



Steel slag promoted electrocoagulation process for the treatment of produced water

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ABSTRACT

Produced water is a by-product produced from the oil and gas industry. It poses a significant threat to the environment due to its high salinity and high pollutant concentration. In this paper, steel slag was used to enhance the efficiency of the electrocoagulation process for the treatment of produced water. The impact of current density, residence time and quantity of steel slag were studied. Results revealed that the slag particles introduced an adsorption surface for the pollutants to adhere to and produced extra coagulating agents which resulted in higher pollutant removal efficiency. For a residence time and current density of 10 min and 10 mA/cm², respectively, the steel slag containing system (with slag concentration of 5 g/L) achieved 89.7% removal for total suspended solids compared to 55.7% for the conventional system without steel slag. The total operating cost which is comprised of the electrical energy and electrode material costs was maintained minimal at 0.039 \$/m³.

Keywords: Electrocoagulation; Adsorption; Produced water; Steel slag; Total suspended solids; Oil and grease

1. Introduction

Produced water (PW) is a by-product produced from the oil and gas industry. The quantity of produced water surpasses the amount of extracted oil by a volumetric ratio of 4:1 [1]. This amounts to around 250 million gallons a day on a global scale [1,2]. The quality of produced water from oil fields varies widely depending on the age of the well, the extraction method, the underground geological formation, the hydrocarbons extracted and the reactions of the water with the subterranean compounds [3]. Produced water primarily contains high concentrations of total dissolved solids and long-chain hydrocarbons which, if discharged without treatment, are toxic for the environment [4]. PW is

usually re-injected into the oil wells, dumped into the sea or reused in further applications [3,5]. However, these applications require adherence to strict environmental regulations with regards to the final effluent quality, thus PW has to be treated [4].

The primary objective of PW treatment is to remove oil, soluble organic compounds, suspended solids, dissolved gases, and trace contaminants and any naturally occurring radioactive materials [5]. This can be accomplished by membrane filtration, biological processes, adsorption, air flotation, reverse osmosis, gravity separation, and other physical-chemical treatment processes [2,6,7]. However, these treatment technologies have some drawbacks in terms of large space requirements, high energy requirements, high

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sludge production, limited treatment efficiency, process complexity and the generation of toxic by-products and chemical residues [1,5,6]. Thus, there is a scope to improve PW treatment technology.

Coagulation and flocculation are a widely used technology for wastewater treatment [8]. Coagulation is a process where a chemical coagulant is used to merge small pollutant particles to form large pollutant particles known as floc [9]. Electrocoagulation (EC) is an advanced coagulation process that is known to achieve high-quality effluents without the need to add chemical reagents. The sludge produced in EC is denser and has lower water retention compared to conventional coagulation. In addition, the EC process requires short residence time, which makes it an attractive option for facilities receiving high flow rates of wastewater [10,11]. Electrocoagulation has been considered a suitable technology to treat wastewaters contaminated by organics, solids, oils, and dyes [11,12].

EC is an electrolytic process where the electrodes are usually made of aluminum (Al) or iron (Fe) and the wastewater acts as the electrolyte [7]. Passing electricity through the electrolytic cell would result in the generation of ions (Fe^{2+} or Al^{3+}) from the sacrificial anode, while H_2 gas and hydroxide (OH^-) ions would be generated at the cathode [11]. The generated anions and cations form the metal hydroxides ($\text{Fe}(\text{OH})_2$, $\text{Al}(\text{OH})_3$) would act as the coagulants. Coagulants are expected to increase the ionic strength of water, subsequently reducing the zeta potential of the colloidal particles present in solution [11,13]. Zeta potential is the potential difference between the surface of the particle and the bulk fluid in which the particle is present as shown in Fig. 1 [14]. The decrease in the zeta potential makes the Van der Waal's forces between the particles more dominant [13]. This will cause the particles to aggregate where they become large enough in size that they can be separated by gravity settling [15]. In addition, the generation of hydrogen (H_2) gas and oxygen (O_2) at the cathode and anode, respectively, would carry some light pollutants to the top by electro flotation where they can be easily collected and removed [16].

Several studies have focused on the use of the EC process for the removal of oil and grease (O&G) and other pollutants from water samples using various configurations and operating conditions. Xu and Zhu [11] studied the effect of pH, current density, residence time, electrode distance and inlet concentration on the removal efficiency of oil and grease from refractory wastewater using EC. At a current density of 1–1.4 mA/cm^2 and 30 min residence time, 95% of removal efficiency were achieved [11]. An electrocoagulation process coupled with electro flotation was used by Bande et al. [1] to separate oil from the oil field produced water. The study demonstrated that more than 90% of oil can be removed at a pH of 4.72 and 30 min residence time [1]. Similarly, Zheng [17] used EC for the treatment of produced water. It was found that EC can remove 98.3%, 99.0%, 98.8%, 98.1%, and 94.3%, of chemical oxygen demand (COD), O&G, turbidity, total suspended solids (TSS), and polyacrylamide, respectively. The removal percentages were achieved by applying a current density of 35 mA/cm^2 , the pulsed duty cycle of 0.3 and the residence time of 40 min [17]. The high removal percentage was aided by generated H_2 gas at cathode [18].

