Implications of advanced wastewater treatment: electrocoagulation and electroflocculation of effluent discharged from a wastewater treatment plant

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Abstract

In this research, wastewater treatment was inspected on a pilot-scale wastewater treatment plant by electrochemical techniques, electrocoagulation (EC), electroflotation (EF) and electrophoretic deposition (EPD). The wastewater samples have been characterised by applying different parameters to determine the optimum working conditions of the electrocoagulation reactor. Two electrodes have been tested separately with an outflow coming from the primary and secondary sedimentation tank. The outflows from these tanks are introduced in the EC reactor, and then EC reactor efficacy is determined for the removal of; chemical oxygen demand (COD), suspended solids, micropollutants and amount of coagulants in agglomerates, at different current densities. The amounts of suspended solids (SS) in the influent and effluent streams were determined by the membrane filtration technique. The operational applied current values range from (1–4 A) in case of COD removal by Fe and Al, while for SS aggregation the applied current ranges from (0.5–3 A) and inflow rate is tested from 250–500 L/h. The pH of the outflows increase by an increase in

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the applied current and both these parameters were found a positive increase in the amount of SS aggregations after EC treatment. The COD removal efficiency was found to be 56–57% and 12–18% in case Fe and Al electrode respectively after EC treatment. The results showed that the applied current is the most effective parameter, whereas the aluminium electrodes have produced more amounts of flocs and bubbles in comparison to iron electrodes at a similar amount of current density.

Keywords: Advanced wastewater treatment; Electrocoagulation; Micropollutants; Suspended solids; Pollution and Cost analysis.

1 Introduction

The removal of anthropogenic micropollutants emitting from industrial, agricultural, domestic and urban sources is one of today’s major challenges. The number of such micropollutants is significantly large and many of these are found in excessive quantities. Pathogenic, non-pathogenic organisms, pharmaceutical and drug residues viruses and vaccines present in large amount in wastewaters. These micropollutants can have direct and indirect effects on the living organisms by bio magnification along the food chain. All the mentioned sources of wastewater produce a huge amount of pollutants; total organic carbon, biochemical and chemical oxygen demand (BOD, COD), total suspended solids, total nitrogen and total phosphorus [1, 2]. The main treatments till now available for the removal of these anthropogenic pollutants and micropollutants involve aerobic biodegradation, filtration, flocculation, adsorption, froth floatation and EC [3]. Some other methods have been applied in combination to overcome the shortcomings of the individual process, including photo-electro-Fenton, electro-Fenton and electro-oxidation [4]. EC is a highly studied process in this field these days. It is a multistep process which involves the agglomeration of contaminants, via electrodes (coagulant) through redox reaction carried out by applying an electric current. Conventional electrocoagulation process was carried out by the help of inorganic chemical species as coagulants including $(NH_4)_2SO_4$ and $FeCl_3$.

Various other electrochemical and photo-assisted electrochemical processes have been examined for the purification of wastewater [5], whereas preference is given to the EC method. The EC process as proceeds by electric current using metallic electrodes, therefore, it is an electrochemical process being used for the removal of contaminants from wastewater [6, 7]. It involves the conversion of hazardous organic pollutants of wastewater via redox reactions to non-hazardous materials. The EC process is famous as a green technology because of its simple assembly, safety, short reaction time, selective capacity, negligible usage of chemicals, easy to handle/ or operate and good water purification efficiency [7, 8]. The electric current (I) supplies the necessary force (electromotive) to drive the redox reactions, resultantly the particulate/ or contaminant will reach the stable state; solid, that is relatively less emulsifiable, less soluble and less colloidal in comparison to the equilibrium values. When this happens, the stable solids convert into hydrophobic compounds/ or precipitates which can be easily separated out by different separation techniques. The EC method uses a negligible amount of chemicals, therefore no need for neutralization reaction as there is no secondary contamination [9].

Three stages of EC technology implicate in the purification of wastewater are; (1) electrolytic oxidation of sample water to generate coagulants; (2) pollutant destabilization, emulsion, deterioration and particle suspension; (3) agglomeration of resultant particles to generate flocs: comprised of colloids entrapped sludge blanket formed from coagulation reaction [10]. These flocs are similar to chemical flocs and are larger, acid-resistant, bounded less water and stable, that’s why can be separated out by rapid sand filtration. [11, 12]. EC process is economical as it produces relatively less amount of sludge in comparison with conventional processes [13]. There are a number of electrochemical reactions take place at anode and cathode as discussed in equations (1–7). During EC, H_2 is evolved at the cathode in the form of bubbles, discards particles by flotation known as electroflotation [14]. Numerous hydroxide of metallic electrodes (anode: Fe/ or Al) and coagulant compounds are generated from these chemical reactions to deteriorate, coagulate, and adsorb the pollutants [11]. Aluminium and iron electrodes are widely used in literature for wastewater treatment because of their increased ions production potentials [15, 16]. The cations of iron (Fe^{+2}) and aluminium (Al^{+3}) dissolve from the relevant anode in the aqueous phase of the reactor as shown in reaction 1 and 4. Al^{+3} and Fe^{+2} cationic species may form a number of monomeric and polymeric hydroxide entities during the course of electrochemical reactions relevant to each electrode. The transformation of metallo cationic species, into $Al(OH)_3$ (reaction 3) and $Fe(OH)_2$ (reaction 5 and 7) hydroxides, is pH-dependent. These final species then act as micropollutant adsorbents.

Aluminum electrode reactions during EC:

Anode:

$$Al(s) \rightarrow Al^{3+} (aq) + 3e^{-} \qquad (1)$$

Cathode:

$$3H_2O + 3e \rightarrow 3/2H_2 (g) + 3OH^{-} \qquad (2)$$

Overall:

$$Al^{3+} (aq) + 3H_2O \rightarrow Al(OH)_3 + 3H^{+} (aq) \qquad (3)$$

Iron electrode reactions during EC:

Anode:

$$Fe (s) \rightarrow Fe^{2+} (aq) + 2e^{-} \qquad (4)$$

Cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (6)$$

Overall:

$$Fe\ (s) + 2H_2O \rightarrow Fe(OH)_2 + H_2 \quad (7)$$

In literature, mostly efficiency of different electrodes including steel [17], Al [7], Mg [14] and Fe [18] has been evaluated for the removal of COD, colour, total phosphorus and ammonia at different pH and high values of current densities. There is a lack of literature regarding the complete study of a suitable EC reactor, optimisation of different operating parameters, coagulant's nature effect on flocs generation and calculation of the amount of suspended solids and micropollutants using advanced scale wastewater treatment plant. Therefore, this study is of much worth, as it is about the testing of a pilot-scale plant EC reactor for the removal of suspended solids and micropollutants from the effluent's discharged from the wastewater treatment plant using green technology. Two types of effluents from primary and secondary sedimentation tank have been used. Membrane filtration technique (AFS) has been applied for the calculation of SS in effluents. Different flow rate and current densities have been used to determine the optimum conditions and limitations of this scale EC reactor. Furthermore, operational cost analysis of the EC reactor is determined to verify the feasibility of the designed test EC reactor plant for micropollutant removal from the wastewater.

2 Experimental

2.1 Wastewater sampling and characteristic

Wastewater samples were collected from a local wastewater treatment plant. Mainly two types of samples depending upon their quality are used in the tests; one type was taken from the outflow of primary sedimentation tank and the other was taken from the secondary sedimentation tank of the wastewater treatment plant. Primary tank effluent has a higher amount of pollutant in comparison to secondary tank effluent. Their wastewater characteristics are discussed in Table 1. Inflow and outflow point is situated on the EC reactor from where samples were taken after constant conditions of operation of the EC setup. Samples were not taken at once but with constant short intervals of time, to ascertain the homogenous composition of the sample.

2.2 Experimental assembly of EC reactor

The experimental setup is schematically shown in Fig. 1. A 150 L open tank is used as a feed tank. Some of the pollutants like suspended solids (SS) might settle during an experimental run, hence the feeding 150 L tank is equipped with a stirrer for continuous stirring and maintaining a consistent influent to the treatment system. The feed tank is fed with primary or secondary sedimentation tank effluent one by one according to the experiment by changing the feed lines. The effluent from the feed tank is fed to the EC reactor using a pump (range 250–1500 L/h) and a flow meter connected in line to ensure the operating 500 L/h inflow to the EC reactor. The pilot plant setup is mainly divided into two main parts. The first part consist of an EC reactor and the second part consists of EF setup and EPD discs. The EC reactor is a fibre box having two chambers in series provided with slits to insert the metal plates inside which act as electrodes. Each cell has 17 plates and on the whole, there are 34 plates of one material (either Fe or Al) used at a time in the whole EC reactor. The slits inside the EC cells are fitted with plastic cylindrical objects of about 3 cm in length and 3 mm in diameter to raise the height of the plates to ensure better operation. The plates act as bipolar electrodes in a parallel connection and are connected to a DC power supply through a polarity changer circuit. The polarity changer circuit has various time settings to change the polarity on the connecting electrodes that ensure the proper functionality of electrodes. In the bipolar systems, the side of the electrode facing the anode is negatively charged and vice versa on the other side of the cathode. In EC reactor there is an inlet and an outlet, the inlet is just a circular hole where the connecting pipe fits in to provide the inflow to the reactor.

The outlet of the reactor is provided with an overflow rectangular opening and a circular hole at the bottom for the outflow. The EC reactor is provided with an auxiliary plastic glass cover, to ensure a better view of the EC process inside the reactor and controlling the parameters by visually viewing the process. The plates used inside the EC reactor are 300 mm × 155 mm × 3 mm of dimensions and have an effective surface area of about 1.488 m^2 [3]. In this experiment, Al and Fe electrodes are used separately by applying different values of current densities. The current density applied for the Fe electrodes and Al electrodes range from 0.67–2.69 A/m^2 and 0.34–2.02 A/m^2 respectively. The amount of suspended solids in case of Al electrodes agglomeration was carried out nicely with lower current densities but for Fe electrodes higher current densities were required for noticeable treatment. In the presence of these observations and due to economic factor, lower current densities were applied for Al electrodes treatment. The inflow to the electrocoagulation reactor was maintained at about 500 L/h and for some reactions 250 L/h. The pH of inflows was maintained with NaOH and H_2SO_4, where required. The pH of the effluents was examined by the help of a pH meter (Hanna Ins. 301). A typical pH meter consists of a special measuring probe (a glass electrode) connected to an electronic meter that measures and displays the pH reading. There is a bulb at the bottom of the probe, the bulb is a sensitive part of a probe that contains the sensor. To measure the pH of a solution, the probe is dipped into the solution. The probe is fitted in an arm known as the probe arm.

