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Treatment of domestic sewage using electrocoagulation followed by ion exchange – parametric and kinetic studies

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ABSTRACT

Viable and low treatment cost is a challenge for municipal wastewater, therefore, an efficient and cost-effective electrocoagulation (EC) process was studied to treat domestic sewage (DS) in laboratory batch process using SS-304 as electrode material. Effects of various parameters such as pH, current, electrode configuration in numbers and treatment time (t_R) were tested to find optimum operating condition for COD and other pollutants removal. The optimum 78.47% COD reduction of initial COD = 288 mg/dm^3 was obtained at pH = 8, number of plates = 6, current density (CD) = 27.78 A/m^2 (2A) and t_R = 20 min. At this operating condition, the treatment cost in terms of electrode loss and energy consumption was evaluated to be 187.54 Rs/m^2. The kinetic parameters such as rate constant, reactant (COD) order and current density (CD) order were also evaluated by using experimental data fitted to MATLAB solver. The order with respect to COD was found to be 1.4 and with respect to CD 0.64. The EC-treated DS was further treated by ion exchange process to reduce hardness, COD and total dissolved solid. The two-stage treatment reduced water pollutant to significant level and could be used for irrigation and other household purpose.

Keywords: Electrocoagulation; Domestic sewage; Ion exchange; Kinetic studies

1. Introduction

The treatment of wastewater earlier to its discharge in the surface or water receiving bodies is very important, because it contains various microbiological, organic and inorganic substances. Large amount of DS is generated all over the world, DS includes wastewater generated from kitchen, toilets, washing and other household activities. In DS, less amount of organic and inorganic pollutants contain in comparison with industrial effluents, but its quantity is much. In integrated modern township, DS is treated separately, but in most of the places DS is mixed with municipal wastewater (MWW) and it is sent for treatment. MWW includes the wastewater generated from agricultural activities, shops, very small industries and household activities. Municipal Corporation collects all these water and treat it in their treatment cities. Various processes have been applied to treat MWW which includes coagulation [1], electroFenton [2], membrane separation [3] and biological processes such as activated sludge and sequential batch reactor [4], etc. For the treatment of DS various processes have been reported [5–7]. Literature studies show much work have been done in the field of MWW treatment and few in DS treatment. Many under-developing and developing countries use septic tank as primary collection of DS and its treatment, here, only up to 40% biological oxygen demand (BOD) is removed and most of the organic pollutants and pathogenic bacteria still remain in the effluent [2,8]. In most of the places, biological methods are used to treat DS and MWW, which is low-cost operation but not so effective. Membrane separation process requires high capital and operational cost, thus, it is not cost effective. EC

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process has been reported to treat various industrial effluents [9] and MWW [10]. This process is simple and very effective to remove inorganic and organic contaminants contained in effluent; other advantage is that no secondary pollutants are generated during the treatment. Apart from this, sludge generation is very low and it could be separated easily by sedimentation. Sludge can also be used as a fuel material if it contains organics, and for building material to prepare bricks if it contains inorganics. Due to all these advantages, the EC process has been chosen in the present studies. As per literature available, EC of DS has not been reported in literature till date. The EC-treated DS was further treated by ion exchange (IE) for removal of hardness and other inorganic ions present in DS. The combination of both the process is able to give water quality better to river located near the Raipur City, India. It was also comparative with inland surface water in terms of many water quality parameters [11].

2. Materials and methods

2.1. Electrocoagulation process

The electrochemical treatment was performed in 2 dm^3 electrochemical reactors (ECR) in which electrodes were inserted inside the reactor for proper contact with DS. The SS-304 was used as electrode material. Its composition is found to be Fe 67%–71%, Ni 8%–12%, Cr 18%–20%, Mn max 2% [12]. Current (1–5 A) and voltage (1–30 V) were supplied by using D.C. power source. The reactor was placed on the digital magnetic stirrer platform for mixing as shown in Fig. 1a. To perform the experiment, the 1.7 dm^3 DS at desired pH was taken in ECR. The electrodes were dipped in it and connected to a DC power supply. Wastewater suspensions were stirred using a magnetic stirrer adjusted to 200 rpm. The current and the voltage across the electrodes were displayed in DC power supply unit. Before EC run, the electrodes were washed with 10% HCl to remove surface impurities [13]. The schematic view is shown in Fig. 1.

2.2. Ion exchange process

Two polyacrylic tubes of 5 cm diameter was used for ion exchange column arrangement in series which contained cation resin (INDION 225 H) and anion resin (INDION NIP) in equal ratio of 15 cm each. The EC-treated DS was fed in the column with varying flow rate from 2 to 10 dm^3/h for further removal of total dissolved solid (TDS) and hardness of water. Samples were taken at different flow rate and different time for analysis of various pollutants parameters. The diagram of IE unit is presented in Fig. 1b.