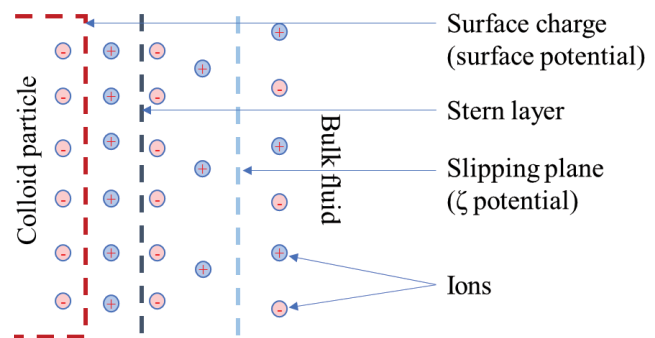


Fig. 1. Zeta potential between the particle surface and bulk fluid.

To enhance the efficiency of the EC process aluminum chloride (AlCl_3) and powdered residual (burnt sludge) from a water purification plant have been used as additives [19,20]. The addition of AlCl_3 in oil sands produced water improved total organic carbon removal efficiency by 40% [19]. And, the addition of powdered residue improved dye removal efficiency by 65% [20].

Steel slag is a by-product of the steel manufacturing industry, where limestone is used as a melting point reducing agent to remove the impurities in the iron ore which gets deposited as steel slag [21]. Steel slag is usually generated in large quantities and its disposal poses a significant burden on steel factories [21]. This waste by-product possesses a porous structure with a high surface area and contains oxides such as FeO – Fe_2O_3 – SiO_2 – CaO – Al_2O_3 . These oxides show characteristics that are similar to coagulants. They have high adsorption capacity and have been used effectively in many studies to remove ammonia, nitrogen, phosphorus, and metals from water through adsorption and precipitation [22–25]. Yin et al. [26] removed 90% of COD from non-degradable organic wastewater using steel slag as a catalyst in an oxidative degradation process. Feng et al. [27] used steel slag as an adsorbent to treat acid mine wastewater. Since the density of steel slag is between 3.3 and 3.6 g/cm^3 , they can be easily separated from water by gravity settling [22].

This paper will study the effectiveness of steel slag as a potential additive for the enhancement of the EC process. The impact of current density, reaction time and quantity of added steel slag on the removal efficiency of TSS and oil and grease was studied. The produced sludge volume and anode consumption were also evaluated. Finally, the operating cost of the enhanced EC process was analyzed.

2. Materials and set up

2.1. PW characteristics

Produced water (PW) used in this study was prepared by mixing salts, solids, and oil in deionized (DI) water. Selected salts included, iron sulfate (FeSO_4), calcium chloride (CaCl_2), potassium chloride (KCl), magnesium chloride (MgCl_2), sodium chloride (NaCl) and calcium sulfate (Ca_2SO_4). All salts were of an analytical grade purchased from Sigma-Aldrich (United States). The required oil and grease concentration was added by adding a commercial engine and

gearbox oil. Oil and grease were mixed in a high shear mixer for 4 h to ensure complete emulsion of oil in water. Solids were then added to act as suspended solids. The characteristics of the prepared produced water are given in Table 1. The composition of the synthesized PW is comparable with raw PW data available in literature.

2.2. Steel slag characteristics

The steel slag used in this study was provided by Qatar Steel. The composition of steel slag was analyzed using energy-dispersive X-ray spectroscopy (EDAX). The EDAX analysis in Fig. 2 shows that 40% of the total weight of steel slag is made up of iron oxides and calcium oxides. In addition, other metals such as magnesium (Mg) and aluminum (Al) are present in small quantities. The steel slag particles have gravel-like texture and a blackish color. Moreover, white dust particles are found within the steel slag. To remove the dust particles, the slag particles were washed with distilled water. Subsequently, the slag particles were ground using a Planetary Ball Mill (PM 100 cm, Retsch, Germany) for 5 min at 500 RMP and then passed through a 40-micron filter. Thus, collecting steel slag particles with an average size of 425 μm . The ground steel slag can be seen in Fig. 3.