2.3 Characterisation of wastewater samples

Wastewater from the primary sedimentation tank was treated with Fe and Al bipolar electrodes to examine the COD reduction efficacy of the test pilot plant at the above mentioned variable current densities [6]. The COD of samples were calculated by the help of spectrophotometer (Hach Dr 5000, USA). While samples collected from the secondary sedimentation tank were examined for their amount of SS substances before (inflow) and after (outflow) EC treatment. The outflow of secondary tank had not been tested for COD removal, because of the characteristic lower level of COD. The effluent from the primary sedimentation tank is treated at higher current densities to see the effect of electrocoagulation on the COD removal efficiency. Similar to COD measurement, amount of SS substances in samples were inspected by using separate Fe and Al coagulant, at different current densities and resultant pH values to identify the conditions at which the EC set-up work efficiently. The measurement of SS substances in the samples was done by using membrane separation technique, according to DIN 19643-2 and is called after filtration solids (AFS) [19].

According to DIN 19643-2 [19], the filtration done by a pre-weighed filter for a specific volume of each sample at air pressure up to 6 bars. Some important steps are described here. Filtration is done by a specific nitrogen pressure of 5 bars and during filtration the filter paper allows only the particles which have the diameter of less than 0.45 µm. After filtration, the wet filter paper is again dried in the oven for 1 hour at 105 ^{o}C temperature. It evaporates all the water content and collects only the solids with it, which needs to reside in the desiccator to cool it down for 30 minutes. Finally, again measuring the weight of the filter paper, the total SS are calculated in the treated wastewater. Each sample was subjected to AFS setup three times and the average value was taken for the experimental calculation. The AFS of inflow and outflow samples were made to compare the quantitative analysis on the basis of flocs formation and coagulant dissolution.

After the calculation of AFS, the amount of coagulants dissolved during the generation of flocs was calculated experimentally and theoretically to observe the reliability of the process. Experimentally, to calculate the amount of Fe and Al coagulation dose in the outflows specifically in the case of used pilot plant setup was a major task of this study. For the total amount of Fe in the outflow, spectrophotometric analysis is performed while for Al in the outflow gravimetric analysis are done [20]. Moreover, the theoretical amount of Fe and Al coagulation dose is calculated according to equation (1) [21].

$$\mathrm{Cx} = \frac{\mathrm{Mtotal, x}}{\mathrm{Vtotal, liquid}} = \frac{\mathrm{I\ X\ t\ X\ mx\ X\ N}}{\mathrm{Q\ X\ t}} = \frac{\mathrm{I\ X\ mx\ X\ N}}{\mathrm{Q}} \tag{1}$$

where C_x = dosage of released metal (Fe or Al) from the outlet of the electrolysis cell (mg/L); $M_{total,x}$ = total mass of released metal (mg) by Faradays law within the retention time (t, s); $V_{total,liquid}$ = total volume of the effluent (L) within the retention time: I = applied current (amperes); N = number of channels in the electrolysis cell; Q= flow rate (L/s), and m_x = electrochemical equivalent of the metals. The electrochemical equivalent of aluminum metal is (0.093 mg/C) and of iron metal is (0.193 mg/C).

The particle-size distribution (PSD) of a powder, or granular material, or particles dispersed in fluid, is a list of values or a mathematical function that defines the relative amount, typically by mass, of particles present according to size. The samples from the effluent streams after the EC process with Fe and Al electrodes are subjected to PSD characterization. During the course of experiments, every time when the samples were subjected to PSD, 1 litre sample was taken in order to examine the resulting flocs in detail. The samples were taken separately for Fe and Al electrodes at their respective amount of applied current densities. PSD is then performed with the help of a laser granulometer, the Mastersizer 3000 from Malvern [22]. With this device, particles can be measured with a size of 0.01 to 3500 microns. For the measurement, two light sources, one red at 632.8 nm and other blue at 470 nm were used. At last, the operational cost analysis for the optimum operating current densities of Fe and Al electrode was also performed to verify the feasibility of the designed test EC reactor plant for micropollutant and suspended solid removal from the effluents (equation 2). While the energy consumption for this process was determined by using equation (3) [8].

$$\text{Operating cost} = \text{energy cost} + \text{material cost} \tag{2}$$

$$\text{Energy consumption} = \frac{V\ X\ I}{Q} \tag{3}$$

Where "V" is the voltage applied on EC reactor, "I" is the current applied in Amperes on the EC reactor and "Q" is the flow of the influent through the EC reactor in m^3/h. Energy consumption is then expressed in Wh/m^3.

3. Results and discussion

3.1 Treatment from primary sedimentation tank

3.1.1 COD removal efficiency of Fe and Al electrodes

Applied current or current density is the most important operational parameter, in electrochemical EC process. To test the role of current in COD removal, different current densities have been used in case of Fe and Al electrode at the same initial pH of 7.30 and a flow rate of 500 L/h. In the case of Fe electrode, basically, two types of settings were used. In the first run, the current was applied at 3 A (current density= 2.02 A/m^2) and in the second run current applied was 4 A (current density= 2.69 A/m^2). It was observed with the samples that the flocs were formed within 5 minutes after the samples were placed in the Imhoff cones (Fig. 2) and the COD was also measured afterwards. The settling of the flocs formed at 3 A are shown in Fig. 2 as a function of time for settling. It can be seen clearly from Fig. 2 that after 30 minutes of settling, the amount of solids in the outflow was noticeably settled to an amount of 32 mL/L. On the other part, the suspension in the inflow was still very stable and was nowhere near settling during the 30 minutes of reaction. The greenish colour of the outflow after EC process indicated that the flocs formed contain purely $Fe(OH)_2$ which shows the dissolution of Fe electrodes in the form of Fe (II), also showed by [23-25].

The outflow samples were tested for the amount of COD removal, the results as shown in Fig. 3 that with 3 A, COD was removed from 233 to 100 mg/L and with 4 A, COD was removed from 250 to 109 mg/L. This shows a significant amount of COD removal from the water of the primary sedimentation tank up to 56–57 % via Fe electrocoagulation as shown in Fig. 6, and also shows that increase of current did not make a significant difference in the COD removal, as it is also mentioned in the [26], that more COD removal with Fe electrodes was achieved at lower currents. There have been studies where high removal of organic matter was obtained with iron electrodes, such as [27] and [28]. However, the electric charge per volume has been really high .e.g; [28] measured 70.5% removal of COD (from 254 to 75 mg/L) of COD from paper mill effluent when they used 17280 C /L.

While in case of Al electrode, wastewater from primary sedimentation tank was introduced in the EC reactor, the current was applied in the range of 1–2 A and the corresponding current density values were 0.67-1.34 A/m^2. The COD removal as shown in Fig. 4 with 1 A applied current was decreased from 121 to 107 mg/L and with 2 A current was decreased from 105 to 86 mg/L. The sample treated with 1A applied current was put in the Imhoff apparatus to see the settling effects of the solids and watched for a 30 minutes interval. It can be seen in Fig. 5 that there was no significant colour imparted to the outflow and the settling with a half-hour interval was quite good indicating the amount of flocs produced which is almost doubled before and after EC process. The results showed a COD removal in the range of 12–18% which is almost 3 folds less than the COD removal achieved in the case of Fe electrodes as shown in Fig. 6. It is stated in [24, 26] that Fe electrodes are more efficient than Al electrodes in colour and COD removal.

3.2 Treatment from secondary sedimentation tank

3.2.1 Effect of current density on AFS in Fe coagulation

When Fe electrodes were used and the wastewater from secondary sedimentation tank was introduced in the EC reactor, the current was applied in the range of 1-3 A and current density was changed from 0.67–2.02 A/m^2. Different operating conditions had been opted for secondary sedimentation tank effluent analyses as because of their changed characteristics. Higher current densities were applied in primary sedimentation tank analysis in comparison with lower values of current densities of secondary sedimentation tank analysis. This is because the higher amount of contaminants were detected in the primary sedimentation tank, while very little values were observed in secondary tank effluents Table 1. According to AFS amounts found in the inflow and outflows after the EC reactor, it can be seen in Fig. 7 that the amount of AFS produced is directly proportional to the amount of current applied. The higher amounts of outflows in comparison to the inflows indicated that a large amount of electrode dissolution happened during the course of the EC process. Also, it is showed in [23, 29] that dissolution of the Fe electrodes is the primary reaction at anodes during typical current densities when the pH approaches neutral values. Each experiment was run thrice to check the reproducibility of the results and named as WW-Fe-01, WW-Fe-02 and so on. Similar was the case with Al coagulation.

In Fig. 8 coagulation dose of Fe, theoretical amount of Fe and AFS in the outflows are compared against the different current densities values. The measured amounts of Fe in the outflow based on the equation (7), where one mole of Fe (s) reacts with two moles of water to produce one mole of $Fe(OH)_2$. Here it was assumed first that all the iron electrodes produce $Fe(OH)_2$ precipitates which were dirty green in colour and the amount of which were then tested by Hach Lange test cuvettes, to prove the fact that the whole amount of Fe which produced as coagulation dose by Fe electrodes is in the form of $Fe(OH)_2$.

According to the results, current density has a direct effect on the dissolution rate in the studied range (0.67–2.02 A/m^2 or 7.19–21.58 C/L) (Fig. 9). Iron dissolved at the rate of 2.93 mg Fe/C, while the theoretical value for dissolution of Fe (II) is 3.09 mg Fe/C. It can be concluded that iron dissolved in Fe (II) form and dissolution followed Faraday's law. This was consistent with the results of other researchers [23-25]. This result is very important because it is established that Fe (II) is a poor coagulant and should be oxidized to Fe (III) form before it is employed to remove organic matter [1].

In order to test the volumetric inflow parameters of the EC reactor, a set of experiments is done with a low flow rate of about 250 L/h, the results of which are compared to the inflow rate of 500 L/h. The amount of AFS obtained during different flow rates is shown in Fig. 10. The results in Fig. 10 clearly show that when the inflow rate is decreased from 500 to 250 L/h, the amount of AFS is increased to almost doubled, provided the current applied remains constant. These results also support the arguments, that if charge per litre volume of inflow is increased the amount of AFS and hence the coagulation dose of Fe is also increased linearly. In other words, if inflow rate to EC reactor has an indirect effect on the AFS produced provided the current density is kept constant. But this rapid agglomeration couldn't be helpful, as it needs more coagulation dose and might not be cost effective. Therefore, this parameter was not further optimised.