2.3. Analysis of domestic sewage

The samples were collected from sewage line located in campus of NIT Raipur, C.G, India, and kept in deep freezer at about 4°C for subsequent experiments. Water parameters were determined as per standard method given in American Public Health Association 22nd ed., 2012. For COD estimation, the samples were digested for 2 h at 148°C in a COD digester (CR-3200, WTW, Germany), then after digestion, it was allowed to cool, and further titrated with standard 0.1 N ferrous ammonium sulphate. Other parameters such as hardness and chloride were determined by titrimetric method [14]. In our experiments, the chloride contained in DS was maximum 405 mg/dm^3, at such low concentration of chloride there is no effect on COD estimation. Sulphate and phosphate were determined by colorimetric method using visible spectrophotometer (Prove 300, MERCK, Germany). pH was measured by digital pH meter (EI-111, India).

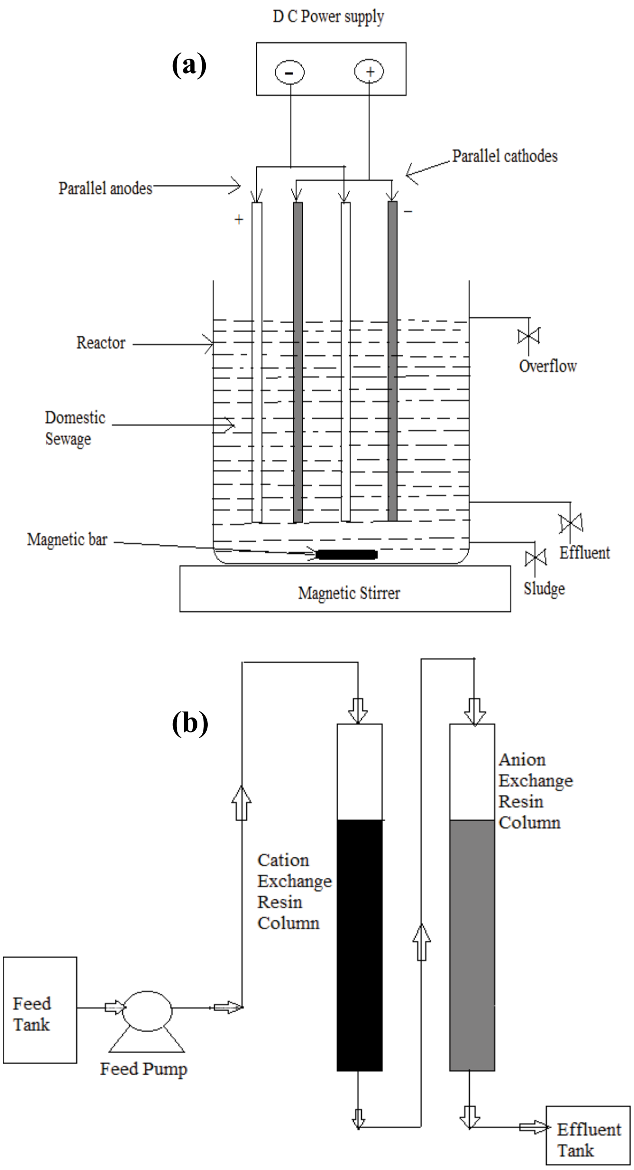


Fig. 1. Schematic diagram of (a) electrocoagulation reactor and (b) ion exchange unit.

3. Mechanism of electrocoagulation

During the EC process, degradation and removal of pollutants occur, which is due to oxidation and EC precipitation [15]. When potential is applied across the iron electrode, the following reaction takes place.

Reaction at anode

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{1}$$

At alkaline pH, Fe^{2+} changes into iron hydrides

$$Fe^{2+} + 2\,OH^{-} \rightarrow Fe(OH)_2 \tag{2}$$

At acidic pH, the electrode is attacked by H^+

$$Fe + 2H^{+} \rightarrow Fe^{2+} \tag{3}$$

In the presence of water and dissolved oxygen, iron hydroxides and ferric ions are formed by following reaction

$$Fe^{2+} + \frac{1}{4}O_2 + \frac{5}{2}H_2O \rightarrow Fe(OH)_3 + 2H^{+} \tag{4}$$

$$Fe^{2+} + \frac{1}{4}O_2 + \frac{1}{2}H_2O \rightarrow Fe^{3+} + OH^{-} \tag{5}$$

