Techno-economic evaluation of electrocoagulation for Cattell slaughterhouse wastewater treatment using aluminum electrodes in batch and continuous experiment

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Research Article

Keywords: Electrocoagulation, Cattell slaughterhouse, Treatment, Aluminum electrodes, Current density, Electrical consumption

Posted Date: September 1st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1957686/v1

Version of Record: A version of this preprint was published at Sustainable Environment Research on January 16th, 2023. See the published version at https://doi.org/10.1186/s42834-023-00163-0.

Abstract

This study aimed to investigate, from technoeconomic point of view, cattle slaughterhouse wastewater (CSWW) treatment via electrocoagulation (EC) technique. A novel lab scale electrocoagulation unit with 3L volume was manufactured and tested. The EC unite contains nine identical cylindrical shape electrodes from aluminum material in connection with controllable DC power supply. Investigation of optimum operating parameters in terms of pH, current density (CD), contact time and electrolyte concentration (TDS) was carried out in batch mode then applied for continuous mode. At each batch, cost analysis was calculated in terms of consumption electrode material and electrical power. The optimum operating conditions at which best removal rate achieved was pH 7, contact time 75 min, TDS = 3000 mg L^{-1} and CD of 4 $mA.cm^{-2}$. After application of these conditions on continuous flow mode, the removal rate of Chemical oxygen demand (COD), color, turbidity, biological oxygen demand (BOD), and oil, grease were 95.3%, 99.8%, 98.7%, 96.5% and 94.5% respectively. The total electrode consumption and electrical consumption were 0.6 kg m^{-3} and 0.87kWh m^{-3} with operational cost about 1.5$ m^{-3}. This proved that EC is techno-economically effective treatment method than other conventional treatment methods for high-rate removal of pollutants of from CSWW.

1 Introduction

Slaughterhouses belong to the food industry sector for the production of meat and its products. This industry specially Cattle slaughterhouses generate large wastewater volumes during the butchering process and intermittent rinsing of remaining particles [1]. A range of 0.4 and 3.1 m^3 of water per slaughtered animal is consumed depending on the procedures used and kind of animal and consequently the composition of cattle slaughterhouse wastewaters (CSWW) is varied [2]. CSWW contain high amounts of organic pollutants in terms of chemical oxygen demand (COD), biochemical oxygen demand (BOD) and nutrients (phosphorus, and nitrogen) due to organic substances exist, such as blood, fat, grease, proteins, urine and feces [3]. Therefore, to prevent serious environmental pollution, Removal of theses pollutants from CSWW is mandatory prior discharge into receiving bodies.

CSWW treatment can be performed by several methods such as physicochemical, biological, and advanced oxidation. Physicochemical treatments such as coagulation and flocculation have good removal efficiency [4]. However, their disadvantage is the high amounts of chemicals utilized in coagulation process and large sludge volume produced[5]. Biological treatment utilized for CSWW such as anaerobic treatment [6] aerobic treatment and combined anaerobic-aerobic treatment [7] are not constantly appropriate because of large land areas required, high operating costs, sensitivity of microorganisms to chemical complexes, and long treatment time [8]. For example, aerobic treatment is energy consuming due to long aeration time [9], while in anaerobic treatment reactor floating fats may accumulated on the top and suspended solids at bottom [10].

Recently, some studies revealed that Electrocoagulation (EC) treatment process is a promising technology for various industrial wastewaters treatment with cost effective operation due to, flexibility, low energy requirements, could be self-automated, environmental and compatibility [11, 12]. The theory of EC treatment process is based on application of an electric field between two electrodes in which metal oxides leached from cathode that reduces stability of surface charge on suspended and dissolved pollutants and establishes the coagulation process in terms precipitation or flotation [13]. Compared to conventional coagulation method, EC requires simple equipment due to minimization or absence of chemicals dosing equipment, reduces treatment time, easily operated, and low sludge production with high settling rate. Also, the salt contents in the treated wastewater does not significantly increase, as happens in chemical coagulation due to chemicals additions. Thus, EC had been effectively investigated for the treatment of various wastewater types such as; urban wastewater [14], yeast wastewater [15], food and protein wastewater [16], textile wastewater [17], olive oil wastewater [18, 19], petrochemical wastewater [20] and landfill leachates [21].

There are different investigations on the use of EC for treatment of different types of slaughter house wastewater (poultry and cattle) [22, 23]. For example Un et al. [22] studied EC process using aluminum and Iron electrode with the aid 0.75 g L^{-1} poly-aluminum chloride coagulant for CSWW treatment. The COD removal efficiency reached 94.4% using iron electrode. However, the process is considered combined EC and chemical coagulation as included addition of coagulant to the process. In another study, Bayar et al. [23] used EC unite equipped with aluminum electrodes to study the influence of current density and mixing speed on the treatment of poultry slaughterhouse wastewater. and they revealed that 150 rpm stirring speed and current density of 1 mA.cm-2 at initial pH 3 was the effective conditions for such wastewater treatment. By applying these conditions, the COD reduced to about 300 mg L^{-1} starting from 2170 mg L^{-1} within 30 min. However, the process needs further post treatment via adding pH adjust system which not technically economic. All past studies were on batch experiments and there is no complete techno-economic data were shown in the application of EC for CSWW in continuous flow mode. The aim of this study to evaluate the use of EC for CSWW technically and economically. The optimum operating parameters is studied in terms of pH, current applied, contact time, and electrolyte concentration on batch mode then obtain optimum parameters were applied on continuous mode. Also, the cost analysis in terms electrical power and electrode consumption will be investigated.