2.3. Experimental setup

A schematic diagram for the experimental setup is shown in Fig. 4. Two beakers containing produced water, one with steel slag and one without steel slag were used. Two rectangular aluminum plates (9.8 cm \times 5.5 cm) of 1 mm thickness were mounted on a polyvinyl chloride spacer with an inter-electrode distance of 2.5 cm were immersed in the used beakers. Prior to being used, the aluminum plates were rinsed from any metal oxidants using hydrochloric acid and polished with sandpaper. The current was provided by a direct current (DC) power supply (GPC-3060D, GW Instek, Taiwan). A magnetic stirrer, operated at a speed of 250 rpm,

Table 1
Synthesized produced water characteristics and comparison with literature [28,29]

| Chemical constituent | Synthesized PW | Range from literature |
|------------------------------------|-------------------|-----------------------|
| pH | 6.3 \pm 0.1 | 6–6.78 |
| Conductivity (mS/cm ²) | 94.4 | |
| Oil and grease (ppm) | 950 \pm 47.5 | 900–1,000 |
| Total suspended solids (ppm) | 3,116 \pm 155.8 | |
| Color | Black | |
| Turbidity (NTU) | 915 \pm 45.8 | |
| Iron (ppm) | 50 | 0–100 |
| Sulphate (ppm) | 600 | 596–836 |
| Calcium (ppm) | 7,200 | 7,132–13,000 |
| Chloride (ppm) | 84,000 | 111,000–85,745 |
| Potassium (ppm) | 400 | 253–847 |
| Magnesium (ppm) | 1,650 | 1,058–1,743 |
| Sodium (ppm) | 52,400 | 37,939–53,550 |

was used to ensure complete mixing within the reactor. The conductivity and pH were monitored throughout the experiments using a WTW (Germany) Multi 3430 multi-parameter meter (Cole-Parmer, United States). At the end of each experiment, samples were extracted from the reactors using a peristaltic pump (FPU5-MT, Omega, Czech).

2.4. Experimental procedure

To investigate the effect of the steel slag on the EC performance, the experiments were run at room temperature, the current densities (CD) were varied between 10, 30, and 60 mA/cm², and the residence time was varied between 10, 30, and 60 min.

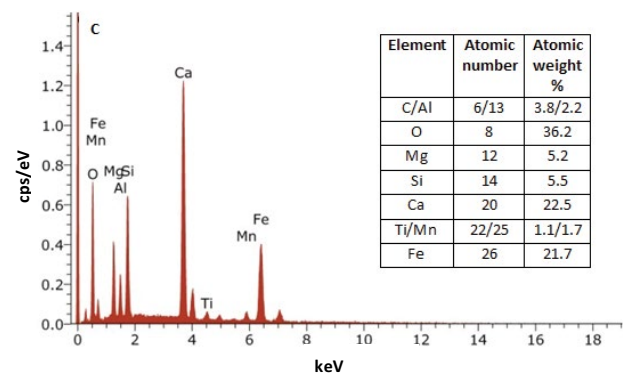


Fig. 2. EDAX analysis of the slag sample prior to EC.



Fig. 3. Ground steel slag sample.

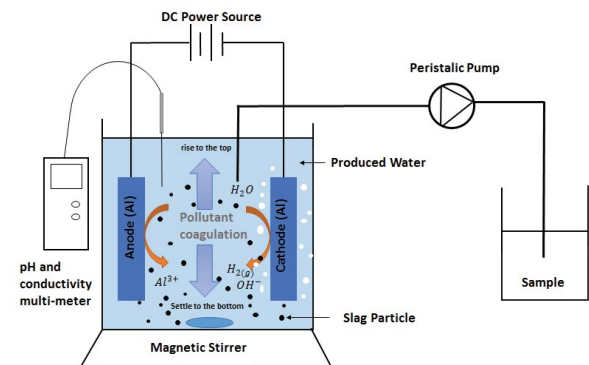


Fig. 4. Schematic diagram of the EC system.

To evaluate the effect of various operating conditions in the EC process, the concentrations of TSS and O&G were measured before and after each run. The concentration of TSS was determined by filtering 50 mL of the withdrawn sample using a 1.5 μm pore size TSS glass fiber filter. The weight of the filter was measured after drying at 105°C for 2 h. O&G concentration was measured using the ASTM D7066-04 standard method method [30]. The method involves liquid separation carried out at different stages. Initially, 100 mL of the withdrawn sample was mixed with a 20 mL of S316 polymeric solvent and a 1 mL of 50% HCl (Hydrochloric acid). This mixture was then agitated for 5 min in a conical flask and left to settle for 10 min. A funnel was then used to remove the solvent and the oil layer was collected and measured for its oil and grease content using the OCMA-350 oil content analyzer (Horiba, Japan). In addition, the amount of sludge after each run was measured by an Imhoff cone.

The mass of electrodes was measured before and after each run. Microscopic observation of the steel slag was carried out using a scanning electron microscopy (SEM) (JCM-6000, JEOL, Japan) before and after each EC process. Fourier-transform infrared spectroscopy (FTIR) analysis using the FTIR spectrometer (Nicolet iS10, Thermo Scientific, United States) was also performed on the steel slag.