The oxygen evolution reaction takes place at the anode by

$$2H_2O \rightarrow O_2 + 4H^{+} + 4e^{-} \tag{6}$$

And at cathode, the following reaction takes place

$$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-} \tag{7}$$

In the above equation, it can be seen that evolution of oxygen at the anode and hydrogen at the cathode takes place (Eqs. (6) and (7)) due to this, dissolved and suspended organic materials are floated on the surface of water. The anode material Fe oxidizes and changes into Fe^{2+} (Eq. (1)), which further changes in Fe^{3+} by oxygen present in water (Eq. (5)). The electrogenerated Fe^{2+} and Fe^{3+} ions further form monomeric and polymeric species such as $Fe(OH)_2^{+}$, $Fe(OH)^{2+}$, $Fe_2(OH)_2^{4+}$, $Fe(H_2O)_4(OH)_2^{+}$, $Fe(H_2O)_6(OH)_4^{+}$, $Fe(OH)_2$, FeO(OH), $Fe(OH)_3$, $Fe(H_2O)_8(OH)_2^{4+}$, $Fe(H_2O)_5(OH)$ as per pH of solution [16]. Under alkaline condition $Fe(OH)_4^{-}$, $Fe(OH)_6^{-}$ is also formed [15]. All these hydroxide species, Fe^{2+} and Fe^{3+} take part in coagulation/precipitation. Due to this, removal of pollutants takes place at wide pH range. The amorphous metal hydroxides adsorb the pollutants present in water and neutralize it. The neutralized mass, that is, cation–pollutant complexes settle down in the reactor and swaps to pollutants aided removal of pollutants. Overall pollutants removal takes place by mechanisms (i) floating of pollutants by gases, (ii) adsorption, (iii) charge neutralization and (iv) swapping.

4. Results and discussion

4.1. Effect of pH

In EC process for wastewater treatment, the solution pH plays tremendous role, due to this, EC studies were performed in pH range 3–11. The COD removal data are presented in Fig. 2 and other values in Table 1. The initial COD value of DS (288 mg/dm^3) reached 90, 70, 56, 56, 52 and 64 mg/dm^3 at 2 A and operational pH of 3, 5, 7, 8, 9 and 11, respectively, in 20 min of t_R, further increase in t_R to 30 min, the COD value of the DS reached to 94, 72, 70, 72, 64 and 76 mg/dm^3 at these pH. The reason for increase in COD values after t_R = 20 min is due to the formation of excess coagulants species by dissolution of iron electrodes, which causes restablization of colloids present in DS [17]. In the studies, pH 8 was found to best. As discussed in section mechanism of EC, the various coagulant species, that is, metal cations and metal hydroxides are formed. At pH < 4 mainly Fe^{2+} are in predominant and monomer and polymer species are formed much in the pH range 4–9. Further increase in pH causes formation of $Fe(OH)_3$. Monomer and polymer species are active coagulants, moreover, formation of coagulant species depends on pH of solution [9,16]. However, formation rate of these coagulant species could not be explained presently. The DS contained proteins, reducing carbohydrate, fatty acids and inorganics. At normal temperature, protein deneutralized and produces negatively charged amines. The carbohydrate contains carboxylic and hydroxyl functional groups which have net negative charge [18]. The negative charged compounds come in contact with coagulant species, which have positive charged and neutralized and formed heavy mass which settled down in the reactor. Pollution also enmeshed in amorphous flocs. Due to these pollutants removals take place. It has been reported that removal of pollutants are much in the pH range of 5–9 [19], which was also seen in our case.

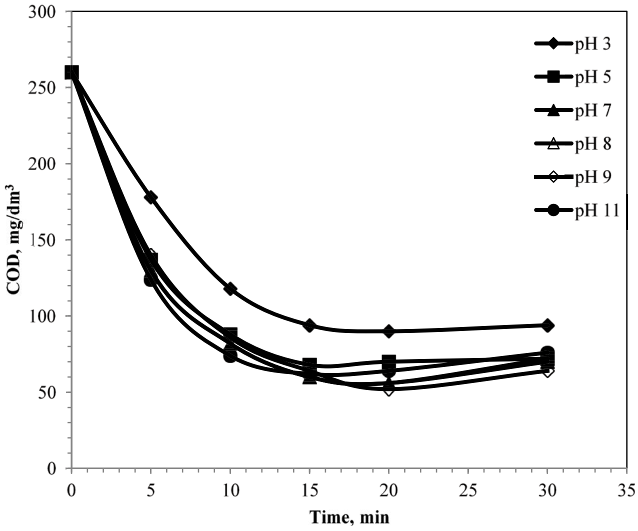


Fig. 2. Effect of pH on COD removal of DS, no. of plates = 6, CD = 27.7 A/m^2 (2 A).

4.2. Comparison of pH 7 and 8 at different current

As discussed above, pH 7 and 8 gave good results, therefore, at these pH values, current was varied to observe its effect. The values in terms of COD reduction and pH variation of DS were noted, which are shown in Figs. 3a and b. In Fig. 3a, COD removal with respect to time is presented. From the figure, it can be seen that the COD removal was

Table 1
Characteristics of raw and treated DS

Influent parameters (mg/dm3, except pH)	Raw	Treatment by electro coagulation	Treatment by electro coagulation followed by ion exchange	CPCB norms, 1986	Kharun River, Raipur, India
pH	7.5	8.2	7.45	6.0 – 8.5	7.15
COD	288	62	54	200	63
BOD	148	24	20	30	–
Total hardness	410	150	10	200	210
TDS	672	464.8	272	500	89.87
Sulphate	4.74	3.13	0.46	200	1.03
Phosphate	0.348	0.043	0.027	5	1.18
Chloride	364	300	160	200	70

COD = Chemical oxygen demand, BOD = biological oxygen demand, TDS = total dissolved solids, CPCB = Central Pollution Control Board, 1986,