2 Materials And Method

2.1 Source of CSWW

CSWW was collected from a cattle slaughterhouse near Giza governorate, Egypt, which have daily of 3–5-ton cattle and may reached to 9 tons d^{-1} in high season. The daily generated wastewater is about 10–70 m^3. The CSWW from slaughterhouse generated from the production process of meat and barn cleaning, which contains bloods, proteins, and lipids. This facility does not apply any kind of wastewater treatment or even separating solid waste from wastewater, and it discharge all on sewerage network. Pre-treatment of the collected wastewater was carried out via manual screening to eliminate large objects such as hair, skins and solids larger than 1 mm before applying electrocoagulation treatment. Table 1. shows CSWW characteristics used in this study.

Table 1
The Characteristics of raw CSWW

Parameters	Units	Range
pH		6.97–7.2
COD	mg L^{-1}	4450–5230
BOD	mg L^{-1}	2040–2320
Color	Pt-Co	4500–6100
TDS	mg L^{-1}	870–1013
TSS	mg L^{-1}	145–187
TKN	mg L^{-1}	193–240
TP	mg L^{-1}	110–160
Oil & Grease	mg L^{-1}	45–78

2.2 Design and operation of EC reactor

The EC unit was designed according to patent No. EGPO 30235 [24]. A schematic diagram of EC unit is shown in Fig. 1. The reactor body is 3 L transparent Perspex glass container with dimensions of 12.5 cm length, 12 cm width and 20 cm height while effluent valve was kept 5 cm from height giving 2.25 L effective volume. Nine cylindrical aluminum electrodes were inserted in a pattern of three rows each one contains three electrodes with 2 cm interspace. Each electrode has a diameter of 1.6 cm and 15 cm height with a surface area of 0.054 m^2 and 12 cm^3 total volume which mean that all electrodes is occupying 0.24 L and the effective volume of CSWW in the EC unit is 2 L. A mechanical mixer was fixed in the middle of the unite while electricity is supplied via controllable D.C power supply. The output DC voltage and current range are 0–30 V and 0–10 A.

2.3 Operating conditions

Batch study was carried out in several experimental runs representing different operational parameters including pH, contact time, electrolyte concentration (TDS of CSWW), and current density. Effective operational time was investigated at pH 7, TDS 1000 mg L^{-1} and current density of 2 $mA.cm^{-2}$ at. At determined optimum time, different pH values (4, 5,6,7 and 8), and current densities (2–8 $mA.cm^{-2)}$ were investigated. To investigate the effect of TDS, different electrolyte concentrations of sodium chloride was prepared and added to CSWW, with molar mass of 17.5, 35, 52.5, 70 and 87.5 mM NaCl to reach TDS concentrations equivalent to 1000, 2000, 3000, 4000 and 5000 mg L^{-1}. The pollutants such as fats and grease may be attached to the electrodes surface by electric forces, thus after each batch, the electrodes were washed to remove grease and the impurities on the electrodes surface, with a mixture solution prepared freshly from hydrochloric acid solution (35%) and chloroform solution with ratio 1:2, then were dried and weighed for determining rate of dissolution.

2.4 wastewater analysis

Chemical oxygen demand (COD), color, turbidity, pH, and conductivity were carried out as monitoring of treatment efficiency during determination of optimum conditions in batch studies. At optimum treatment conditions, characterization of CSWW after applying continuous experiment was carried out in terms of COD, biological oxygen demand (BOD), total suspended solids (TSS), oil and grease, total kjeldahl nitrogen (TKN) and total phosphorus (TP). The characterizations were carried out according to the standard methods for the examination of water and wastewater[25]. The pH was adjusted using 10% $NaOH/H_2SO_4$, while TDS concentration was adjusted using sodium chloride.

2.5 Calculations

The removal efficiency of pollutants is calculated as percentage of removed concentration using Eq. (1):

% Removal = $\frac{C\circ - Ci}{C\circ} \times 100$ (1)

Where C_0 and C_i are the initial and final concentrations of the pollutant (mg L^{-1}).

Operational cost (OC) was calculated based on consumption of electrode material, chemicals added (sodium chloride) and electrical energy costs and expressed as:

OC = electricity consumption (E_C) + electrodes consumption + cost of chemicals added

Where electricity consumption and electrode consumption are related to mounts consumed per m^3 of treated wastewater. calculation of energy consumption is calculated based on Eq. (2):

E_C (kWh.m^{-3})= $\frac{(V \times I \times t)}{v}$ (2)

Where V is applied voltage, I is current in ampere, t is treatment time (seconds), and v is treated wastewater volume (m^3). The electrode consumption was calculated theoretically and actually. electrode material consumption is calculated according to Faradays law in Eq. (3):

Electrode consumption(kg/m^3) = $\frac{(I \times t \times M_w)}{z \times F \times v}$ (3)

Where F is Faraday's constant and equal to 96,485 C mol^{-1}, M_w is the molar mass of aluminum (26.98 g mol^{-1}), and z is the number of electron transfer (z_{Al} = 3), respectively. The actual electrode consumption was calculated by estimation the difference between electrodes masses before and after treatment for a given volume in a given time.

3 Results And Discussion

3.1 Effect of contact time on the EC efficiency

The performance of EC process was investigated under different treatment times between 0 and 150 min with intervals every 15 min to assess optimum treatment time. The experiment was carried out at CD of 2 mA cm^{-2}, TDS value adjusted to be 1000 mg L^{-1} and pH value of 7.2. As shown in Fig. 2 (a and b), COD removal efficiency was about 23% after 15 min operation, then it increased to about 53% at 30 min indicating that more than 50% reduction of organic matter could be removed after 30 min detention time. COD removal efficiency increased gradually in 30–105 min from 53–84% with about 8% removal every 15 minute. The removal rate of COD slightly changed after operating time 105-150-min as it reached to 84.7%, 88.7% and 91.2% at 120, 135 and 150 min respectively. The residual value of COD after 2.5 hours was 360 mg L^{-1} starting from initial concentration of 4200 mg L^{-1}. This result is better compared with conventional treatment methods (combined chemical and biological) that achieved similar results with a total treatment time of about 15 hours [26].