3.2.2 Effect of current density on AFS in Al coagulation

When Al electrodes were used and the wastewater from secondary sedimentation tank was introduced in the EC reactor. The current was applied in the range of 0.5–1.0 A and current density changed from 0.34–0.67 A/m^2. The amount of AFS found in the inflow and outflow; before and after the EC process shown in Fig. 11 indicates that the current applied has a direct effect on the amount of AFS produced. The electrodes dissolution is the primary reaction at anodes, the same is the case with aluminium electrodes.

In Fig. 12 coagulation dose of Al, theoretical amount of Al and AFS amounts in the outflows are presented corresponding to the range of current densities. The measured amount of Al based on the reaction (1–3), where one mole of Al $_{(S)}$ reacts with three moles of water to produce $Al(OH)_3$ and afterwards polymerized to other hydroxide species [6]. On the first instance, it is assumed that the aluminium electrodes produce on the whole $Al(OH)_3$ which is then experimentally proved by the gravimetric test. The test was performed at 1 A current and 0.67 A/m^2 current density applied to the EC reactor. The amount of Al based on the gravimetric measurement, AFS by the EC process and calculated theoretically by following equation (1).

According to the results, the current passing through the EC reactor was directly proportional to the dissolution rate [10] and followed Faraday's law. In the studied range (0.34–0.67 A/m^2 or 2.45–4.82 C/l), Fig. 13 the dissolving rate of Al measured was 1.27–2.39 mgAl/C, whereas the theoretical rate according to Faraday's law was 2.22 mgAl/C. It can be concluded that the amount of dissolution of Al at lower values of current densities was lower than the theoretical values but approaches equal to theoretical values at higher current densities. When the experiments run for Al electrodes at 250 L/h, the same results were obtained as shown in Fig. 10.

3.2.3 Outflows pH

In addition to the applied current, another factor that influences the reactions inside the EC reactor is pH. Literature confirms that pH of the outflows changes in comparison to inflows as reaction taking place at cathode (H_2 evolution) in EC reactor, moreover it also depends on inflow's pH and type of selected anode [1, 5, 6]. In the previous section, it is noted that with an increase in current density amount of outflow AFS is increased. pH factor was also observed, before and after the EC process under the applied operational current densities and resultant AFS for both electrodes. The pH of outflows is observed a correspondent increase with current density for all experiments [6]. In all the experiments performed in both the series, with Al and Fe electrodes, the pH was slightly increased in the outflows. The inflow's pH for all run at variable applied current, in case of Fe is 7.07, and while in case of Al is 7.24. The increase of pH was more in the case of Fe electrodes (Fig. 14) than to Al electrodes (Fig. 15), is in accordance with applied current values.

3.2.4 Flocs production analyses

In the EC process, hydrogen bubbles are produced on the cathodes (reaction 2 and 6) [30]. The production of visible hydrogen bubbles on the electrodes indicates that the EC process is going well. Electrodes material and current density both have an effect on the bubble size and amount. It is observed that very small hydrogen bubbles are produced in both the cases when aluminium or iron electrodes are used [5, 10], according to these, smallest hydrogen bubbles are produced during EC process at neutral or acidic pH. Current density has a direct effect on the bubbles amount, the more the current density, the more bubbles were produced on the electrodes. The gas bubbles produced can carry some of the flocs to the top of the surface of the electrodes, and then the layer can be removed from there in the form of foam.

The flocs layers produced due to the hydrogen bubbles can be seen in Fig. 16. It shows the layers formed during the EC operation with Fe electrodes and aluminium electrodes simultaneously. The sludge formed during the EC process is settable and during the initial test with only the wastewater from the secondary sedimentation tank, it was figured out that sludge sometimes settles down in the EC chambers. So, it was decided to empty the chambers and refill it with water at the end of each day operation. So each time the water is replaced from within the EC cell, the sludge moved out of the EC reactor. At the first instance, a little amount of sludge deposited on in the chambers of the EC cell.

The samples from the effluent streams after the EC process with Fe and Al electrodes are subjected to PSD analysis in the laser granulometer. Fig. 17 shows particle size distribution (PSD) for samples in which Fe and Al electrodes are used for coagulation at 0.5–2 A applied current values.

This PSD analysis shows the cumulative volume % of the particles against the particle diameter in µm. From Fig. 17, it confirms that a higher amount of current produced the bigger amount of flocs with both electrodes, which later on could be separated by secondary separation technique. In the case of Fe electrodes while increasing applied current more amount of flocs are observed while no such increment has been observed in the case of Al electrode. The comparison of PSDs of Al with Fe showed that, at the same value of applied current, Al generates more flocs than Fe.

3.3 Cost analysis of optimum current densities

The operating cost for the current EC process is calculated with equation (2). The energy consumption is then expressed in Wh/m^3. The energy consumption costs for Fe and Al electrodes at 2 A and 1 A operation are found to be 0.03 $€/m^3$ and 0.02 $€/m^3$. From this it is observed that energy consumption is a direct relation with applied current, the greater the applied current the higher will be the consumption of energy [5]. Based on the measured coagulant doses of Fe and Al electrodes as described in the previous section, the amounts of Fe and Al electrodes consumed per day were found 0.011 Kg/m^3 and 0.036 Kg/m^3 at 2 A for Fe and 1 A for Al. Based on these optimum conditions, the used metal plates in the EC reactor can last 86 and 99 days respectively for Fe and Al electrodes at its full capacity of operation at 2A and 1A. The material cost of Fe, Al operating plant at 2 A, 1 A was calculated to be 0.01 € $/m^3$ and 0.02 € $/m^3$ respectively. According to reaction (6), the operating cost of the EC operation for Fe and Al electrodes at the mentioned current values of 2 A and 1 A is calculated as 0.04 € $/m^3$ and 0.03 € $/m^3$ respectively.

4. Conclusions

This study is dealing with the wastewater treatment on a pilot-scale plant set up by electrochemical technology. The electrocoagulation and electroflotation techniques were applied with a revived design to meet the need of the process to remove suspended solids and micropollutants out of the wastewater stream. By using various settings of applied currents, the process is tested for the better quality of effluent using water from the outflow of primary sedimentation tank and treated water from the outflow of secondary sedimentation tank, and results are optimized for a better downstream separation process. Wastewater from the primary sedimentation tank is treated both with Fe and Al electrodes. In the case of Fe electrodes, more than 50% of COD removal is observed which was about 12–18% with Al electrodes. The coagulation dose of Fe and Al electrodes are measured, on the basis of AFS produced and according to Faraday’s Law. With both Fe and Al electrodes, the coagulation dose went on increasing with increasing current density. The best setting for Fe and Al electrodes in terms of current and current densities for effluent from secondary sedimentation tank are 3 A (2.02 A/m^2) and 1 A (0.67 A/m^2) respectively. The higher is the coagulation dose, the bigger are the flocs in size and hence can easily settle down in downstream sedimentation tank. The operating cost of operation for Fe and Al electrodes at the most feasible mentioned current values of 2 A and 1 A are calculated as 0.04 € /m^3 and 0.03 € /m^3 respectively. The work provided good results and comparison with the past work done in this regard by other researchers and provided some new space and enhancements, which can be done to the process for continuing research in this regard. In the future, combination of electrode materials and natural coagulants shall be a good option for efficiency improvement of this reactor at pilot scale.

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List of Tables

Table 1. Wastewater Characteristics.

Variable	Wastewater from primary sedimentation tank	Wastewater from secondary sedimentation tank
pH	7.30	7.30
Conductivity (*μS/cm*)	1350	850–1100
Suspended solids (*mg/L*)	100–150	1.4–6.6
COD (*mg/L*)	233.2	20
Total Phosphorous (*mg/L*)	5	0.45
Total Nitrogen (*mg/L*)	40.9	11.5

List of Figures

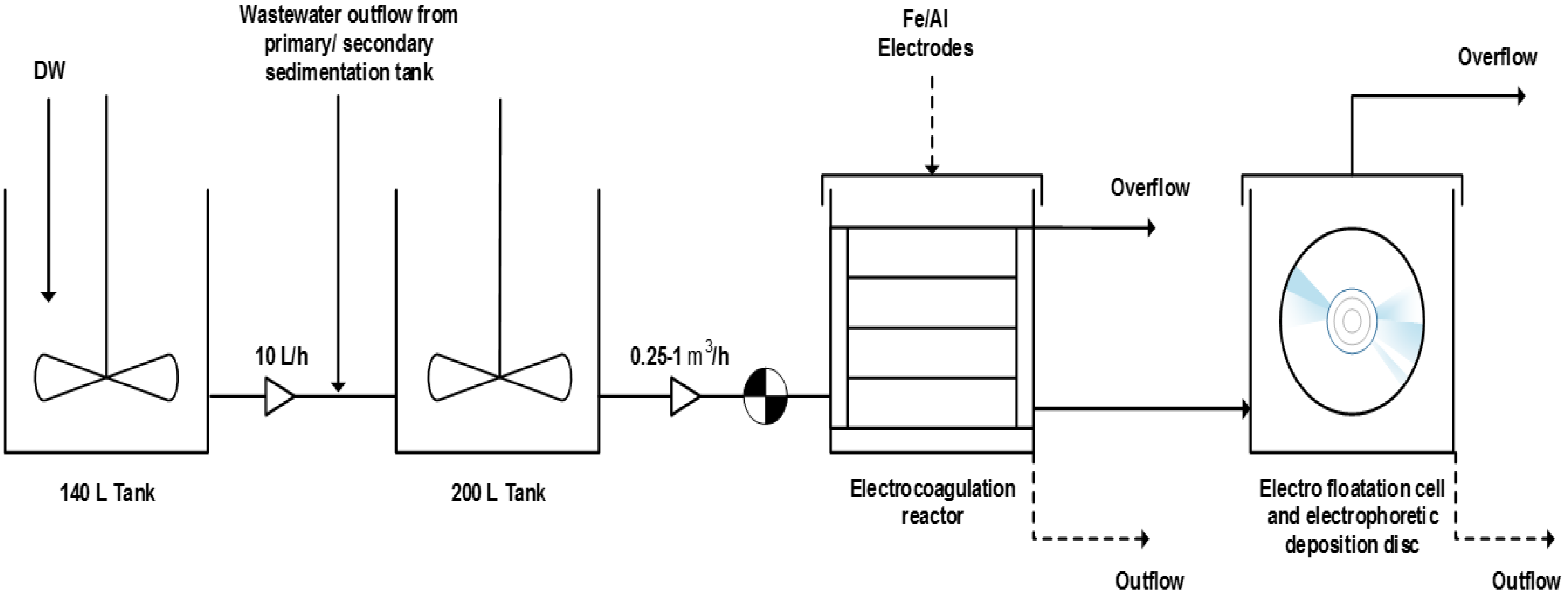

Fig. 1. Electrocoagulation pilot plant process flow diagram.

