–22% was produced. The dewatered sludge was transferred to the sludge disposal facility in the central WWTP.

CONCLUSION

In this study, the treatment of domestic wastewater by EC process has been studied on a real scale. The changes in the characterization and their effects on the EC process were evaluated. Since pH values were within the desired range (6–9), pH adjustment was not required. The process adapted to flow changes since the number of reactors can be changed according to the increase or decrease in the flow rate thanks to the modularity of the system. In order to increase the electrical conductivity, an average of 0.05 kg NaCl (salt)/m^3 was added to the wastewater as an electrolyte. The addition of NaCl can also reduce the

Table 4 | Energy consumption for some pollutant parameters

Month	kWh/month	kWh/m^3	kWh/kg SS	kWh/kg COD	kWh/kg BOD	kWh/kg TN	kWh/kg TP
January	31,600	0.54	4.16	3.80	5.64	29.62	446.71
February	29,800	0.54	4.14	4.14	5.32	40.51	452.34
March	29,400	0.54	2.65	2.68	4.71	26.07	315.87
April	27,800	0.51	4.57	3.07	5.34	44.16	426.88
May	26,500	0.49	4.67	2.31	3.71	29.16	349.95
June	29,500	0.52	4.28	1.94	2.57	28.96	235.62
July	29,600	0.50	4.80	1.72	3.26	24.95	207.95
August	33,500	0.54	4.56	1.68	3.66	31.29	448.46
September	31,100	0.54	4.88	2.49	4.14	75.30	387.28
October	29,700	0.53	4.64	3.24	4.04	58.11	528.85
November	29,800	0.52	4.61	2.89	5.01	30.46	274.15
December	32,400	0.54	4.54	3.72	4.66	80.00	765.69
Average value	30,058	0.53	4.38	2.81	4.34	41.55	403.31

electrical energy consumption of EC, as it increases the conductivity of the wastewater.

The removal efficiencies of pollution parameters were in the range of 72–83% for SS, 67–80% for COD, 69–81% for BOD, 21–47% for TN and 27–46% for TP. Sufficient removal efficiencies were obtained for SS, COD and BOD parameters and discharge limits were achieved for these parameters. However, it was observed that adequate removal efficiencies were not obtained and discharge limits were not achieved for TN and TP parameters. Energy consumption of this plant operated at real scale is 0.49–0.54 kwh/m^3. The operating cost of the plant was calculated to be between 0.24 and 0.28 EUR/m^3. It was concluded that EC process is economically feasible in non-sensitive areas (TN and TP treatment not required).

As a result of this study, since discharge limits for nitrogen and phosphorus parameters could not be achieved for sensitive receiving environments according to the Turkish Urban Wastewater Treatment Regulation, EC process was not considered an appropriate process. However, according to the conditions of the receiving environment, EC can be preferred as a modular system for the treatment of domestic wastewaters where nitrogen and phosphorus removal is not required, especially in settlements where mobile populations are high and there is not enough area for the installation of WWTPs.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wst.2020.128.

REFERENCES

Akbal, F. & Camcı, S. 2011 Copper, chromium and nickel removal from metal plating wastewater by electrocoagulation. *Desalination* **269** (1–3), 214–222.

Al-Aji, B., Yavuz, Y. & Koparal, A. S. 2012 Electrocoagulation of heavy metals containing model wastewater using monopolar iron electrodes. *Separation and Purification Technology* **86**, 248–254.

Al-Shannag, M., Bani-Melhem, K., Al-Anber, Z. & Al-Qodah, Z. 2013 Enhancement of COD-nutrients removals and filterability of secondary clarifier municipal wastewater influent using electrocoagulation technique. *Separation Science and Technology* **48**, 673–680.

Al-Shannag, M., Al-Qodah, Z., Bani-Melhem, K., Qtaishat, M. R. & Alkasrawi, M. 2015 Heavy metal ions removal from metal plating wastewater using electrocoagulation: kinetic study and process performance. *Chemical Engineering Journal* **260**, 749–756.

Aoudj, S., Khelifa, A., Drouiche, N., Hecini, M. & Hamitouche, H. 2010 Electrocoagulation process applied to wastewater containing dyes from textile industry. *Chemical Engineering and Processing: Process Intensification* **49** (11), 1176–1182.

Aswathy, P., Gandhimathi, R., Ramesh, S. T. & Nidheesh, P. V. 2016 Removal of organics from bilge water by batch electrocoagulation process. *Separation and Purification Technology* **159**, 108–115.

Attour, A., Touati, M., Tlili, M., Ben Amor, M., Lapicque, F. & Leclerc, J. P. 2014 Influence of operating parameters on phosphate removal from water by electrocoagulation using aluminium electrodes. *Separation and Purification Technology* **123**, 124–129.