CSWW contains dense red color which it could persist in other treatment methods. In Fig. 2a about 85% color removal efficiency was obtained at 60 min and 99% color removal obtain after 120 min operation. The turbidity value is considered as a mirror image for the existence of suspended solids in the wastewater. Turbidity removal efficiency was investigated (Fig. 2b) and it reached more than 82% after operation of 15 min only while it reached 95.5% in 60 min, which indicated that the majority of suspended and particulate substances was removed from the treated CSWW. Other phenomena were observed as the pH value increased gradually as a function of time. This may be attributed to the formation of metal hydroxides in the solution.

Treatment time is a very essential factor in construction and operation of EC in terms of the economic applicability for CSWW treatment. Accordingly, preliminary determination of electrical power and electrodes consumption at different EC contact time are shown in Fig. 3. The investigation was carried out by running the experiment 10 times in each one the electrodes and power consumption was calculated. The results revealed that increasing contact time in EC process directly increases both energy and electrode consumption. The contact time was varied from 0 to 150 min with 15 min interval and maximum energy consumption reached 30 kWh m^{-3} and maximum electrode reached 0.27 kg m^{-3}. Although the long operational time, the electrical power and electrodes consumption was lower than those investigated in several studies at lower operational time [11, 27]. based on the obtained results, 75 min was selected as optimum contact time in the EC treatment process for determination the other operating parameters. At this time, the energy and electrodes consumption were 13 kWh $m^{-3}$and 0.14 kg m^{-3}.

3.2 Effect of TDS concentrations on EC efficiency

The TDS concentration in the CSWW is another important parameter that affect the EC reactor performance. The more TDS concentration in bulk solution, the more conductivity between electrodes which leads to accelerate electrons and ions movement in the solution between electrodes. To study the TDS effect, the experiment was conducted at current density is 4 mA cm^{-2}, pH value of 7 and operational time between 0 and 150 min with intervals every 15 min. The investigated concentrations were 1000, 2000, 3000, 4000 and 5000 mg L^{-1} and adjusted by adding sodium chloride salt to the solution.

The effect of TDS concentration on EC performance on the removal of COD, color, and turbidity from CSWW is illustrated in Fig. 4 (a-c). As shown in Fig. 4a, TDS concentrations of 1000 and 2000 mg L^{-1} exhibit the same behavior in decrease of COD concentration removal as function of time. After 15 min operation the COD concentration decreased by about 23% while the other investigated TDS concentrations (3000, 4000, and 5000 mg L^{-1}) showed a reduction of more than 70–80% in COD concentrations in the same operation time. Also, results showed that TDS concentration in CSWW strongly affect the operational time as TDS concentrations starting from 3000 mg L^{-1} exhibit COD reduction from 4210 mg L^{-1} to 219 mg L^{-1} with removal rate of 94–96% at operational time 75 min while it was about 1313 mg L^{-1} with removal rate of 68% at the same operational time when TDS concentration was 1000 and 2000 mg L^{-1}. To reach the same performance the operational time should be more than 150 min. Accordingly, increasing TDS concentration in the treatment solution resulted in reduction of COD concentrations rapidly and consequently reduction of operational time.

Color removal efficiency (Fig. 4b) strongly influenced by the TDS concentrations. More than 96% color removal was achieved when TDS concentration was more than 3000 mg L^{-1} at 15 min operational time. In addition, turbidity removal efficiency was investigated (Fig. 4c), and it reached more than 80% after operation of 15 min only while it reached 99% in 60 min at all TDS concentrations investigated.

Based on the obtained results, the optimum operating time was 75 min when adjusting the TDS concentration to be about 3000 mg L^{-1}. Applying These optimum conditions reduced the electrical power and electrodes consumption. According to Fig. 3, the EC operation time will be reduced to the half and consequently the power and electrodes consumption will be about 13.6 kWh m^{-3} and 0.14 kg m^{-3}, respectively. These optimum parameters were used while investigated effect of pH and Current density.

3.3 Effect of pH

pH value has noticeable effect on the implementation of EC process. Investigation of different pH values (4,5,8,7 and 8) effect on the treatment of CSWW during EC, was carried out at current density of 4 mA cm^{-2}, TDS of 3000 mg L^{-1} and 75 min EC time. As seen in Fig. 5a, COD reduction was affected by the pH value of CSWW as the highest reduction was achieved when the pH range was 7–8 where it reached 96% and the residual concentration was 191 mg L^{-1}. At lower pH values the removal efficiency of COD decreased and reached 89%, 89.5 and 91% at pH 4, 5 and 6 respectively. Similarly, the highest color removal was obtained at pH 7 (Fig. 5b). These rates were found to be 99.9% while the minimum removal efficiencies obtained were 96% at pH 4 and 97% at pH 5–6. Figure 5c. showed that highest removal efficiency of turbidity obtained at pH 7 and found to be 98.8%.

As indicated in Fig. 5 (a-c), at lower pH values, a decrease in pollutants removal efficiencies was noticed. pH has a direct effect on the amount of Al^{3+} hydrolysis from electrodes[28]. From the obtained results of COD, color, and turbidity, the optimum pH values ranged between 7 and 8. Also, results showed slight increase in pH value by 0.5–1.5 at lower initial pH values in the treated solution after EC. The values increased from 4-4.5, 5-5.2 and 6-6.5 while at initial pH, 7 and 8 slight increase was noticed by about 0.2. Studies on EC supported this findings and reported an increase in pH value during EC at lower original solution pH [22]. This can be attributed to formation of hydroxide ions in bulk solution as results of water hydrolysis during the process and hydrogen evolution at cathodes [29].