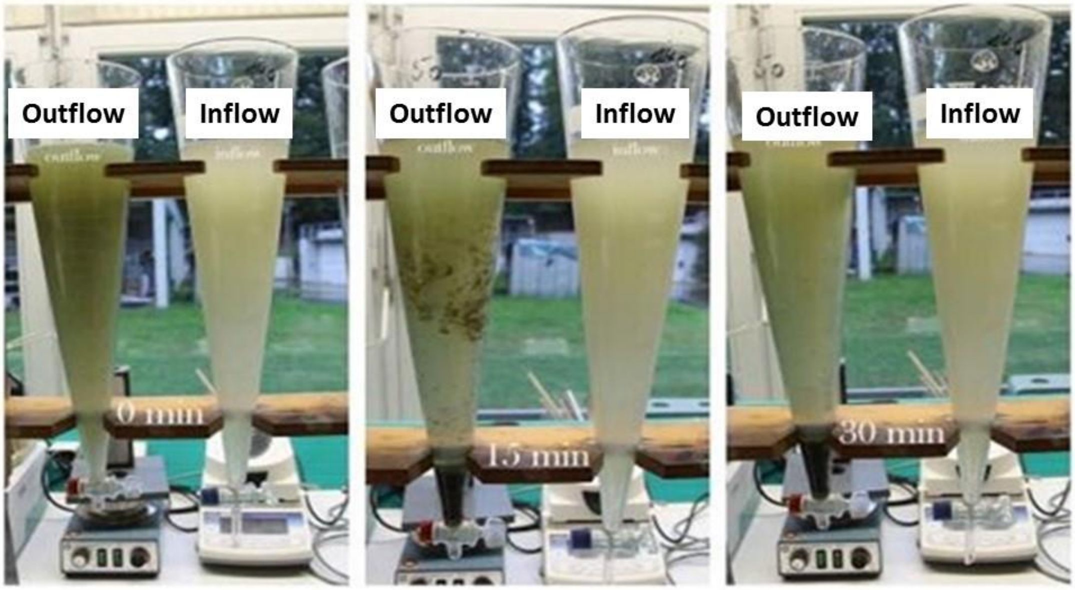

Fig. 2. Change of colour with Fe electrodes before and after EC treatment with time.

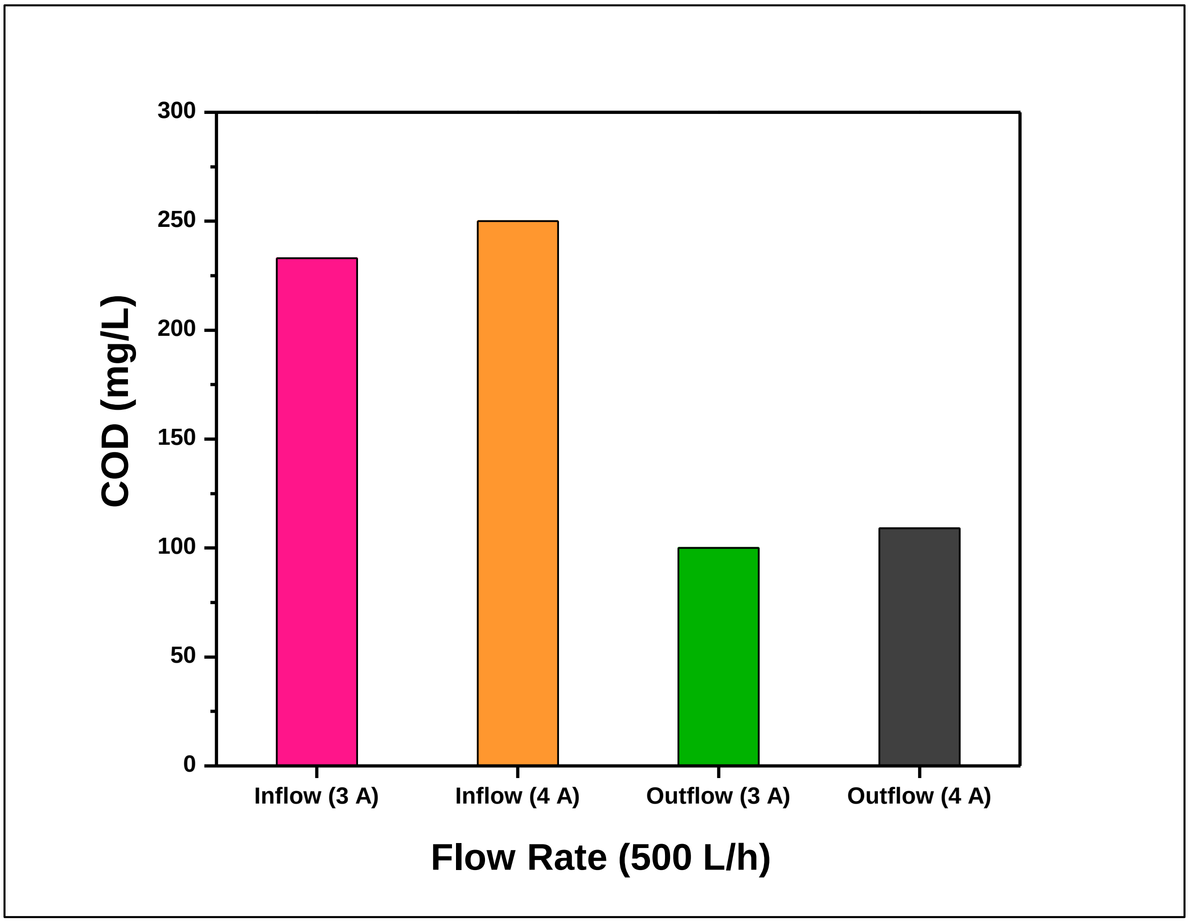

Fig. 3. COD removal of wastewater from primary sedimentation tank using Fe electrodes.

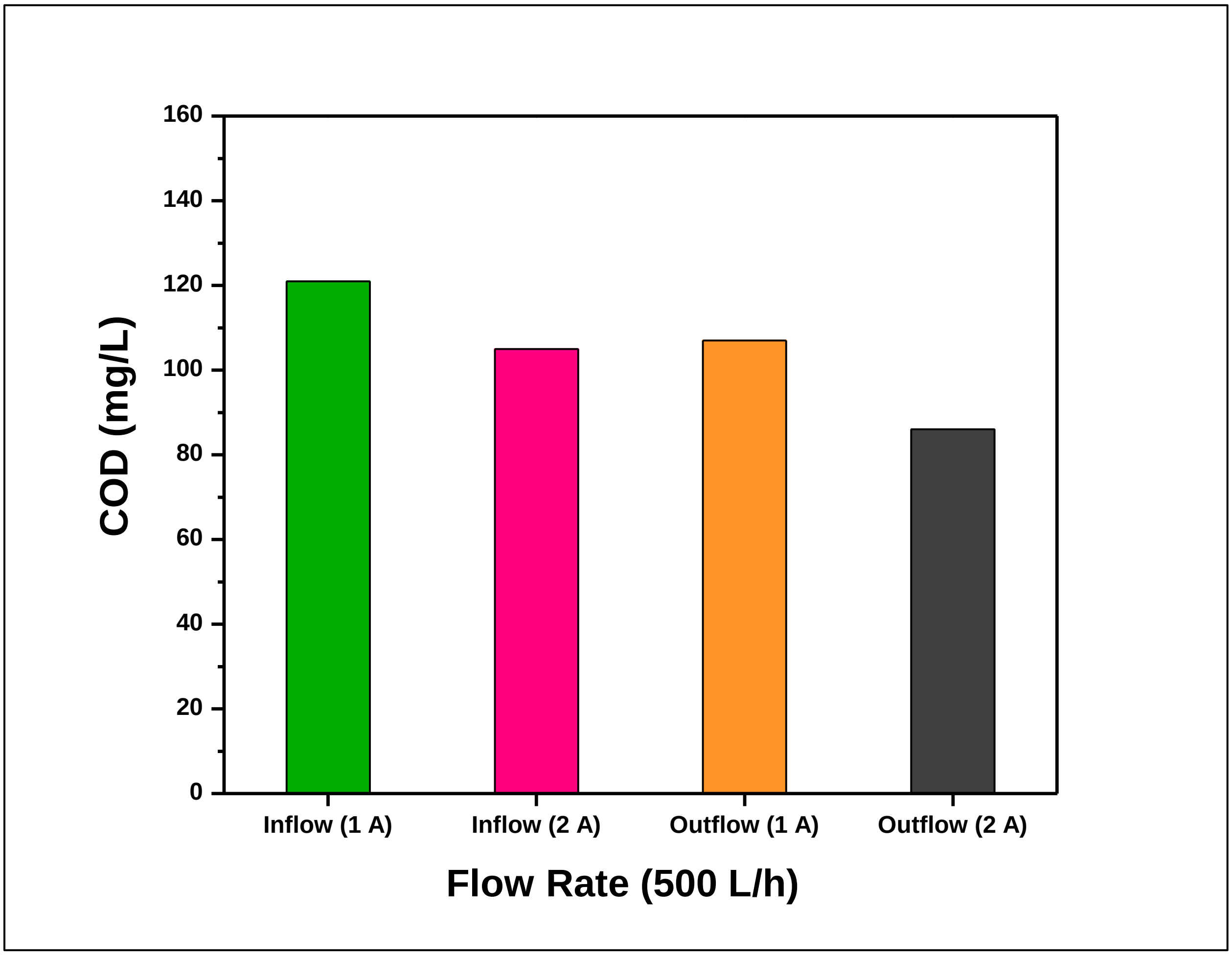

Fig. 4. COD removal of wastewater from the primary sedimentation tank using Al electrodes.