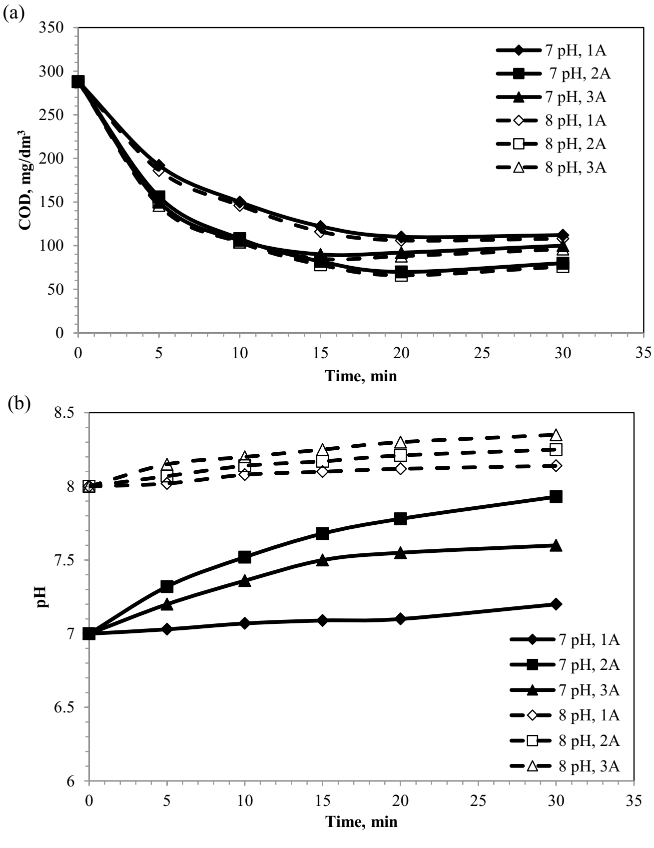


Fig. 3. Effect of pH and current on (a) COD removal of DS and (b) variation in pH, No. of plates = 6, $\mathrm{COD_i}$ = 288 mg/dm^3, EG = 1.5 cm. 1 A = 13.89 A/m^2, 2A = 27.78 A/m^2, 3A = 4 1.67 A/m^2.

increased with increase in current up to 3A and till 12 min of EC process, after 12 min, COD reduction was found to be more in 2A as compared with 3A current, which may be due to the excess coagulant species formation for 3A current. Excess coagulants to that of desirable cause the re-stabilization of colloid particles present in the effluent, consequently low removal of pollutants [15]. COD removal at pH 8 was maximum 4% more to that obtained at pH 7. At 7 pH and 1 A, 2 A and 3 A current, respectively, COD of DS 288 mg/dm^3 reduced to 110, 70 and 78 mg/dm^3, while COD values of 106, 66 and 74 mg/dm^3 were noted at pH 8 at corresponding current after 20 min of treatment. These data show treatment at pH 8 is better to pH 7.

The pH value of DS solution at different time was also noted. pH of the solution was found to increase at all the current. At 1 A, 2 A and 3 A current, respectively, the solution pH 7 reached to 7.2, 7.5 and 7.6. Similarly, pH 8 reached to 8.14, 8.25 and 8.35. In the EC process as time proceeds, the change in solution components and change in charges (+ or -) of metal hydroxides also takes place. The $\mathrm{OH^-}$ ions generated at the anode also regulates pH (Eq. (5)). The metal hydroxide cations which have positive charge participate in EC, and its amount decrease in the solution, while the negative charge anions still retain in the solution. Due to all these, pH of solution was found to increase.

4.3. Effect of CD on COD removal, electrode loss and energy consumption

Current density (CD) is an important parameter which significantly affects the COD removal in EC process, CD is defined as the ratio of applied current to the surface area of electrode. CD not only regulates ion production rate but also to bubble production rate and its size as well, which overall affects removal efficiency of pollutants. The amount of ion produced with CD is represented by Faraday's law.

$$m = \frac{M \times \mathrm{CD} \times t}{Z \times F} \tag{8}$$

where CD is current density (A/cm^2), t is time in sec, M is relative molar mass of the electrode concerned and F is the Faraday's constant, 96,500 C/mol. Effect of CD was studied on COD removal, electrode loss and specific energy consumption (SEC). The SEC was evaluated using the following equation:

$$\mathrm{SEC}\left(\frac{\mathrm{Wh}}{\mathrm{dm}^3 \times \mathrm{COD\ removal}}\right) = \frac{VIT}{\mathrm{Treated\ volume}\left(\mathrm{dm}^3\right) \times g\mathrm{COD\ removal}} \tag{9}$$

where V is voltage across electrode, I is current and t is time in hour.