Bazrafshan, E., Mohammadi, L., Ansari-Moghaddam, A. & Mahvi, A. H. 2015 Heavy metals removal from aqueous environments by electrocoagulation process – a systematic review. *Journal of Environmental Health Science and Engineering* **13** (1), 1–16.

Bazrafshan, E., Alipour, M. R. & Mahvi, A. H. 2016 Textile wastewater treatment by application of combined chemical coagulation, electrocoagulation, and adsorption processes. *Desalination and Water Treatment* **57** (20), 9203–9215.

Bibi, S., Kamran, M. A., Sultana, J. & Farooqi, A. 2017 Occurrence and methods to remove arsenic and fluoride contamination in water. *Environmental Chemistry Letters* **15**, 125–149.

Brillas, E., Sires, I. & Oturan, M. A. 2009 Electro-Fenton process and related electrochemical technologies based on Fenton's reaction chemistry. *Chemical Reviews* **109**, 6570–6631.

Bukhari, A. A. 2008 Investigation of the electro-coagulation treatment process for the removal of total suspended solids and turbidity from municipal wastewater. *Bioresource Technology* **99** (5), 914–921.

Butler, E., Hung, Y. T., Yeh, R. Y. L. & Al Ahmad, M. S. 2011 Electrocoagulation in wastewater treatment. *Water* **3**, 495–525.

Calvo, S., Leclerc, J. P., Tanguy, G., Cames, M. C., Paternotte, G., Valentin, G., Rostan, A. & Lapicque, F. 2003 An electrocoagulation unit for the purification of soluble oil wastes of high COD. *Environmental Progress* **22** (1), 57–65.

CEC (Council of the European Communities) 1991 Council Directive 91/271/EEC concerning urban wastewater treatment.

Chen, G. 2004 Electrochemical technologies in wastewater treatment. *Separation and Purification Technology* **38**, 11–41.

Chen, X., Chen, G. & Yue, P. L. 2000 Separation of pollutants from restaurant wastewater by electrocoagulation. *Separation and Purification Technology* **19**, 65–76.

Chou, W. L., Wang, C. T. & Chang, S. Y. 2009 Study of COD and turbidity removal from real oxide-CMP wastewater by iron electrocoagulation and the evaluation of specific energy consumption. *Journal of Hazardous Materials* **168**, 1200–1207.

Den, W. & Huang, C. 2006 Electrocoagulation of silica nanoparticles in wafer polishing wastewater by a multichannel flow reactor: a kinetic study. *Journal of Environmental Engineering* **132** (12), 1651–1659.

Esfandyari, Y., Mahdavi, Y., Seyedsalehi, M., Hoseini, M., Safari, G. H., Ghozikali, M. G., Kamani, H. & Jaafari, J. 2015 Degradation and biodegradability improvement of the olive mill wastewater by peroxi-electrocoagulation/electrooxidation-electroflotation process with bipolar aluminium electrodes. *Environmental Science and Pollution Research* **22** (8), 6288–6297.

El-Naas, M. H., Alhaija, M. A. & Al-Zuhair, S. 2014 Evaluation of a three-step process for the treatment of petroleum refinery wastewater. *Journal of Environmental Chemical Engineering* **2** (1), 56–62.

Ensano, B. M. B., Borea, L., Naddeo, V., Belgiorno, V., Luna, M. D. G., Balakrishnan, M. & Ballesteros, F. C. 2019 Applicability of the electrocoagulation process in treating real municipal wastewater containing pharmaceutical active compounds. *Journal of Hazardous Materials* **361**, 367–373.

Fenga, C., Sugiura, N., Shimada, S. & Maekawa, T. 2003 Development of a high performance electrochemical wastewater treatment system. *Journal of Hazardous Materials* **103** (1–2), 65–78.

Gatsios, E., Hahladakis, J. N. & Gidarakos, E. 2015 Optimization of electrocoagulation (EC) process for the purification of a real industrial wastewater from toxic metals. *Journal of Environmental Management* **154**, 117–127.

Hashim, K. S., Shaw, A., Khaddara, R. K., Pedrola, M. O. & Phipps, D. 2017 Iron removal, energy consumption and operating cost of electrocoagulation of drinking water using a new flow column reactor. *Journal of Environmental Management* **189**, 98–108.

Holt, K., Bartona, G. W. & Mitchell, C. A. 2005 The future for electrocoagulation as a localised water treatment technology. *Chemosphere* **59** (3), 355–367.

Ihara, I., Kanamura, K. & Shimada, E. 2004 High gradient magnetic separation combined with electrocoagulation and electrochemical oxidation for the treatment of landfill leachate. *IEEE Transactions on Applied Superconductivity* **14** (2), 1558–1560.