3. Results and discussion

3.1. Effect of current density

3.1.1. Effect of current density on removal efficiency

Fig. 5 shows TSS removal efficiency and produced sludge at different current densities for pure and steel slag containing produced water. It can be seen that at 10 mA/cm² current density (CD10) the slag containing sample showed a better TSS removal efficiency of 89.7% compared to 55.7% achieved by the pure sample. At a current density of 30 mA/cm² (CD30), the slag containing the sample still shows a better TSS removal efficiency of 98.7% compared to 91.7% achieved by the pure sample. However, at 60 mA/cm², both pure and steel slag containing samples show similar TSS removal efficiency. The increase in current density is expected to result in the production of additional Al³⁺ ions in the solution. This would result in the formation of more Al(OH)₃ which would act as a coagulant. Thus, the TSS removal efficiency increases with the increase of current density as shown from the behavior between CD10 and CD30 in Fig. 5.

The PW sample containing steel slag achieved higher TSS removal efficiency than the sample without steel slag because extra metal ions were produced from the steel slag. The EDAX analysis of the steel slag in Fig. 2 showed that steel slag contains iron oxides and calcium oxides, along with other metals such as magnesium and aluminum. These ionic metal oxides form metal ions in water. The metal ions form metal hydroxides that work as extra coagulants in solution as demonstrated in Fig. 6. As a result, the ionic strength of the solution increases. This in return will further reduce the zeta potential of the suspended particles which will enhance their removal [22–25]. Moreover, the floating steel slag particles are expected to become positively charged by the electric field of the EC cell [10,31]. Subsequently, the Fe and Fe oxides on the charged slag surfaces will be ionized to produce

ferrous iron (Fe²⁺). This Fe²⁺ ion would combine with hydroxide (OH⁻) present in water and form Fe(OH)₂, which will also act as coagulant [32].

As the current density increases to 60 mA/cm² (CD60), it was noticed that the TSS removal efficiency was similar for both steel slag containing PW and PW without steel slag (i.e., 90%). Moreover, for the slag containing sample, the removal efficiency of TSS at CD60 was 10% less than the removal efficiency at CD30. This is because in CD60 the pH of the solution becomes 7.3 because of the increased pollutant removal. Increasing pH above 7 or decreasing pH below 5 would result in lower removal efficiencies [33]. This occurs due to the amphoteric nature of Al(OH)₃. Al(OH)₃ decomposes to Al³⁺ ions at low pH values and Al(OH)₄⁻ at higher pH values. These water-soluble ions would lose their ability to reduce zeta potential of the suspended particles and lose their coagulation property resulting in reduced final TSS removal efficiency [3].

The sludge volume increases with the increase of current density as seen in Fig. 5. At CD10 the sludge volume is 10 and 13 mL/L for pure PW and PW with steel slag. This increases to 50 and 80 mL/L for pure PW and PW with steel slag at CD60. The increase of removal efficiency from CD10 to CD30 supports this finding. However, for PW with steel slag, between CD30 and CD60, the removal efficiency is decreasing while the sludge volume is increasing. This is due to the increase of metallic sludge from anodic decomposition at a higher current density. Moreover, additional decomposition

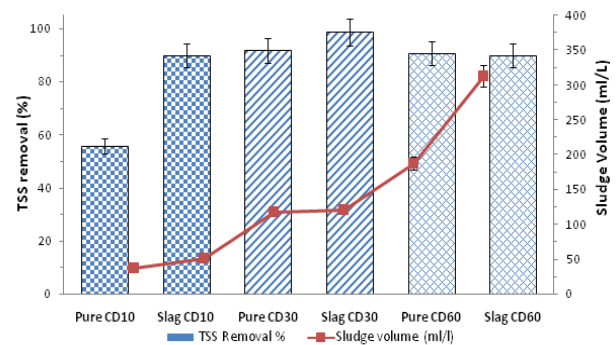


Fig. 5. Effect of current density on TSS removal efficiency and sludge volume production.

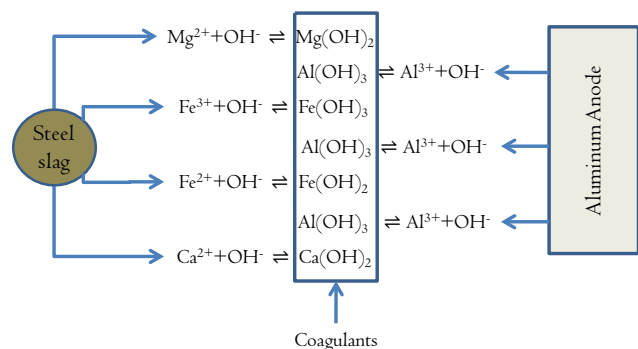


Fig. 6. Extra coagulant produced from steel slag.

of $\text{Al}(\text{OH})_3$ at CD60 is responsible for producing more sludge than PW without slag.