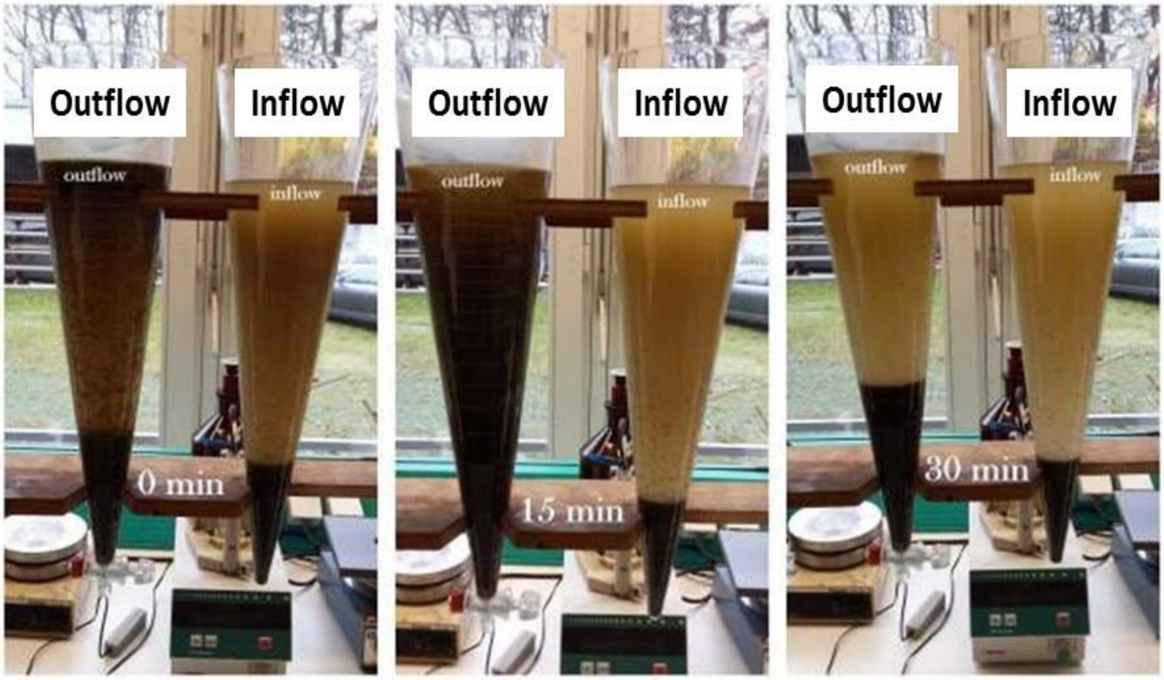

Fig. 5. Change of colour with Al electrodes before and after EC treatment with time.

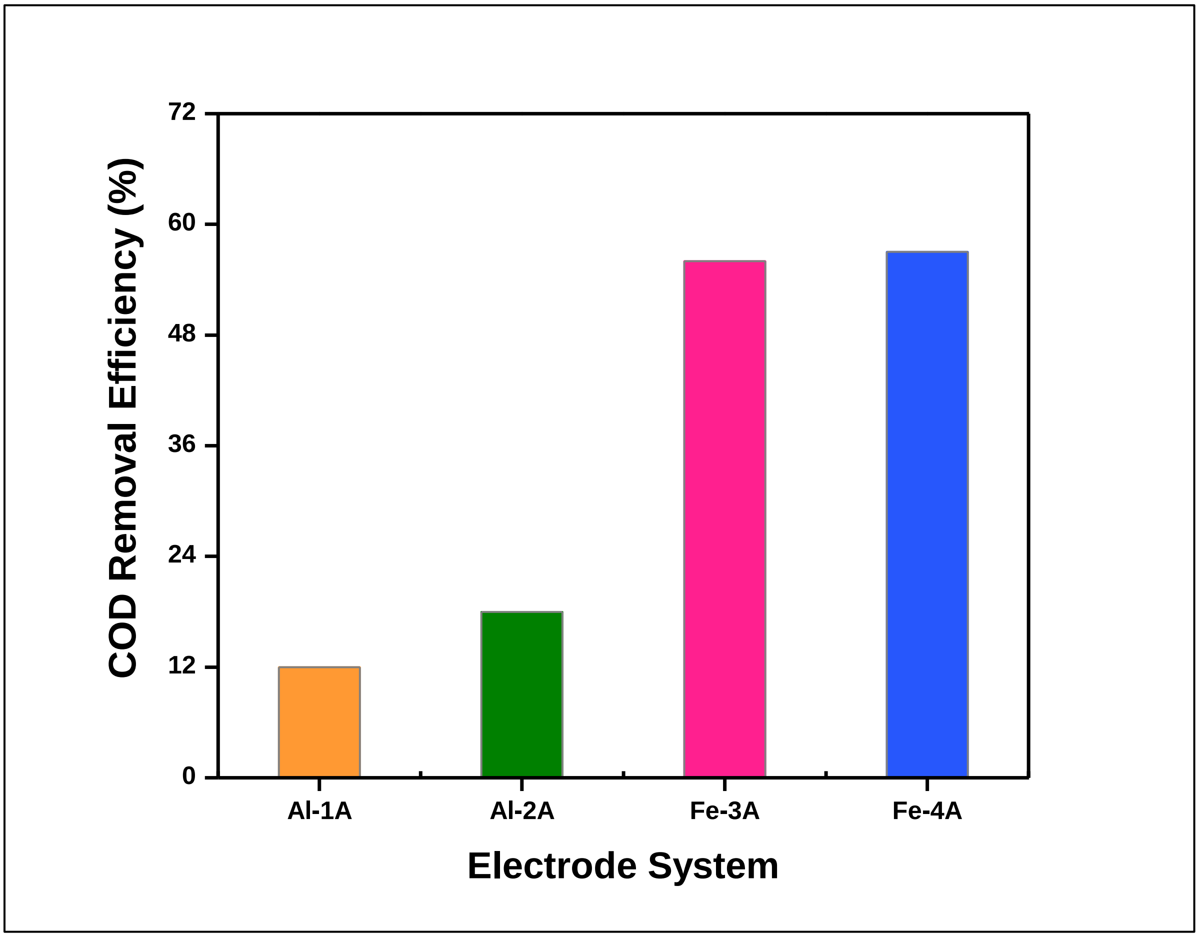

Fig. 6. The COD removal efficiency of Fe and Al electrodes at selected current densities.

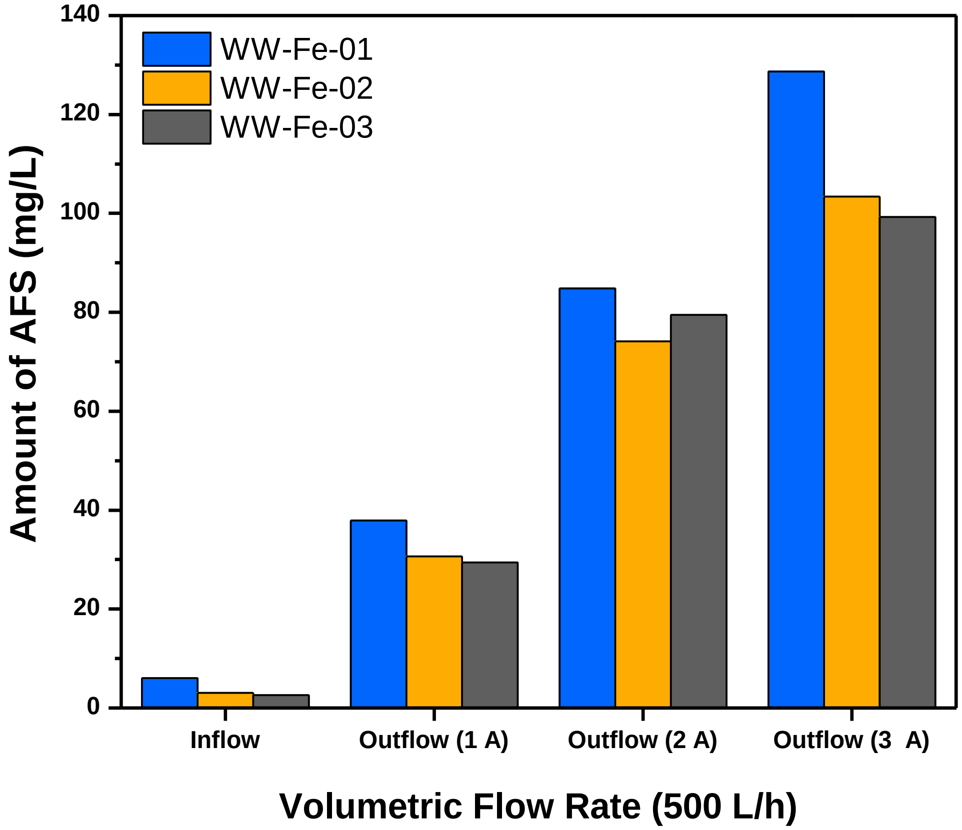

Fig. 7. Amount of AFS after applying current from 1–3 A on the EC reactor.