The results are shown in Fig. 4. The CD was varied for various plate configuration 2, 4 and 6 nos. For 6 plate configuration at CD of 13.89 (1 A), 27.78 (2 A) and 41.67 (3 A) A/m^2, respectively, COD value 288 mg/dm^3 reduced to 118, 62 and 76 mg/dm^3 in 30 min; electrode loss was found to be 0.262, 0.46 and 0.852 g/dm^3; SEC was 7.412, 21.25 and 81.66 Wh/dm^3.gCOD removal. At 4 plate configuration, COD reduced to 116, 80 and 82 mg/dm^3; electrode loss was found to be 0.241, 0.358 and 0.771 g/dm^3 and SEC was 11.116, 35.745 and 77.08 Wh/dm^3.gCOD removal. For 2 plate configuration, COD reduced to 128, 106 and 98 mg/dm^3; electrode loss was found to be 0.21, 0.312 and 0.729 g/dm^3; SEC was 23.143, 78.214 and 137 Wh/dm^3.gCOD removal. The above values were calculated at pH 8 for EC time of 30 min. Results reflect increase in COD removal efficiency with increase in CD. The dissociation of metal increases with CD, which resulted in greater amount of coagulant and precipitate production, consequently, higher removal of pollutants. From the above data, it can also be seen that among various plate configurations, 6 plate configuration is best because COD removal and SEC are best and electrode loss is slightly more to that obtained for 2 and 4 plate configuration. The COD reduction depends on number of cations generated, electrode gap and pH. In 6 plate configuration, higher number of cations is generated because electrode loss was more to 4 and 2 plate. If electrode gap is less, resistance is less, thus power requirement is less by formula power $P = I \times R$. Electrode gap is reduced by increasing number of plates, but if number of plate increases, the power requirement also increases, because each plate take power. Overall all factors affect COD reduction and SEC. The pollution parameters reduced much at CD = 27.78 A/m^2 (2 A). Overall pH 8, 2 A current and 6 plate configuration looks optimum. Other parameters such as total hardness, calcium hardness, chloride, phosphate, sulphate and TDS were also less in 6 plate configuration (Table 2).

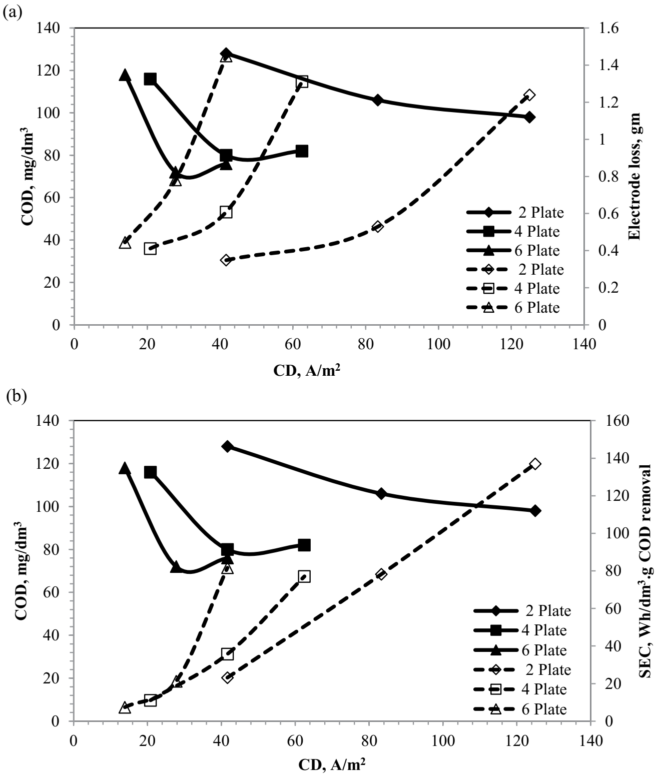


Fig. 4. Effect of CD on (a) COD removal of DS and electrode loss and (b) COD removal of DS and SEC at optimum pH 8, COD$_i$ = 288 mg/dm^3, EG = 1.5 cm. ---- EL and SEC, — COD.

The electrocoagulation (EC) of DS has been not reported till now; however, treatment of municipal wastewater (MWW) and gray waters has been performed by various authors (listed in Table 3). The results show pollution removal to better in present case.

4.4. Kinetic studies

When current is passed across the electrodes, the metal cations Fe^{2+} and Fe^{3+} are generated, which further changes into metal hydroxide cations. These cations remove the organic content in DS in form of solid residue by various mechanisms such as charge neutralization, adsorption, enmeshment and sweeting. As a result, the supernatant is contained in the reactor at the top and solid residues at the bottom. The organic removal process can be mentioned as

$$\text{Domestic sewage} \xrightarrow{\text{current}} \text{Liquid organic} + \text{Solid residue} \quad (10)$$

Various organics contained in DS can be represented together as COD and Eq. (10) can be written as

$$\text{COD} \xrightarrow{\text{current}} \text{Liquid organic} + \text{Solid residue} \quad (11)$$