3.1.2. Effect of current density on anodic decomposition

Fig. 7 shows the rate of anodic decomposition at different current densities. For CD10, the anodic decomposition percentage is identical for PW with and without steel slag. As predicted by Eq. (1), the anodic decomposition increases with increasing the current density. However, for CD30, the anodic decomposition rate is 25% higher for pure PW. This can be attributed to the presence of high amounts of Fe_2O_3 and CaO in the studied steel slag [24]. These oxides will possess a net positive charge making the overall surface charge of the slag positive. Consequently, the positive slag surface will compete with the anode and would reduce the extent of the anodic dissolution. At CD60, the anodic decomposition for PW containing steel slag is 25% higher than the anodic decomposition for pure PW. This significant increase in the anode consumption, particularly for the slag containing sample can be explained by the increase in hydroxide ions (OH^-) release from the water reduction reactions and steel slag decomposition at higher pH values in the electrolyte solution [34]. Since the pH of the solution increased from 6.3 to 7.3, this theory can be confirmed. Moreover, the FTIR results in Fig. 8 show that the hydroxide ions tend to deposit on the slag surface. Consequently, at higher pH values the slag surface developed an overall negative charge that reacted with the Al anode and resulted in significant anodic consumption and an increased amount of produced sludge for CD60.

From the FTIR analysis, it is evident that extra species have been adsorbed on the steel slag surface. Prior to initiating the EC process, the infrared spectrum for the surface of the slag sample showed a band at $1,438\text{ cm}^{-1}$ which is assigned to the Fe–O bond, indicating the presence of iron oxide and iron hydroxide compounds. Moreover, a band at 875 cm^{-1} denotes that a Si–O bond is also present in the steel slag. Following the EC treatment process, the FTIR analysis revealed the presence of other functional groups predominantly the hydroxide group (O–H) with a strong band stretch at $3,337\text{ cm}^{-1}$ and the $1,630\text{ cm}^{-1}$ band is assigned to the bent vibration of H–O–H. Thus, the results indicate that pollutants and hydroxyl species have been adsorbed on the surface of the steel slag.

Steel slag can act as an adsorbent. Uncrushed steel slag and crushed steel slag, with $425\text{ }\mu\text{m}$ average particle size were tested for their adsorption ability without EC (Fig. 9). As shown in Fig. 9 the smaller particle size steel slag used in the EC reactor has better TSS removal ability compared to the uncrushed steel slag. The smaller the particle size the higher the surface area available for adsorption. Moreover, the highest TSS removal efficiency using crushed steel slag was at a steel slag concentration of 5 g/L ; whereas, for uncrushed steel slag, the highest TSS removal efficiency was at a steel slag concentration of 10 mg/L . The increase of steel slag concentration above these optimum values will cause extra turbidity in solution due to the excess amount of steel slag.

Additionally, the deposition of pollutants on the slag surface can be confirmed by the SEM images in Fig. 10.

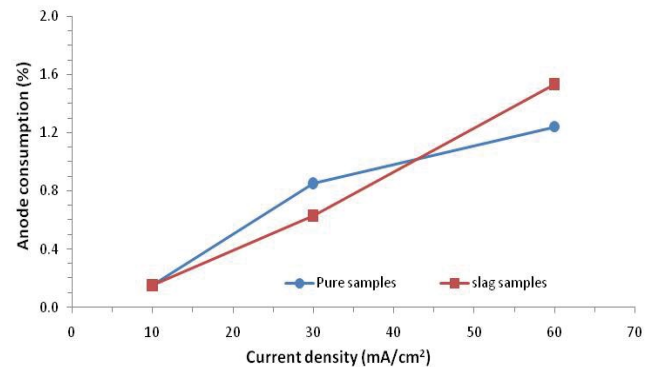


Fig. 7. Effect of current density on percentage anode consumption, for pure samples and slag containing samples at 10 min reaction time.

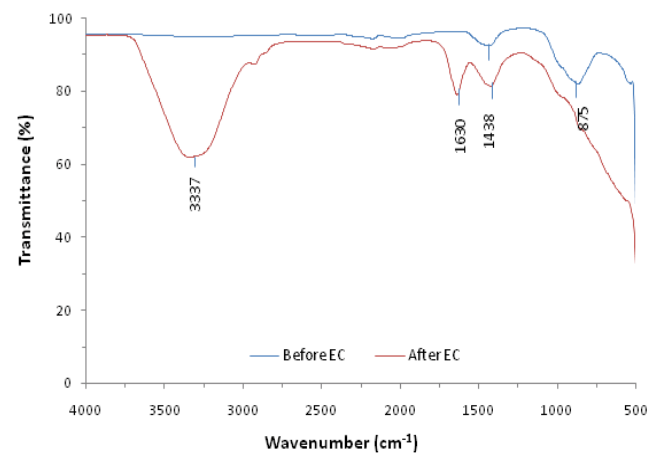


Fig. 8. FTIR analysis for the slag sample before and after the EC treatment process at 10 mA/cm^2 and 10 min residence time.