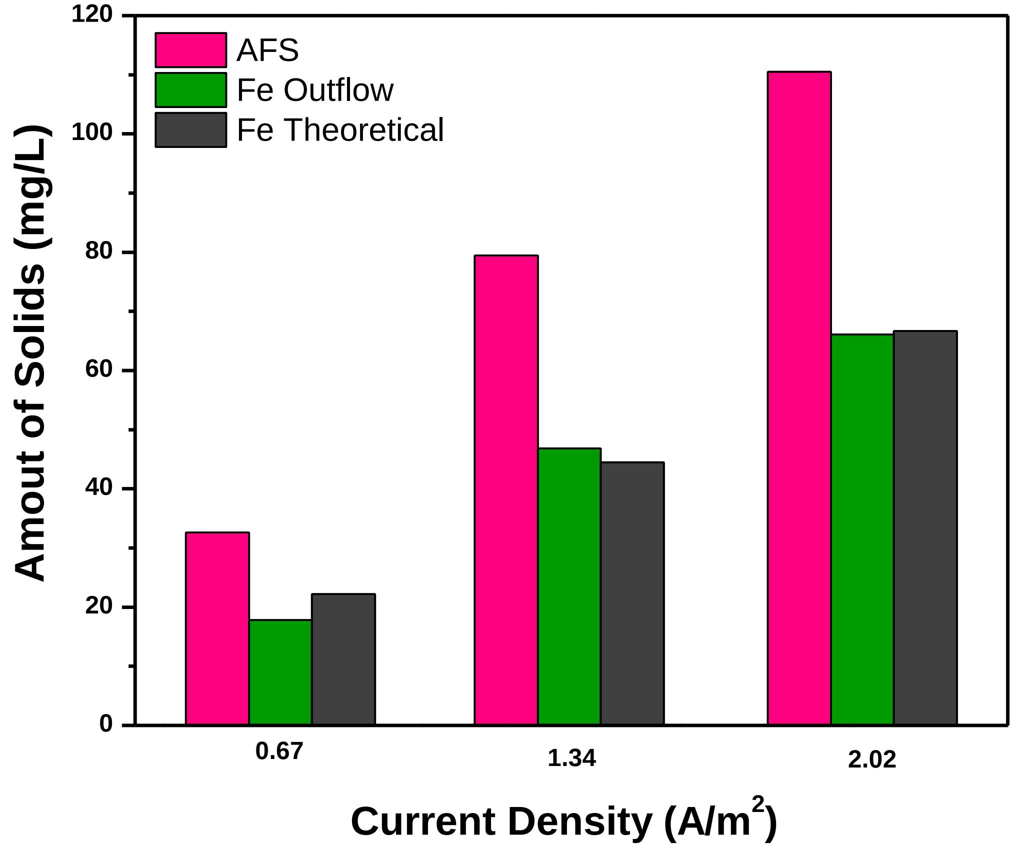

Fig. 8. Amount of AFS, Coagulation dose of Fe and theoretical amount of Fe in the outflow against various amount of current densities.

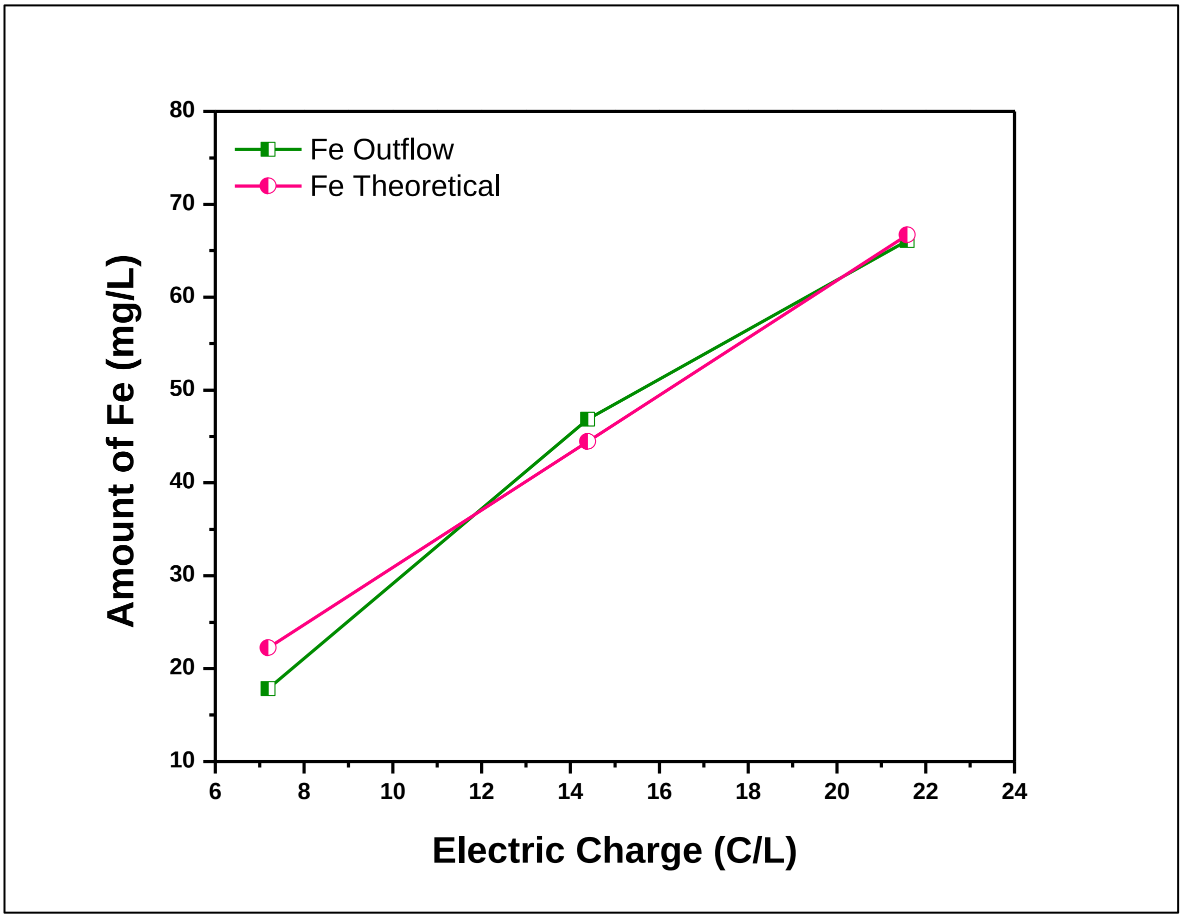

Fig. 9. Amount of Fe in the outflow and theoretical amount of Fe against the charge per litre of influent stream.

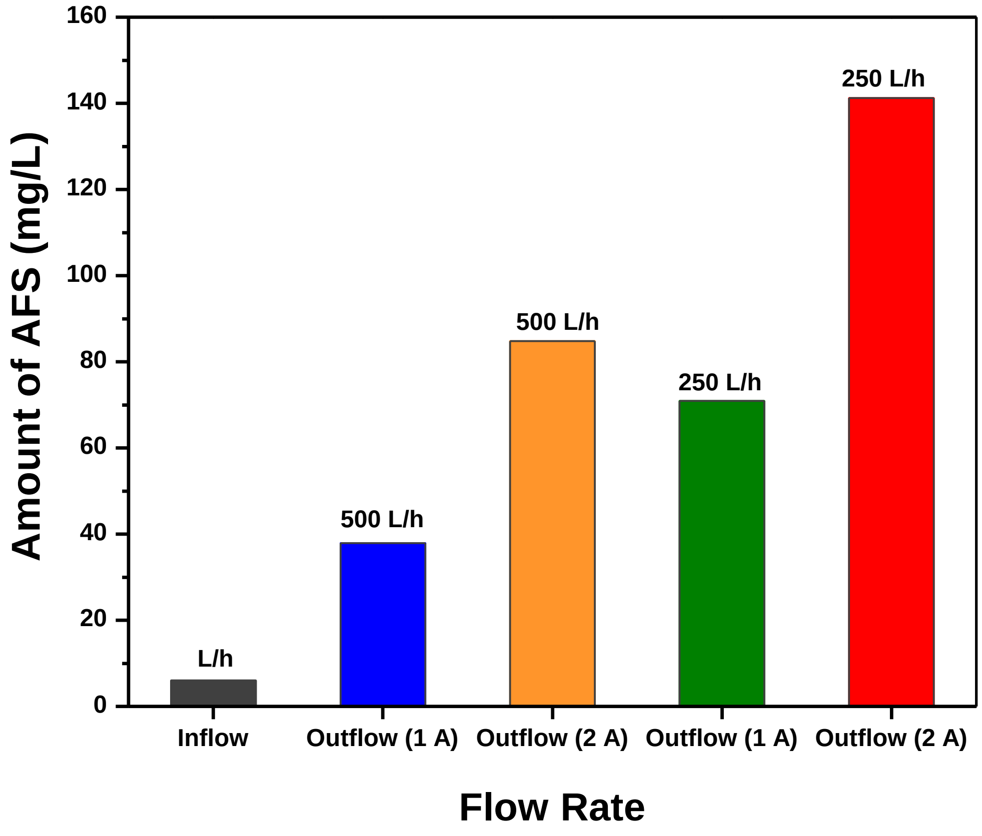

Fig. 10. Amount of AFS determined in the outflow after varying the current from 1–2 A and volumetric inflow rate from 250–500 L/h through the EC reactor.

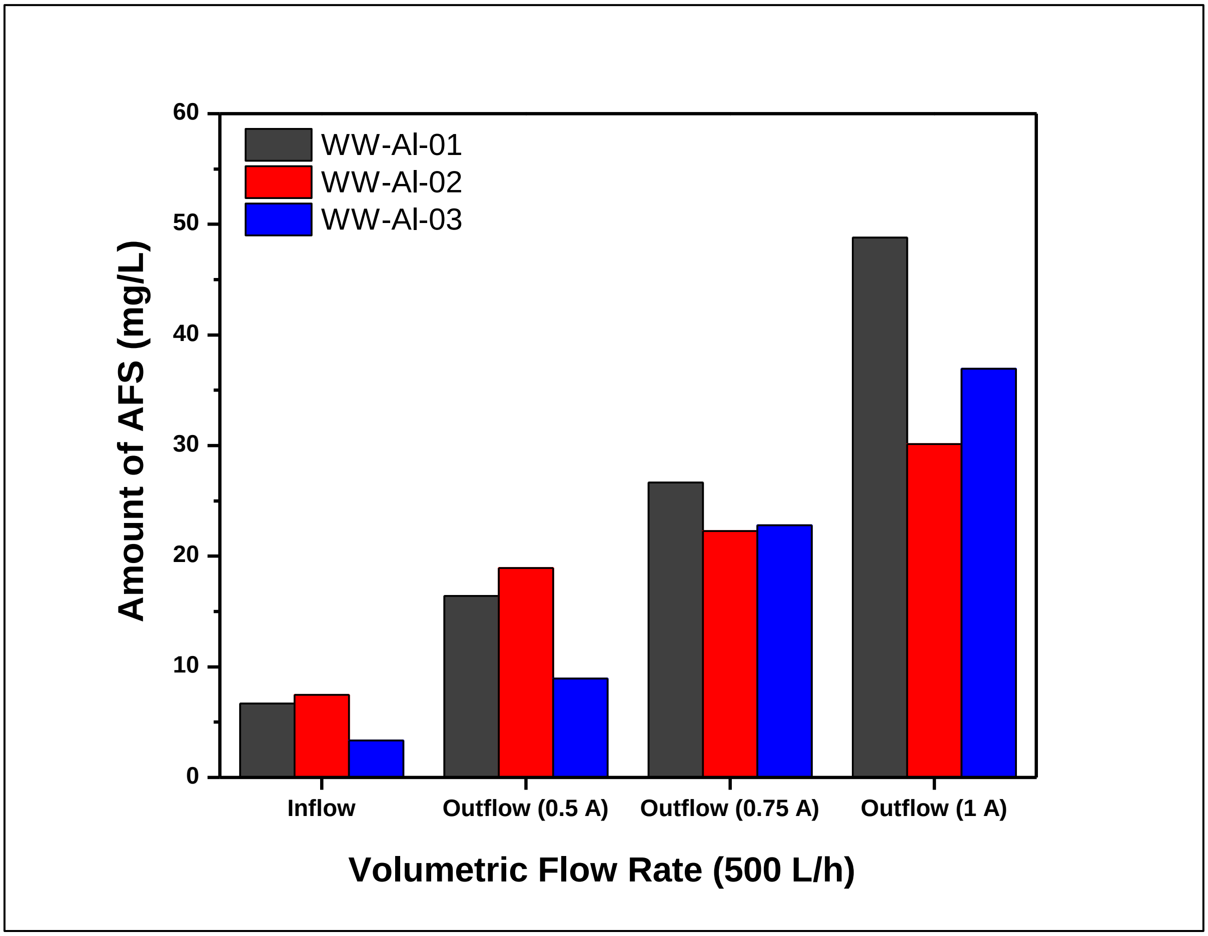

Fig. 11. Amount of AFS determined in the outflow after applying current at 0.5 A, 0.75 A and 1 A through the EC reactor.