Increase in CD up to certain limit increases the COD reduction, thus, the global rate equation for COD removal in EC process can be written as

$$\frac{d}{dt}\text{COD} = k\,\text{COD}^n C_D^m \quad (12)$$

where n is in order with respect to COD and m with respect to CD, k is the reaction rate constant. Eq. (12) was solved numerically using MATLAB. There are various ways to solve Eq. (12). First way is to assume the order (n) of organics (COD) at constant value of CD, and integrate the differential equation. By plotting the graph between t (abscissa) and values of ordinate, the reaction rate constant k is determined. This type of kinetic studies had been performed by some researches [22,23]. In this, number of steps is required and value of n is not so desirable. Another way is to assume the value of n and determine k at different reaction time. If values of k are consistent at all different times, the average value of k is taken and order (n) assumed is considered to be accurate. If values of k are not consistent, the new value of n is assumed and again value of k is determined. It is repeated till values of k are similar at different time [13,24,25]. Computer programming using Euler and Runge–Kutta method is used to get predicted values of COD for the rate constant k, which should be near to experimental values of COD. This process gives somewhat better results to earlier one. In the third way, Eq. (12) can be solved numerically using MATLAB as performed by researchers [26,27]. This process gives more

Table 2
Characteristics of untreated and treated DS at different operating condition and operating cost at pH 8

Parameter	Raw	2 Plate			4 Plate			6 Plate		
		1 A	2 A	3 A	1 A	2 A	3 A	1 A	2 A	3 A
Total hardness mg/dm^{-3}	410	270	300	240	300	180	225	180	150	110
Calcium hardness mg/dm^{-3}	340	200	170	185	175	80	190	80	110	70
Chloride mg/dm^{-3}	364	352	360	372	410	364	405	364	300	368
Phosphate mg/dm^{-3}	0.348	0.07	0.012	0.05	0.385	0.15	0.012	0.06	0.043	0.04
Sulphate mg/dm^{-3}	4.74	8.54	_	1.83	_	1.65	_	3.43	3.13	1.94
COD mg/dm^{3}	288	128	106	98	116	80	82	118	62	76
TDS mg/dm^{-3}	672	540	489.3	344	649.5	400	493.5	444	464.8	424
pH	7.5	7.7	8.1	8.5	8.1	8.6	7.7	8.3	8.2	8.8
Electrode loss, g	–	0.3488	0.53	1.2401	0.411	0.6085	1.311	0.4447	0.781	1.4494
Sludge, g	–	0.7608	0.35	2.2206	0.7288	1.6273	0.0401	0.8755	1.867	2.0729
EG, cm	–	2	2	2	1.5	1.5	1.5	1.5	1.5	1.5
Voltage, V	–	12.59	24.2	29.5	6.5	12.64	18	4.29	7.8	19.62
Energy consumption (EC), Wh/dm^{3}	–	3.703	14.235	26.03	1.912	7.435	15.88	1.26	4.59	17.312
SEC, Wh/dm^{3}.g COD removal	–	23.143	78.214	137	11.116	35.745	77.08	7.412	21.25	81.66
CD, A/m^{2}	–	41.67	83.34	125	20.84	41.67	62.5	13.89	27.78	41.67
Power price ((EC × per unit price) kWh/m^{3}) Rupees		22.218	85.41	156.01	11.472	44.61	95.28	7.56	27.54	103.872
Electrode cost/litre (electrode loss × price of SS304), Rupees		71.504	108.65	254.22	84.255	124.743	268.75	91.163	160.105	297.127
Total price (Rs)		93.722	194.06	410.23	95.727	169.353	364.03	98.723	187.54	400.999
Total price (US$)		1.32	2.72	5.74	1.34	2.37	5.09	1.38	2.64	5.62

COD = chemical oxygen demand, TDS = total dissolved solids, EG = electrode gap, SEC = specific energy consumption, CD = current density.

accurate values of reaction rate constant *k*, order with respect to COD (*n*) and order with respect to CD (*m*). Due to this, in present studies, kinetics parameters were evaluated using MATLAB; moreover, this facilitates to determine kinetics parameters in less steps. The set of kinetic parameters was estimated by a nonlinear optimization technique. The error between the model and experimental data served as the objective function, which was minimized by using optimization routine fmincon available in the MATLAB Optimization Toolbox. The objective function of the optimization problem is given as follows:

$$\phi = \sum_{k=1}^{\text{NC}} \left(C_k^{\text{cal}} - C_k^{\text{exp}} \right)^2 \tag{13}$$

where C_k^{cal} and C_k^{exp} are calculated and experimental values of COD of each experimental point *k*. NC is the number of experimental data points for COD value. The kinetic parameters for COD in range of 56–288 mg/dm^3, and CD in range of 13.69 to 41.67 A/m^2 were obtained by solving the model equation based on the successive guess values of the kinetic parameters. The value of $k = 7.1 \times 10^{-6}$ InlineEqn(1), $n = 1.4$ and $m = 0.64$ was found to fit well with the experimental results. The experimental COD values are shown by point and numerically calculated COD values by line in Fig. 5. It can be observed from the figure that the model predictions are in good agreement with the experimental observations. The average relative error in prediction of COD of DS corresponding to 1 A, 2 A and 3 A current is obtained as 5.58%, 8.08% and 6.93%, respectively. The low values of relative error show the efficiency and predictability of the developed model. Thus Eq. (13) can be written as follows:

$$\frac{d}{dt}\text{COD} = 7.1 \times 10^{-6} \times \text{COD}^{1.4} C_D^{0.64} \tag{14}$$

EC treatment of sugar industry wastewater was also performed by Sahu et al. [28] for which $n = 1.6$ and $m = 0.591$ was evaluated. Guven et al. [29] evaluated $n = 1.2$ for electrochemical oxidation of simulated beet sugar factory wastewater. No EC work has been found to treat DS; however, few works have been reported to treat simulated DS for removal of phosphorous only from it [30,31].