3.4 Effect of applied current density

Figure 6 (a-c) represents the performance of EC unit for COD, color, and turbidity removal from CSWW under the effect of different applied current densities. The experiment was carried out at 75 min contact time, and TDS 3000 mg L^{-1} while pH was adjusted to be around 7 with variable current of 2, 4, 6 and 8 mA cm^{-2}. Applying 2 mA cm^{-2} CD showed low removal rate of COD and the maximum removal efficiency achieved was 88% with residual value of 490 mg L^{-1} while the removal rate for color and turbidity was 97% and 83% respectively. Increasing current density to double value (4 mA cm^{-2}) showed significant reduction of COD to about 94% with residual concentration of 190 mg L^{-1} after 1.25 h with near complete color and turbidity removal (99%). The increase of CD to 6 mA cm^{-2} then 8 mA cm^{-2} showed higher removal efficiency at minimal time reaching to 45 min at which 96% COD removal achieved and final removal efficiency was 97% after 75 min with final residual concentration of 101 mg L^{-1}. Also, color, and turbidity removal efficiencies were 99.9 and 99.2% at 6 and 8 mA cm^{-2}.

The results showed the importance of current density as kay parameter in EC process for pollutant removal from CSWW. The formation of metal hydroxide and the reaction rate in the electrocoagulation process is directly affected with current density as it could control the dissolution rate of metal coagulant from electrode, and bubble evolution and accordingly, influences the development of flocs [30]. The dissolved metal hydroxide (Al_2O_3) released from electrodes combines with suspended particulates and results in settling of this formed floc and consequently removal of organic matter, turbidity and color.

Although high removal efficiencies achieved at higher current densities, obtained experimental results, from the techno-economic approach, it would be unfavorable to apply high current density due to high operational costs. Increasing current density will increase the rate of metal ions dissolution electrode and causes high electrode consumption. The calculated electrode consumption in this study at current density 2, 4,6 and 8 mA cm^{-2} were found to be 0.152, 0.287, 0.482 and 0.61 kg m^{-3} respectively. Based on this, it can be concluded that 4 mA cm^{-2} is the optimum current density which achieved satisfactory removal rate with suitable electrode consumption.

3.5 Techno-economic evaluation of EC process in continuous flow for CSWW at optimum operating parameters.

The results from experiments revealed optimum parameters for operation of EC reactor treating CSWW at contact time 60–75 min, pH 7–8, TDS ≤ 3000 mg. L^{-1}, and current density 4 mA cm^{-2}. A continuous flow experiment was carried on CSWW sample that was adjusted at these optimum conditions. The CSWW was fed to EC unit via peristaltic pump to simulate the application of full-scale EC reactor. The TDS of CSWW was adjusted to be about 3000 mg L^{-1} while the pH was 7.1 and current density 4 mA cm^{-2} with 60 min operation time. The influent and effluent wastewater was analyzed the results depicted in Table 2. The results indicated a satisfactory elimination of all pollutants under these optimum operating conditions.

Table 2
CSWW characteristics before and after continuous EC treatment at optimum operating conditions

Parameters	Units	CSWW before treatment	After Treatment	% Removal	Discharge limits
pH		7.1	7.87	–	6–9
COD	mg L^{-1}	4879	230	95.3	1100
BOD	mg L^{-1}	2530	89	96.5	600
Colour	Pt-Co	5610	12	99.8	–
Turbidity	NTU	580	8.5	98.5	–
TDS	mg L^{-1}	3018	3125	–	–
TSS	mg L^{-1}	156	4.5	97.1	800
TKN	mg L^{-1}	213	42	80.3	100
TP	mg L^{-1}	130	15	88.5	25
Oil & Grease	mg L^{-1}	66	3.6	94.5	100

After application of this continuous experimental, at the optimum operating parameters of EC, the electrodes were weighed to determine the electrode consumption to be included in the actual operational cost calculation. The electrode consumption found to be 0.6 Kg/m^3 and the electrical consumption was 0.876 kWh m^{-3}., The local cost of electricity in Egypt for commercial use is L.E 1.6 /kWh (about 0.09 $/kWh) while the cost of commercial aluminum metal is L.E 40/ kg (2.2 $/kg). The ranges of operation cost at current density from 2 to 8 mA cm^{-2} are from 14.4 L. E/ m^3(0.88 $\$/m^3$) to 57.5 L.E/m^3 (3.6 $\$/m^3$). The cost of operation at these optimum conditions (pH 7, 4mA/Cm^2 and 60 min) was calculated and found to be 26.4 L. E/ m^3 (1.5 $\$/m^3$). This value is very low compared to conventional treatment that could achieve the same treatment efficiency for CSWW using chemical coagulation followed by biological treatment.

4 Conclusions

In this study electrocoagulation of CSWW is investigated and evaluated through different operating parameters including contact time, pH, current density, and TDS concentration in batch and continuous mode. Increasing TDS concentration and current density resulted in decreasing the treatment time of EC process. However, high TDS and current density values economically disadvantageous because of increasing operation cost related to power consumption and amount of chemical added to adjust the TDS value. At optimum conditions, more than 94% of the organic matter and 98% of color removal was achieved after 75 min time TDS 3000 mg L^{-1}, pH 7 and current density of 4 mA cm^{-2} at initial COD concentration of about 4450 mg L^{-1}. After application continuous experimental study at the optimum operating parameters of EC on CSWW, The total operation cost related to energy and electrode consumptions was determined as 1.5 $\$/m^3$ in the optimum operation conditions.

Declarations

Availability of data and materials

All data generated or analyzed during this study are available upon request

Competing interests

The authors declare they have no competing interests.

Authors' contributions

Mohamed Hellal provided experimental work, analyze data and writing the manuscript, Hala Doma writing the manuscript and revising data analysis, Enas Aboutaleb, supervising the work, data revision

All authors read and approved the final manuscript.