Ilhan, F., Kurt, U., Apaydin, O. & Gonullu, M. T. 2008 Treatment of leachate by electrocoagulation using aluminum and iron electrodes. *Journal of Hazardous Materials* **154** (1–3), 381–389.

Joffe, L. & Knieper, L. 2000 Electrocoagulation technology quickly removes barium, total suspended solids from a water-retention pond for fractions of a cent per gallon. *Industrial Wastewater* **5**, 1–5.

Juttner, K., Galla, U. & Schmiede, H. 2000 Electrochemical approaches to environmental problems in the process industry. *Electrochimica Acta* **45** (15–16), 2575–2594.

Kobya, M. & Demirbas, E. 2015 Evaluations of operating parameters on treatment of can manufacturing wastewater by electrocoagulation. *Journal of Water Process Engineering* **8**, 64–74.

Kuokkanen, V. 2016 *Utilization of Electrocoagulation for Water and Wastewater Treatment and Nutrient Recovery*. Juvenes Print, Tampere.

Kurt, U., Talha, G. M., Ilhan, F. & Varinca, K. 2008 Treatment of domestic wastewater by electrocoagulation in a cell with Fe-Fe electrodes. *Environmental Engineering Science* **25** (2), 153–161.

Lacasa, E., Cotillas, S., Saez, C., Lobato, J., Canizares, P. & Rodrigo, M. A. 2019 Environmental applications of electrochemical technology. What is needed to enable full-scale applications? *Current Opinion in Electrochemistry* **16**, 149–156.

Lakshmanan, D., Clifford, D. A. & Samanta, G. 2009 Ferrous and ferric ion generation during iron electrocoagulation. *Environmental Science & Technology* **43** (10), 3853–3859.

Mahmad, M. K. N., Rozainy, M. R., Abustan, I. & Baharun, N. 2015 Removal of iron and total chromium contaminations in landfill leachate by using electrocoagulation process. *Key Engineering Materials* **660**, 279–283.

Mahvi, A. H., Al-din Ebrahimi, S. J., Mesdaghiniaa, A., Gharibi, H. & Sowlat, M. H. 2011 Performance evaluation of a continuous bipolar electrocoagulation/electrooxidation–electroflotation (ECEO–EF) reactor designed for simultaneous removal of ammonia and phosphate from wastewater effluent. *Journal of Hazardous Materials* **192**, 1267–1274.

Maitlo, H. A., Lee, J., Park, J. Y., Kim, J.-C., Kim, K.-H. & Kim, J. H. 2019 An energy-efficient air-breathing cathode electrocoagulation approach for the treatment of arsenide in aquatic systems. *Journal of Industrial and Engineering Chemistry* **73**, 205–213.

Malakootian, M., Mansoorian, H. J. & Moosazadeh, M. 2010 Performance evaluation of electrocoagulation process using iron-rod electrodes for removing hardness from drinking water. *Desalination* **255** (1–3), 67–71.

Ministry of Environment and Forestry 2010 *The Technical Procedure Communique of Wastewater Treatment Plants*. Ministry of Environment and Forestry, No. 27527, Ankara, Turkey.

Mishima, I., Hama, M., Tabata, Y. & Nakajima, J. 2018 Long-term investigation of phosphorus removal by iron electrocoagulation in small-scale wastewater treatment plants. *Water Science & Technology* **78** (5–6), 1304–1311.

Mohora, E., Roncevi, S., Agbaba, J., Tubic, A., Mitic, M., Klasnja, M. & Dalmacija, B. 2014 Removal of arsenic from groundwater rich in natural organic matter (NOM) by continuous electrocoagulation/flocculation (ECF). *Separation Science and Technology* **136**, 150–156.

Mollah, M. Y. A., Morkovsky, P., Gomes, J. A. G., Kesmez, M., Parga, J. & Cocke, D. L. 2004 Fundamentals, present and future perspectives of electrocoagulation. *Journal of Hazardous Materials* **114** (1–3), 199–210.

Moussa, D., El-Naas, M., Nasser, M. & Al-Marri, M. 2016 A comprehensive review of electrocoagulation for water treatment: potentials and challenges. *Journal of Environmental Management* **186**, 1–18.

Moussa, D. T., El-Naas, M. H., Nasser, M. & Al-Marri, M. J. 2017 A comprehensive review of electrocoagulation for water treatment: potentials and challenges. *Journal of Environmental Management* **186** (1), 24–41.

Naji, T., Dirany, A., Carabin, A. & Drogui, P. 2017 Large-scale disinfection of real swimming pool water by electro-oxidation. *Environmental Chemistry Letters* **16** (2), 545–551.