4.5. Cost of electrocoagulation

In EC, the electricity consumption and electrode loss are considered to be major cost involving components. In the present process, pH 7–8 is best for treatment. The DS also has pH 7.5–8, thus, addition of chemicals is not required to maintain optimum operational pH for EC. Cost of treatment depends on conductivity of wastewater, characteristic of wastewater and fluctuating parameters (COD, BOD, organics and inorganics). The cost of electrode and energy consumption can be evaluated from experimental data. The sum of energy cost and electrode material cost gives operating

Table 3
Comparison of results for electrocoagulation of gray/MWW/DS

S. No.	Type of wastewater	Operating conditions	Influent parameters	Effluent parameters/% reduction	References
1	Grey water	pH = 7–8 SS-Al electrode EG = 10 mm	Turbidity = 20–120 NTU, TS = 350–450 mg/dm^3, SS = 15–84 mg/dm^3, COD = 27–128 mg/dm^3	Turbidity = 1.2–1.7 NTU, SS = 4–19 mg/dm^3, COD = 14–44 mg/dm^3	Lin et al. [5]
2	MWW	Fe electrode pH = 7.3	COD = 260–360 mg/dm^3 SS = 95–120 mg/dm^3 BOD = 145–210 mg/dm^3 Chloride = 295–330 mg/dm^3	COD = 60 %–70%	Kurt et al. [6]
3	MWW	pH = 7.5 ± 1 t_R = 30 min EG = 5 cm CD = 247 A/m^2	COD = 420 ± 3 mg/dm^3 TSS = 236 ± 5 mg/dm^3 Turbidity = 415 ± 5 NTU	COD = 77.2% TSS = 68.5% Turbidity = 91.8%	Saleem et al. [20]
4	MWW	pH = 7.8 Al and Fe electrodes EC time = 10 min CD = 100 A/m^2	COD = 350 mg/dm^3 SS = 150 mg/dm^3 P = 12.9 mg/dm, Turbidity = 98 NTU	COD = 72% P = 98% Turbidity = 98%	Ozyonar and Karagozoglu [7]
5	Gray water	pH = 5.9–7.8 EG = 4 cm	COD = 320–733 mg/dm^3 TSS = 288–788 mg/dm^3 TDS = 455–1483 mg/dm^3	COD = 70%, Pathogens = 99.9%	Vakil et al. [21]
6	DS	pH = 8, EC time = 30 min, CD = 27.78 A/m^2 (2A) No of plate = 6 EC + IE	COD = 288 mg/dm^3 TDS = 672 mg/dm^3 P = 0.348 mg/dm^3 SO_4 = 4.74 mg/dm^3 Hardness = 410 mg/dm^3 Hardness = 150 mg/dm^3 COD = 62 mg/dm^3	COD = 78.47% TDS = 31% P = 87.6 % SO_4 = 34% Hardness = 63.4% Hardness = 10 mg/dm^3 COD = 54 mg/dm^3	Present studies

cost. On treating 1.7 dm^3 DS, 78.47% COD removal was obtained at optimum pH 8 with 6 plate configuration and 2 A current.

Energy cost:
In India average electricity cost/unit = Rs. 6/- [32]

Power consumption to treat 1.7 dm^3 DS from experiment was found to be 7.803 Wh, which reflect power consumption to treat 1 dm^3 DS = 4.59 Wh, that is, 4.59 kWh energy to treat 1 m^3 DS.

Cost of energy consumption = 4.59 kWh × 6 = Rs. 27.54/m^3

Electrode cost:
Cost of SS-304 = 205/kg [33]

Electrode loss to treat 1 m^3 DS from laboratory experiments was evaluated to be 0.781 kg

Cost of electrode to treat 1 m^3 DS = 205 × 0.781 = Rs. 160.0

Total operating cost = 27.54 + 160 = Rs. 187.54/m^3 (US$ 2.64/m^3) DS treated.

The cost calculated and treated water parameters are listed in Table 2.

4.6. Electrocoagulation followed by ion exchange

The EC-treated DS contained high TDS (490 mg/dm^3), hardness (300 mg/dm^3) and COD (82 mg/dm^3), therefore, it was further treated for its removal. The ion exchange resins have two types of structures, gel structure and macro porous structure [34]. In present studies, styrene divinylbenzene copolymer having sulphonic acid group as cation exchange resin and styrene – EDMA copolymer having benzyl dimethyl ethanol amine as anion exchange resin was used. These resins are used widely for removal of pollutants contained in wastewater [35].