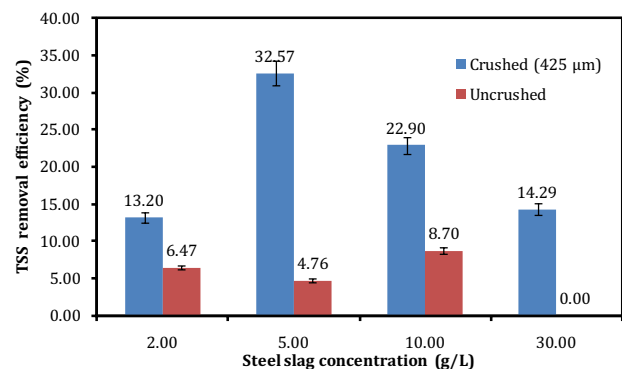


Fig. 9. Effect of crushed ($425\text{ }\mu\text{m}$) and uncrushed steel slag on turbidity removal efficiency.

The images were taken for the slag sample before and after the EC treatment process at 10 mA/cm^2 current density and 10 min residence time. The images reveal that prior to the treatment process the slag surface possesses a large structure with wide gaps. These gaps became smaller after the

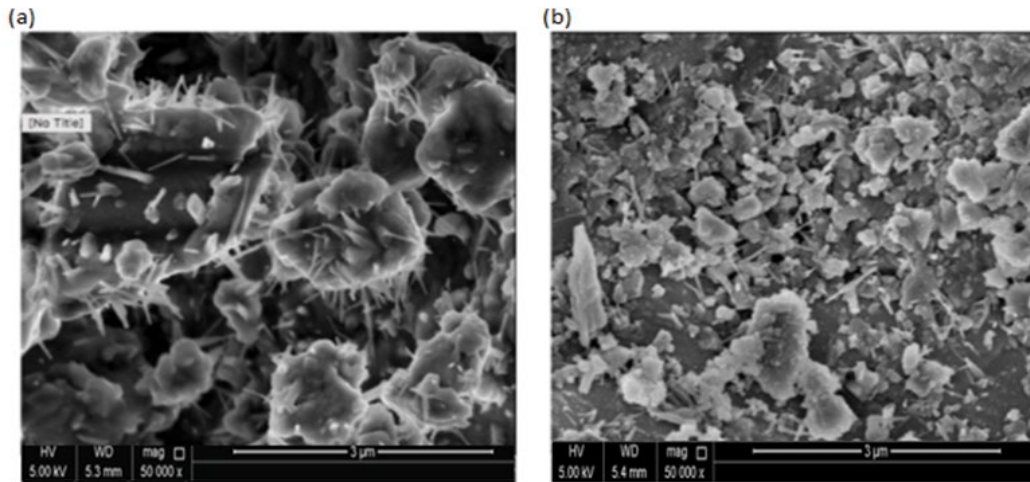


Fig. 10. SEM images for two slag samples at different magnifications, (a) Pre-EC treatment at X50k and (b) Post-EC treatment at X50k.

treatment process owing to the sorption of suspended solids on the surface of the steel slag.

3.1.3. Effect of current density on O&G removal

The oil and grease removal percentages after 10 min residence time are illustrated in Fig. 11 for the same three slag containing samples and the three pure PW samples, at different current densities. It can be seen that the O&G removal remained high and consistent in the vicinity of 99% for all the samples regardless of the increasing current density and the added steel slag. These high removal efficiencies for oil and grease are in agreement with most of the studies conducted on wastewater treatment in which current densities as low as 1.5 mA/cm^2 were able to remove around 99% of the O&G concentrations [11]. Therefore, it is expected that at the used experimental running conditions the O&G was highly removed. O&G are immiscible with water. Thus, if enough time is given, O&G will separate itself from the mixture and form an immiscible layer above water [35]. In EC, this process is enhanced by the production of H_2 gas at the anode. Oil and gas are moved up towards the surface by the H_2 gas bubbles [35]. The formation of foam inside the vessel further proves the formation of H_2 gas at the cathode. The increased ionic strength of water, due to the presence of coagulants in water, makes the size of hydrogen bubbles smaller. Due to the smaller size of H_2 bubbles, the surface area of the produced H_2 bubbles increases. This gives more opportunity for oil and gas to get attached to the H_2 bubbles [36].

3.2. Effect of residence time

3.2.1. Effect of residence time on removal efficiency

To study the effect of reaction time on the electrocoagulation process for the slag containing samples and the pure samples, the current density was kept constant at 10 mA/cm^2 while the reaction time was changed. Three pure samples and three slag containing samples with 5 g of added slag were used. The reaction times were set to 10, 30, and 60 min.