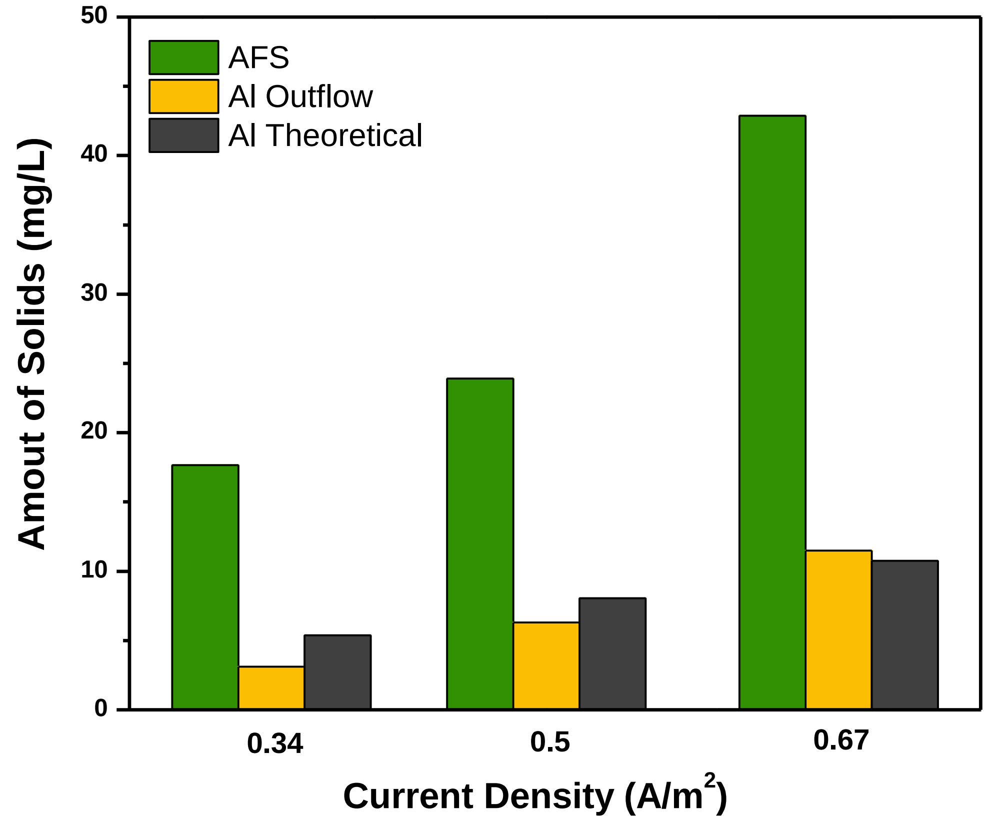

Fig. 12. Amount of AFS, Coagulation dose of Al and theoretical amount of Al in the outflow against various amount of current densities.

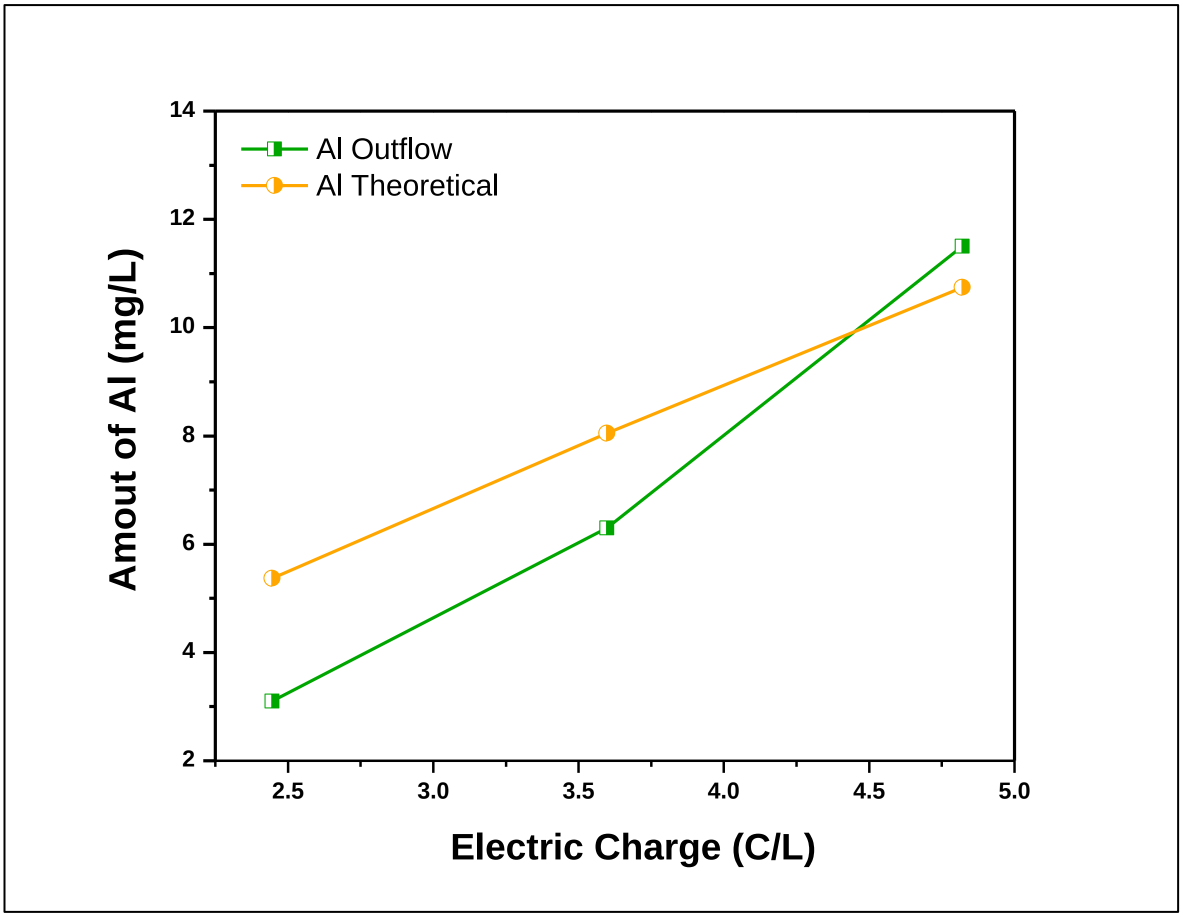

Fig. 13. Amount of Al in the outflow and theoretical amount of Al against the charge per litre of influent stream.

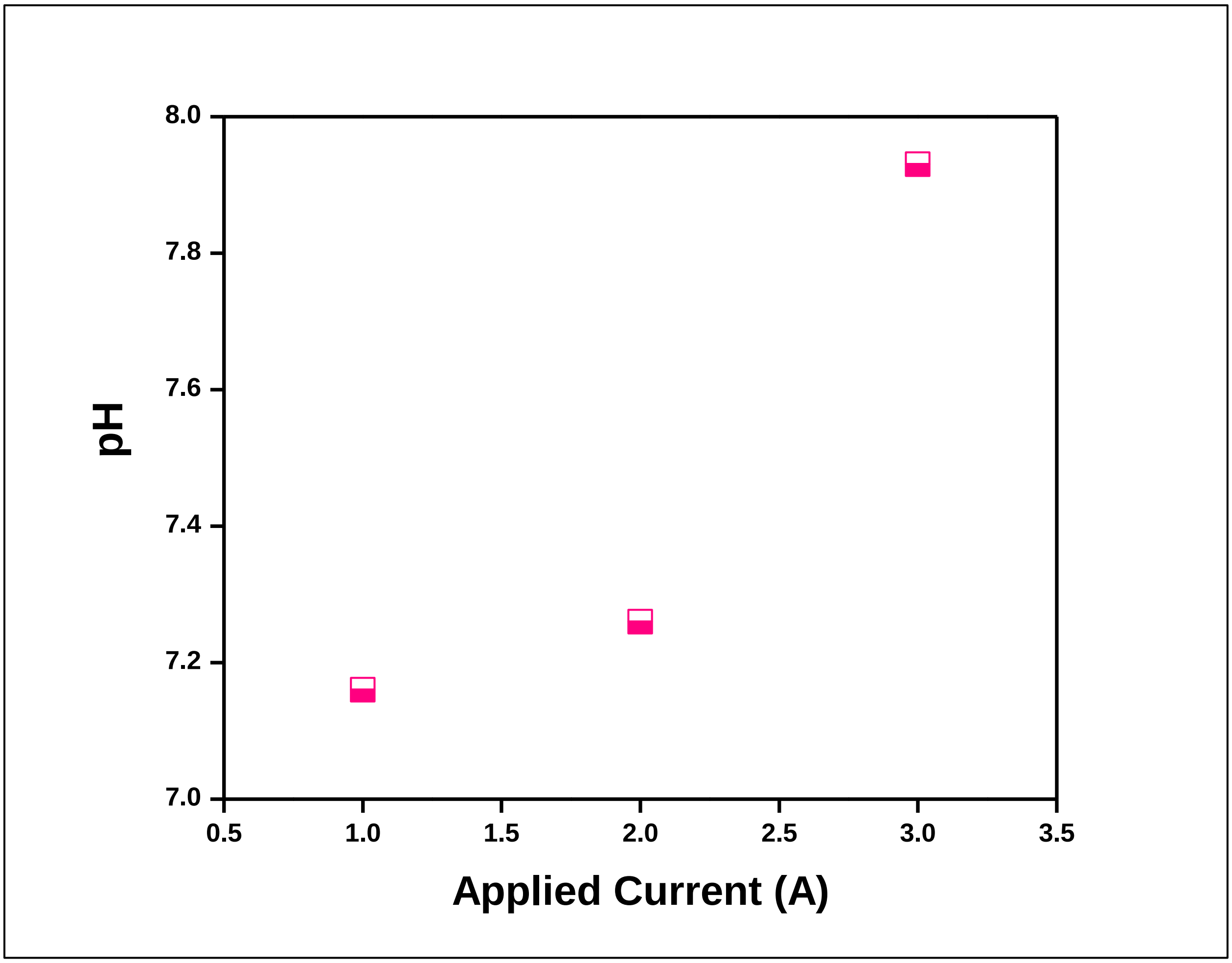

Fig. 14. Effect of applied current on outflow pH in the case of Fe electrodes EC treatment.