Funding information

Not Applicable

Acknowledgements

The authors acknowledge all technical and financial support as a research grant from the Academy of Scientific Research and Technology (ASRT), Ministry of Research, Technology, and Higher Education, Egypt.

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Figures

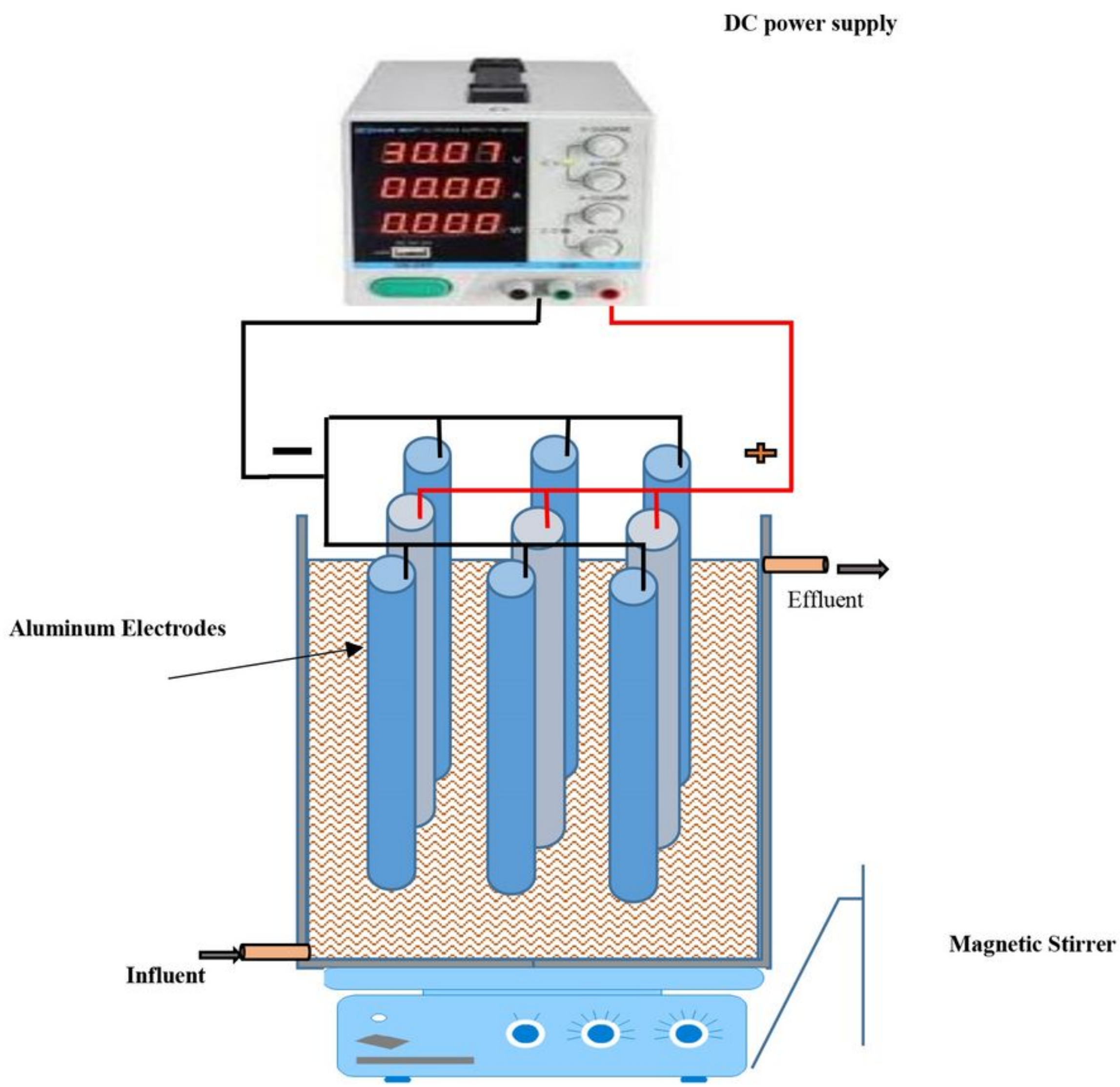

Figure 1

Electrocoagulation treatment cell

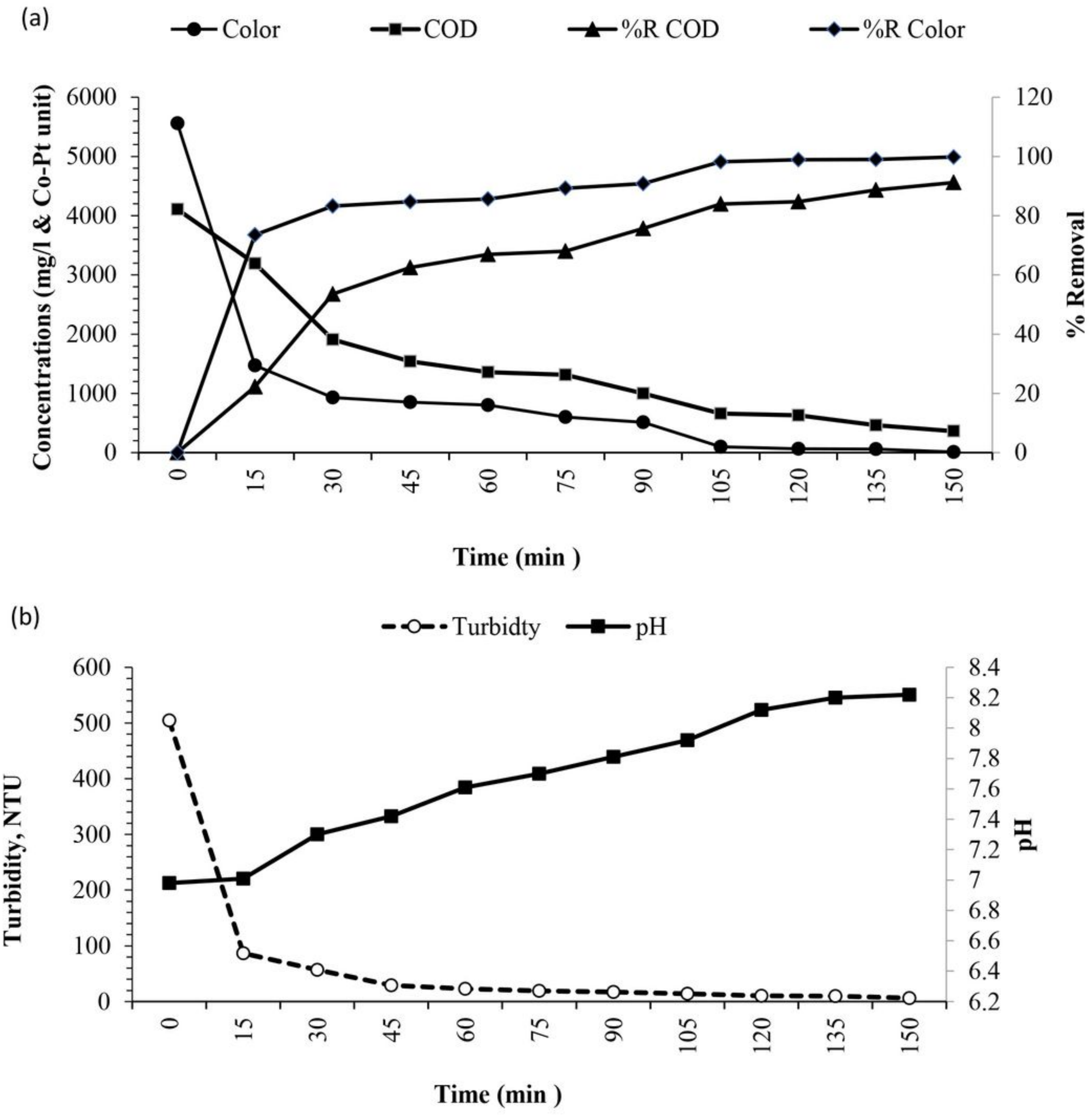

Figure 2

Effect of contact time on the removal efficiency of: (a) COD and color, (b) Turbidity