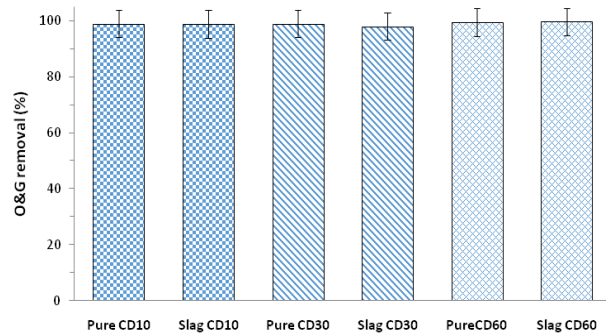


Fig. 11. Effect of current density on percentage O&G removal for pure samples and slag containing samples at 10 min reaction time.

Fig. 12 summarizes the results obtained for the percentage of TSS removal and the amount of sludge formed. When the reaction time increases, the TSS removal also increases due to the formation of more metal ions and their corresponding hydroxide as predicted by Eq. (1). It can also be seen that the slag containing samples continue to show good performance with regards to TSS removal efficiencies. For instance, as the reaction time increases from 10 to 60 min, the TSS removal increases from 89.7% to 97.6% for the slag containing sample. The increase in contact time between pollutants and slag particles led to an increase in the pollutant adsorption potential [26]. The amount of sludge formed also increased with the increase in the residence time for all the samples. The slag containing samples produced the highest amounts of sludge in all runs due to the high pollutant removal.

3.2.2. Effect of residence time on anodic consumption

The anode consumption for the case of the slag containing samples at running residence time of 10 and 30 min remains fairly low at 0.15% and 0.61%, respectively as seen in Table 2. However, after 60 min reaction time, the anode

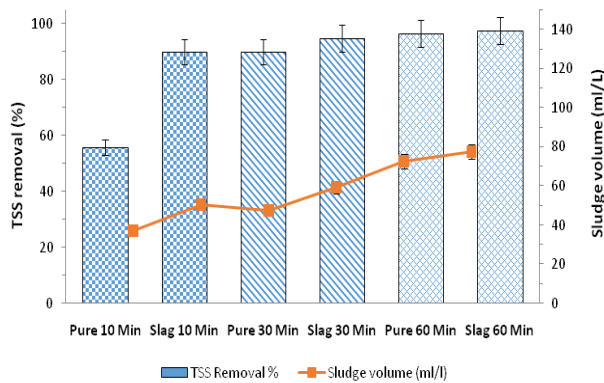


Fig. 12. Effect of reaction time on %TSS removal and sludge volume produced for pure samples and slag containing samples at 10 mA/cm² current density.

consumption is 9 times higher due to a large amount of electrode material being sacrificed over longer residence time.

3.3. Effect of steel slag concentration on removal efficiency

To study the effect of steel slag on the EC performance, three different doses were used in the system: 5, 10, and 15 g/L. The current density and the residence time were held constant at 10 mA/cm² and 10 min, respectively. The results were compared with the PW with no steel slag. Fig. 13 illustrates the percentage removal of O&G and TSS for each of the 4 different samples. The oil and grease removal continue to show high efficiencies with more than 95% removal in all samples. It is to be noted that, the ability of SiO₂ present in the steel slag to hold on to oil and grease is responsible for reduced O&G removal efficiency at a higher dose of steel slag [37]. As for the TSS removal, the 5 g/L slag containing the sample shows the best performance. Doubling the amount of steel slag from 5 to 10 g/L caused a decline in the percentage of TSS removal by 11.9%. This could be due to the increase of pH value to more than 7. Initially, the steel slag shows similar performance, but when the pH reaches above 7, Al(OH)⁺ is produced and the steel slag would lose its coagulation property. In addition, the excess steel slag concentration could have led to the destabilization of the colloidal particles by reversing their charge [38]. This results

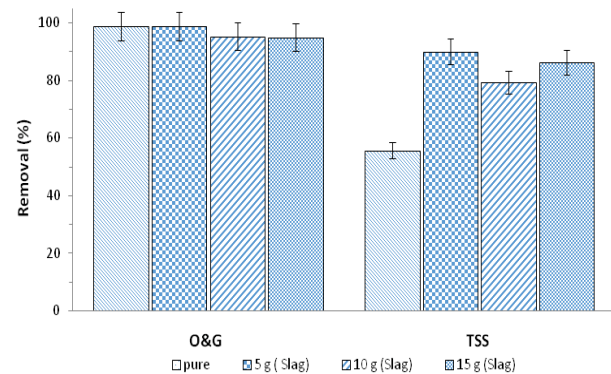


Fig. 13. O&G and TSS percentage removal for pure samples and samples containing 5, 10, and 15 g/L of steel slag, at 10 mA/cm² current density and 10 min reaction time.

in reduced TSS removal efficiency. At 15 g/L steel slag concentration, similar performance may occur at the beginning. But reduced TSS removal rate and additional dust particles from steel slag reduce the pH further below 7 which would facilitate the Al(OH)₃ production. Thus, a concentration of 15 g/L showed a better TSS removal rate when compared to 10 g/L. However, the highest removal rate is obtained at 5 g/L steel slag concentration.