Nanseu-Njiki, C. P., Tchamango, S. R., Ngom, P. C., Darchen, A. & Nigamani, E. 2009 Mercury(II) removal from water by electrocoagulation using aluminium and iron electrodes. *Journal of Hazardous Materials* **168** (2–3), 1430–1436.

Nguyen, D. D., Ngo, H. H., Guo, W., Nguyen, T. T., Chang, S. W., Jang, A. & Yoon, Y. S. 2016 Can electrocoagulation process be an appropriate technology for phosphorus removal from municipal wastewater? *Science of The Total Environment* **563–564**, 549–556.

Pulkka, S., Martikainen, M., Bhatnagar, A. & Sillanpaa, M. 2014 Electrochemical methods for the removal of anionic contaminants from water – a review. *Separation and Purification Technology* **132**, 252–271.

Rajeshwar, K. & Ibanez, J. 1997 Environmental electrochemistry: fundamentals and applications in pollution abatement. In: *Chemical Degradation Methods for Wastes and Pollutants* (M. A. Tarr, ed.). Academic Press, San Diego, CA, USA.

Rice, E. W. & Baird, R. B. 2017 *Standard Methods for the Examination of Water and Wastewater*, 23rd edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Rodrigo, M. A., Canizares, P. C., Buitron, P. & Saez, C. 2010 Electrochemical technologies for the regeneration of urban wastewaters. *Electrochimica Acta* **55** (27), 8160–8164.

Smoczynski, L., Munska, K. T., Kosobucka, M. & Pierozynski, B. 2014 Phosphorus and COD removal from chemically and electrochemically coagulated wastewater. *Environment Protectection Engineering* **40** (3), 63–73.

Smoczynski, L., Kalinowski, S., Ratnaweera, H., Kosobucka, M., Trifescu, M. & Pieczulis-Smoczynska, K. 2017 Electrocoagulation of municipal wastewater – a pilot-scale test. *Desalination and Water Treatment* **72**, 162–168.

Sridhar, R., Sivakumar, V., Prince Immanuel, V. & Prakash Maran, J. 2011 Treatment of pulp and paper industry bleaching effluent by electrocoagulant process. *Journal of Hazardous Materials* **186** (2–3), 1495–1502.

Urban Wastewater Treatment Regulation 2006 Ministry of Environment and Forestry, No. 26047, Ankara, Turkey.

Valero, D., Ortiz, J. M., Garia, V., Exposito, E., Montiel, V. & Aldaz, A. 2011 Electrocoagulation of wastewater from almond industry. *Chemosphere* **84** (9), 1290–1295.

Varank, G., Erkan, H., Yazıcı, S., Demir, A. & Engin, G. 2014 Electrocoagulation of tannery wastewater using monopolar electrodes: process optimization by response surface methodology. *International Journal of Environmental Research* **8** (1), 165–180.

Vasudevan, S. & Lakshmi, J. 2011 Effects of alternating and direct current in electrocoagulation process on the removal of cadmium from water – a novel approach. *Separation Science and Technology* **80** (3), 643–651.

Vepsalainen, M. 2012 *Electrocoagulation in the Treatment of Industrial Waters and Wastewaters*. Doctor of Science (Technology), Lappeenranta University of Technology, Mikkeli, Finland.

Wan, W., Pepping, T. J., Banerj, T., Chaudhari, S. & Giammara, D. E. 2011 Effects of water chemistry on arsenic removal from drinking water by electrocoagulation. *Water Research* **45** (1), 384–392.

Water Pollution Control Regulation 2008 Ministry of Environment and Forestry, Ankara, Turkey.

Yang, C. L. & Dluhy, R. 2002 Electrochemical generation of aluminium sorbent for fluoride adsorption. *Journal of Hazardous Materials* **94** (3), 239–252.

Yang, Y., Liu, L. & Jin, Q. 2008 Study on treatment of municipal domestic sewage by electrocoagulation and electroflotation. *Journal of Xian University of Architecture & Technology (Natural Science Edition)* **3**, 1–24.

Zaleschi, L., Teodosiu, C., Cretescu, I. & Rodrigo, M. A. 2012 A comparatıve study of electrocoagulation and chemıcal coagulation processes applied for wastewater treatment. *Environmental Engineering and Management Journal* **11** (8), 1517–1525.

Zaroual, Z., Azzi, M., Saib, N. & Chainet, E. 2006 Contribution to the study of electrocoagulation mechanism in basic textile effluent. *Journal of Hazardous Materials* **131** (1–3), 73–78.

Zolotukhin, I. A. 1989 A pilot-scale system for the treatment of mine water by electrocoagulation-flotation. *Soviet Journal of Water Chemistry and Technology* **11** (2), 147–151.

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