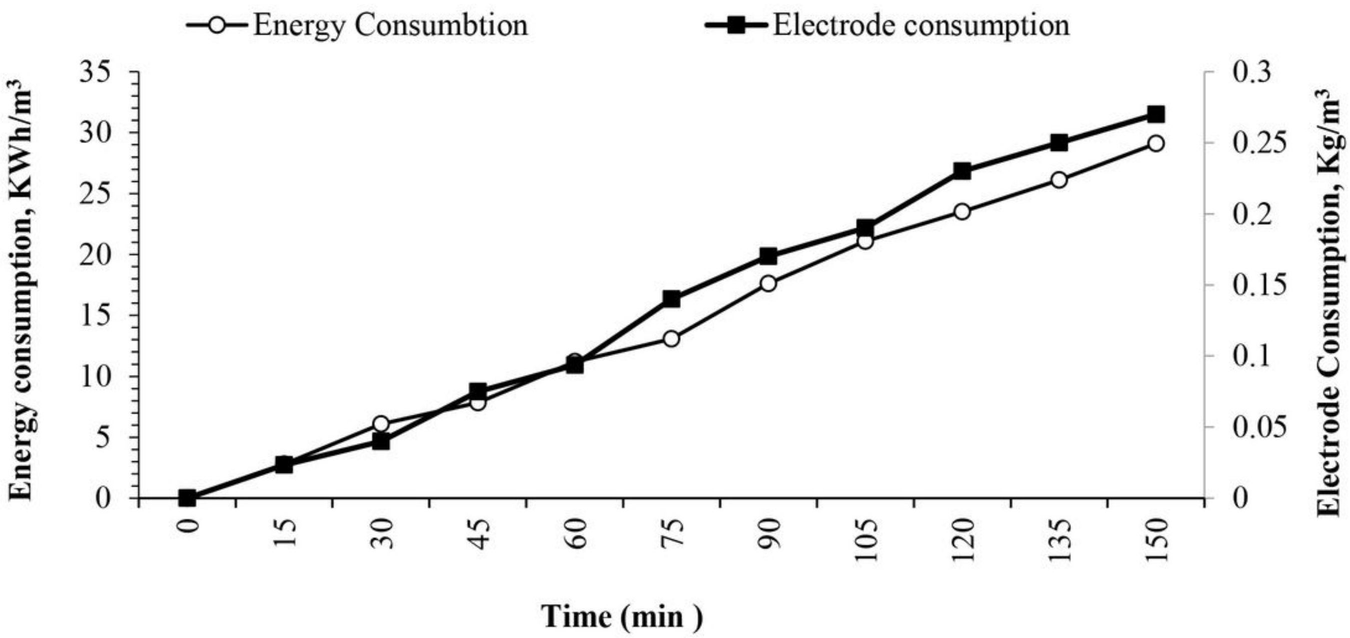

Figure 3

Energy and electrodes consumption as function of time during EC process

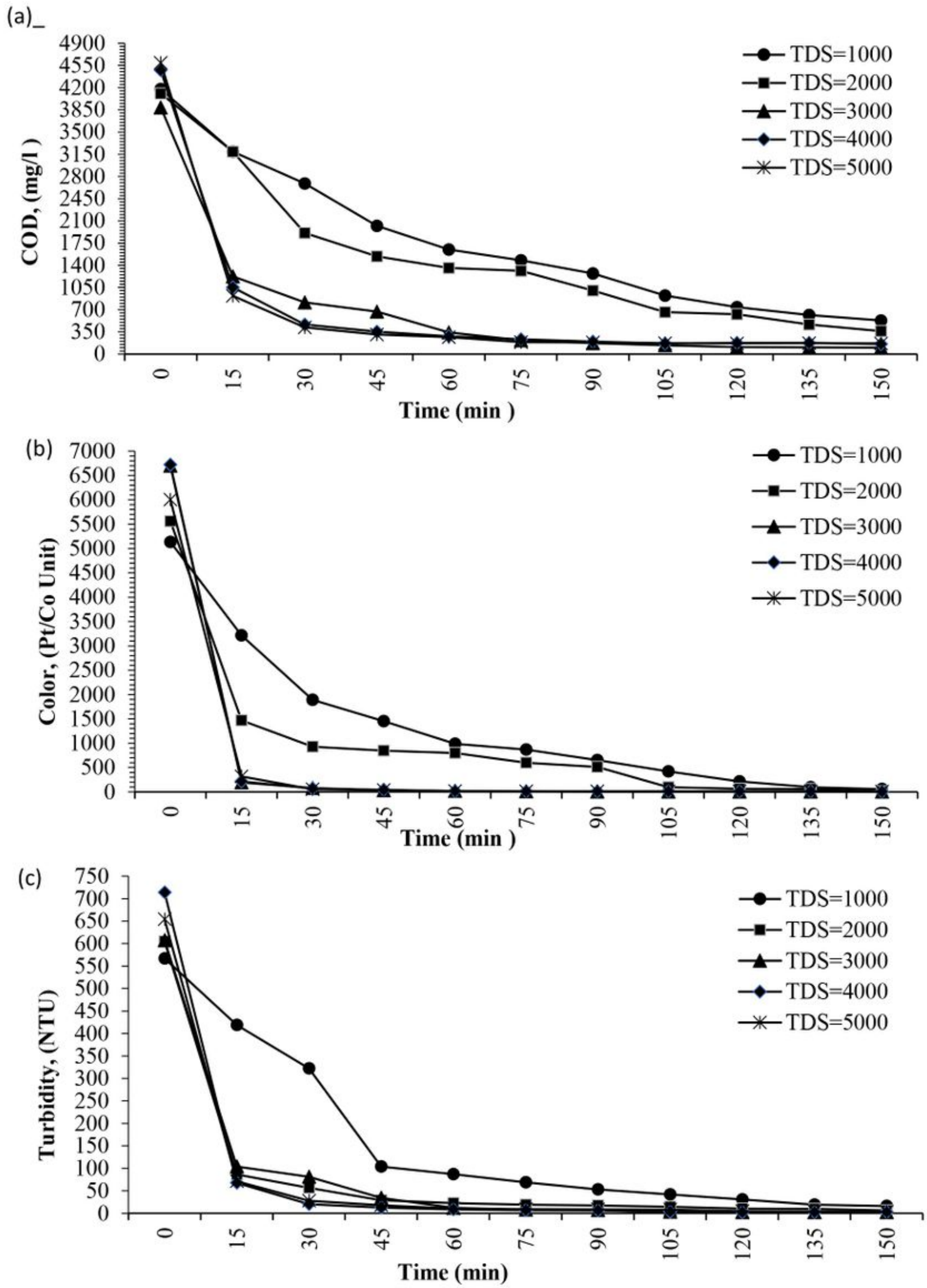

Figure 4

Effect of TDS concentrations on the reduction of : (a) COD, (b) color and (c) turbidity.