3.4. Operating cost

The total operating cost for the current electrocoagulation system with the added steel slag is shown in Table 2. It is assumed in this study that the electrical energy cost and the electrode material are the two major components of the total operating costs. The local energy and electrode material costs are 0.0216 US \$/kW h⁻¹ and 1.852 US \$/kg, respectively. The cost of anode and energy consumption can be calculated as:

$$\text{Cost of electrode} = \text{mass of consumed electrode} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{cost of electrode} \left(\frac{\text{US\$}}{\text{kg}} \right) \quad (1)$$

Table 2

Results for the effectiveness of the performance of the EC process with added steel slag at different operating conditions

| | Residence time 10 min | | | Current density 10 mA/cm ² | | |
|--|--------------------------|--------------------------|--------------------------|---------------------------------------|----------|----------|
| | 10 (mA/cm ²) | 30 (mA/cm ²) | 60 (mA/cm ²) | 10 (min) | 30 (min) | 60 (min) |
| TSS removal (%) | 89.7 | 98.7 | 90.0 | 89.7 | 94.8 | 97.6 |
| O&G removal (%) | 98.8 | 98.0 | 99.6 | 98.8 | 98.6 | 99.3 |
| Electrode consumption (g) | 0.02 | 0.08 | 0.20 | 0.02 | 0.08 | 0.18 |
| Electrode consumption (%) | 0.15 | 0.63 | 1.53 | 0.15 | 0.61 | 1.37 |
| Electrode consumption costs (\$/m ³) | 0.037 | 0.148 | 0.370 | 0.037 | 0.148 | 0.333 |
| Power consumption (kWh/m ³) | 0.093 | 0.556 | 2.083 | 0.093 | 0.278 | 0.602 |
| Power consumption (\$/m ³) | 0.002 | 0.012 | 0.045 | 0.002 | 0.006 | 0.013 |
| Total operating cost (\$/m ³) | 0.039 | 0.160 | 0.415 | 0.039 | 0.154 | 0.346 |

$$\text{Power consumption} = \frac{\text{Voltage (V)} \times \text{Current (A)} \times \text{Time (h)}}{1,000} \times \text{cost of energy} \left(\frac{\text{US\$}}{\text{KW.h}} \right) \quad (2)$$

It is clear that the cost of the electrode dominates over the energy cost and that the total operating cost increased with increasing the current density and the reaction. The operating cost increased from 0.039 to 0.16 \$/m³ by increasing the CD from 10 to 30 mA/cm² and was almost 4 times higher by using 20 min longer reaction times. Using 10 mA/cm² current and 10 min residence time is enough to achieve more than 90% pollutant removal. Thus, one can conclude that a current density of 10 mA/cm² and a 10 min reaction time are sufficient for efficient pollutant removal while maintaining low operating costs and reduced sludge volume.

Preliminary estimates show that the cost of treating produced water using RO can be as high as 10.8 US\$/m³ [39]. When ceramic-based membranes are used, the operating cost for the produced water treatment process is between 0.20 and 0.05 US\$/m³ [40]. So, at 10 mA/cm² current density and 10 min residence time, the operating cost for steel slag activated EC can be less than silicon-based membrane filtration [40]. Moreover, using micro emulsion modified activated carbon filtration, 76% TSS can be removed [41]. Thus, the proposed system shows better TSS removal efficiency at optimum condition of 10 mA/cm² and 10 min residence time.

4. Conclusions

This study has demonstrated that steel slag can act as an additive in the electrocoagulation process and enhance the treatment of produced water. The removal efficiency of the TSS and O&G were studied for PW with and without steel slag, and better performance was observed for slag containing sample at all tested residence time. The steel slag containing the sample was able to achieve 95% removal efficiency at 60 min residence time and 10 mA/cm² current density. Moreover, the effect of current density was also studied, and at 30 mA/cm² current density, the sludge removal was found to be 98% with 10 min residence time. The addition of steel slag increased the ionic potential of PW and decreased the zeta potential of the suspended particles that resulted in enhanced electrocoagulation with high pollutant removal efficiency. At the optimum operating conditions of 10 mA/cm² current density, 10 min residence time and 5 g/L slag, the volume of sludge formed was 50 mL/L. Moreover, the total operating cost was 0.039\$/m³, which was found to be lower than the operating cost of ceramic membrane-based PW treatment. The electrode consumption was 28% less for the PW sample containing steel slag. The addition of steel slag resulted in additional removal efficiency and lower operating cost, which are the two main factors for the sustainable treatment process. More work is needed to check the scalability of the steel slag promoted EC process proposed in this paper.

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