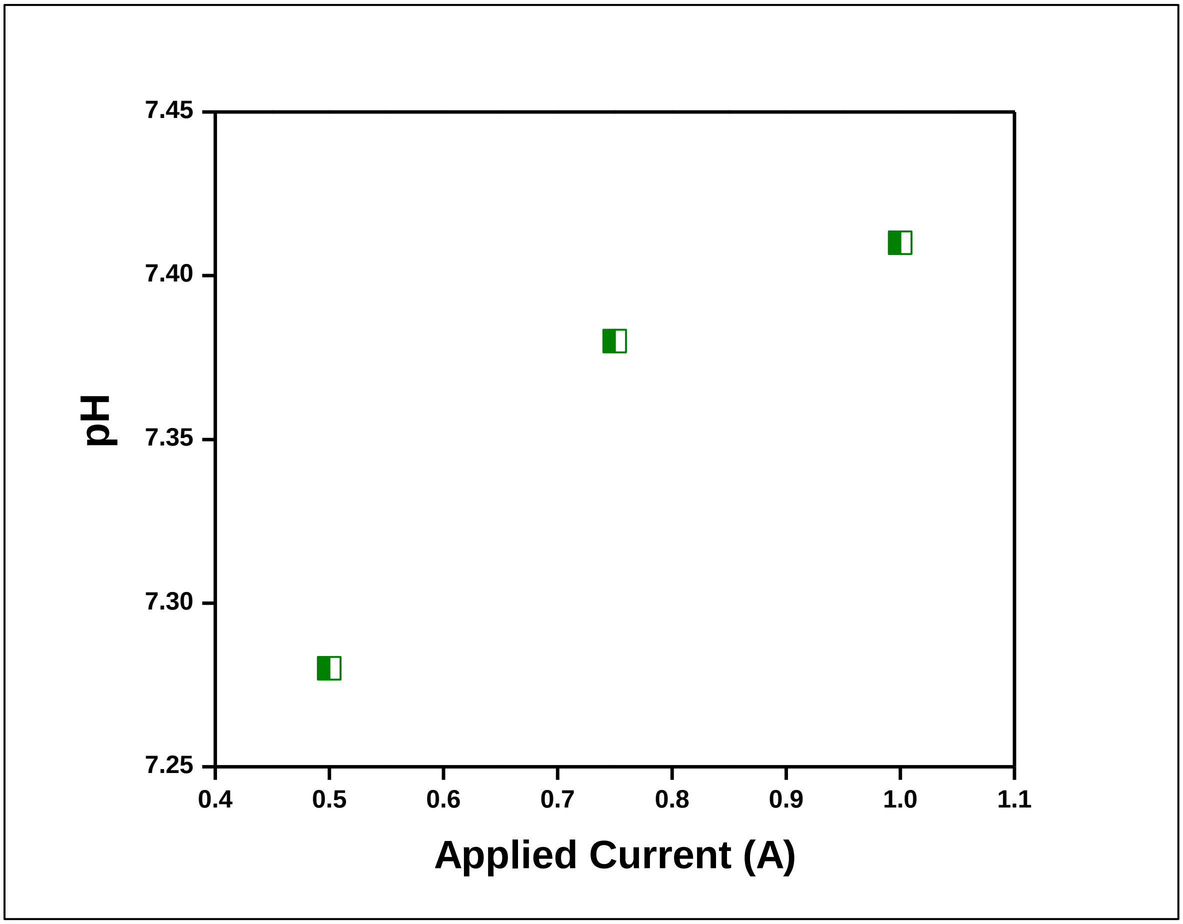

Fig. 15. Effect of applied current on outflow pH in the case of Al electrodes EC treatment.

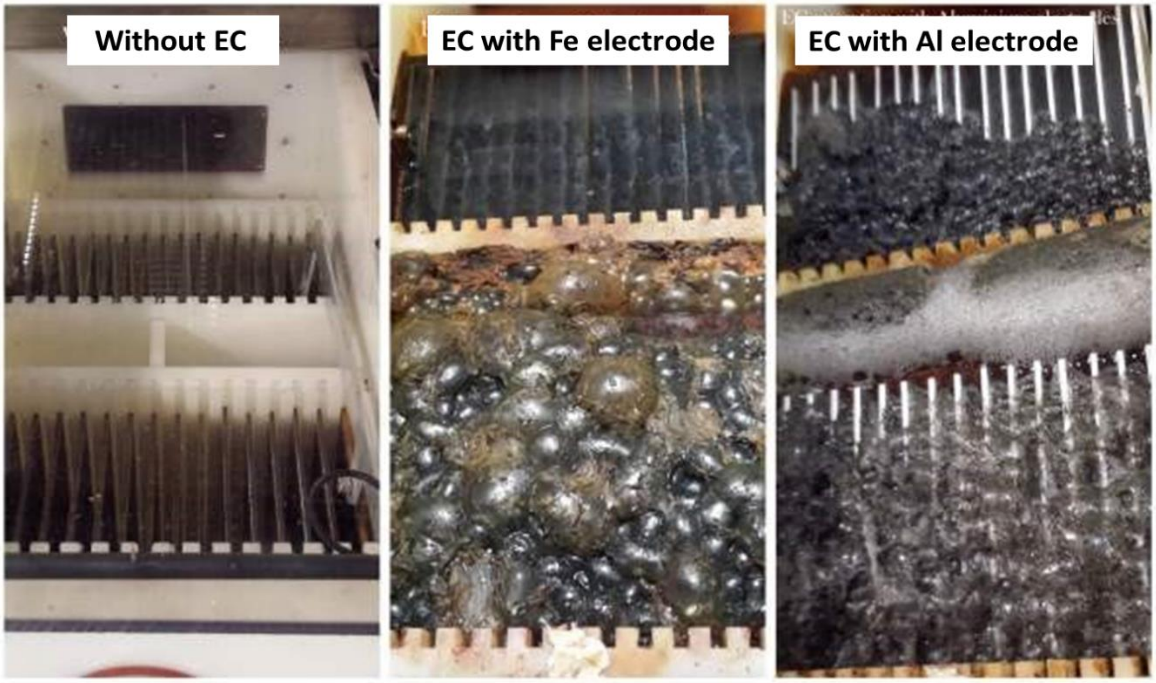

Fig. 16. Flocs layers formed due to hydrogen bubbles with or without EC treatment.

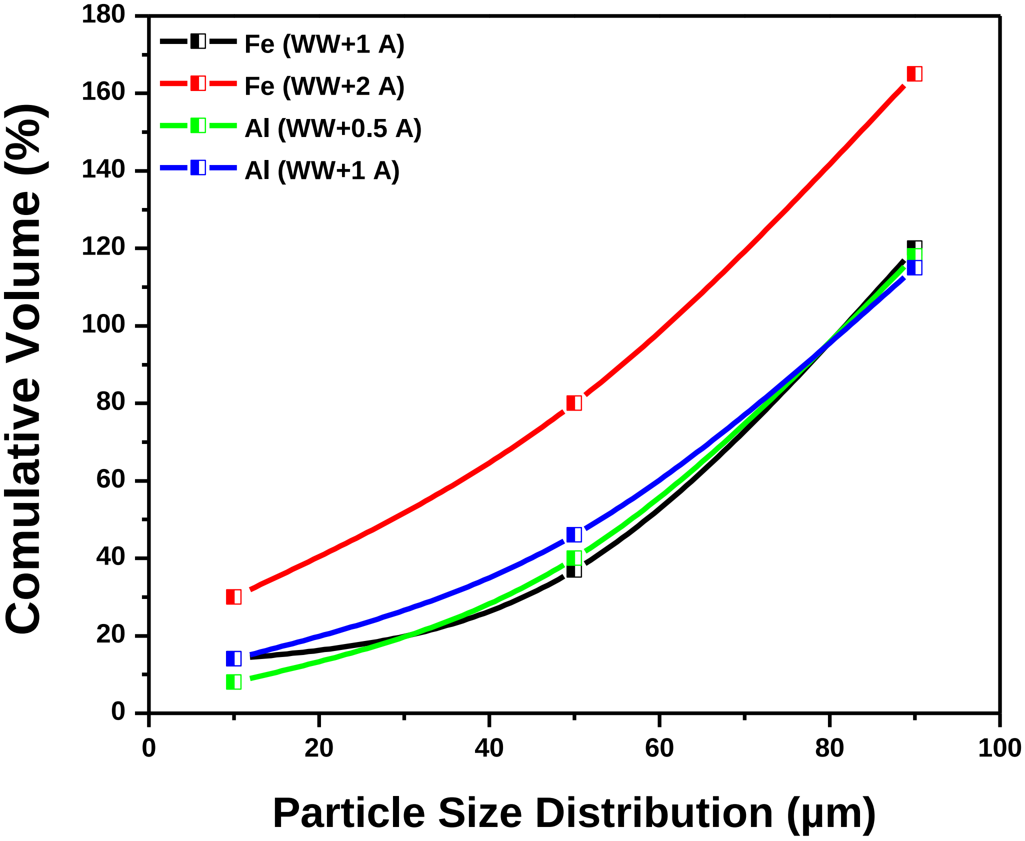

Fig. 17. The particle size distribution of Fe and Al flocs generated by EC reactor.