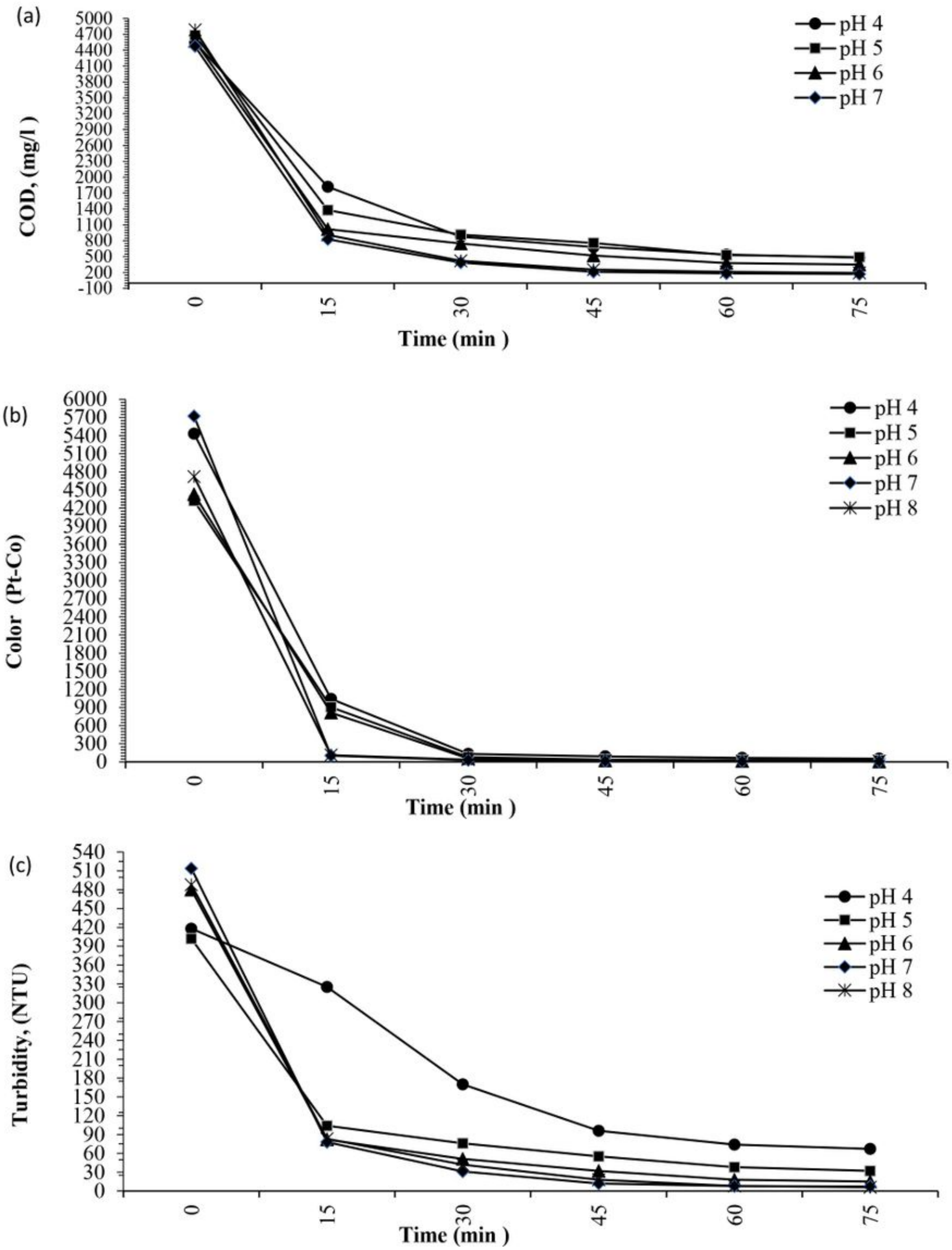

Figure 5

Effect of pH on the reduction of : (a) COD, (b) color and (c) turbidity

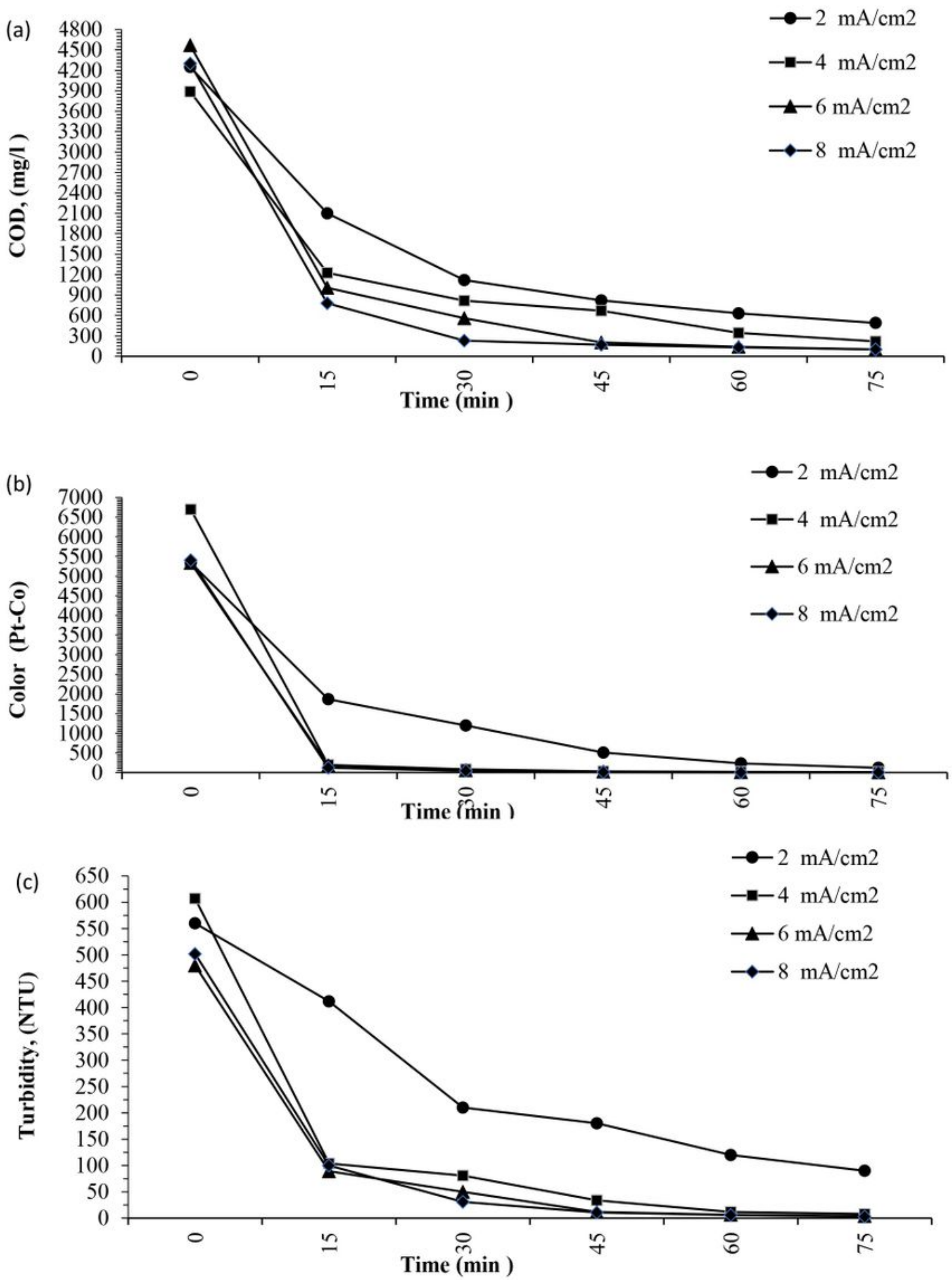

Figure 6

Effect of pH on the reduction of : (a) COD, (b) color and (c) turbidity