For further treatment, the EC-treated DS was fed to ion exchange unit at flow rate of 2–10 dm^3/h. The results are shown in Fig. 6. At all the flow rates, hardness of ion exchange treated DS was lower than 20 mg/dm^3 and COD was in the range of 52 to 58 mg/dm^3. At flow rate 2, 6 and 10 dm^3/h, respectively, chloride of DS after treatment was 130, 150 and 160 mg/dm^3; phosphate was 4.28, 5.1 and 5.27 mg/dm^3 and sulphate was 0.24, 0.38 and 0.46 mg/dm^3. The initial concentration of chloride, sulphate and phosphate was 300, 3.13 and 0.043 mg/dm^3. The COD of effluent was also decreased to 54 mg/dm^3 from 62 mg/dm^3. The resins used here not only reduce to inorganic but also to organics.

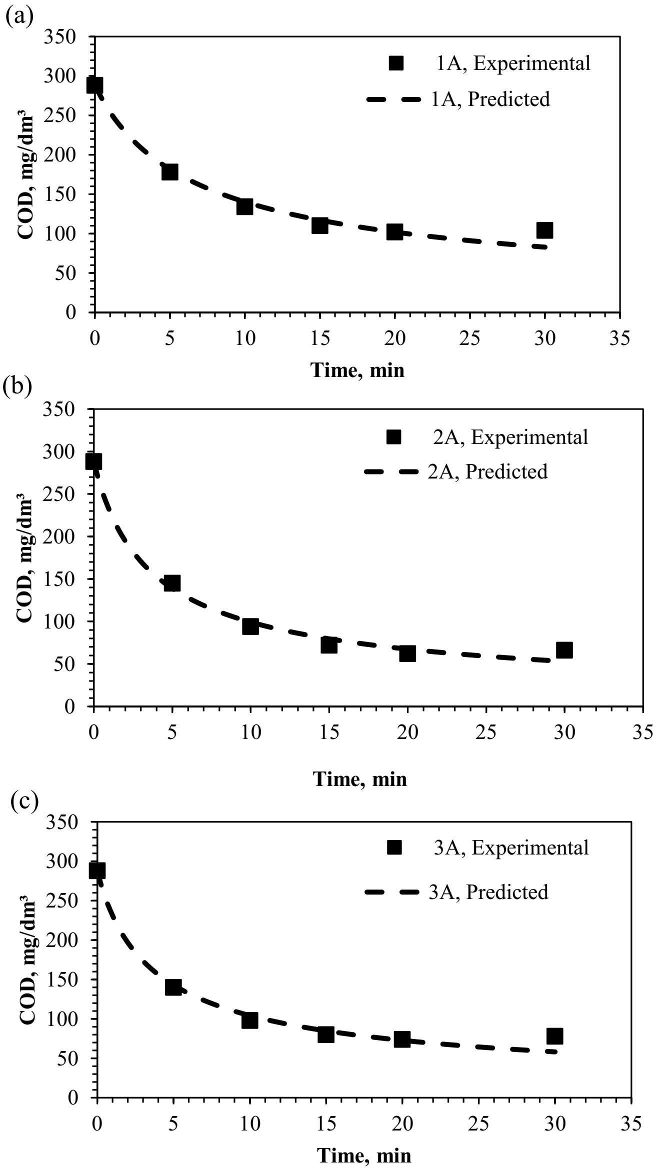
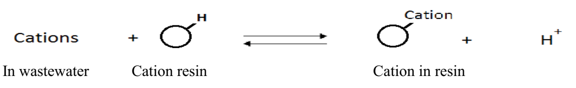
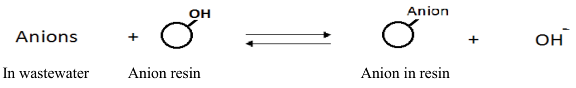


Fig. 5. Kinetic studies for COD removal of DS (a) 1 A, (b) 2 A, (c) 3 A current. 1 A = 13.89 A/m^2, 2 A = 27.78 A/m^2, 3 A = 4 1.67 A/m^2.

In IE process, both inorganic and organic cations present in water exchange with cation of cation resins and inorganic and organic anions exchange with anion of anion resins [36]. Due to this, hardness, TDS and COD of polluted water decreases. The process is explained below.



(15)



(16)

Ion exchange process has been claimed to be more effective than activated carbon, carbonaceous resins, metal hydroxide and metal oxide for natural organic matter removal [37]. In nearby power plant, 4.2 ton resin is used for softening of 1,63,000 m^3 river water. After that it is regenerated frequently and further used for nearly 5 years, which shows it is a low cost process. In present study, the resins exhaust period and cost of ion exchange treatment is not calculated. In global market, the price of anion resin is US$ 2,000/ton and cation resin is US$ 1,000/m^3 [38]. Two-stage treated DS could be chlorinated to kill available bacteria and used for gardening or other purpose.

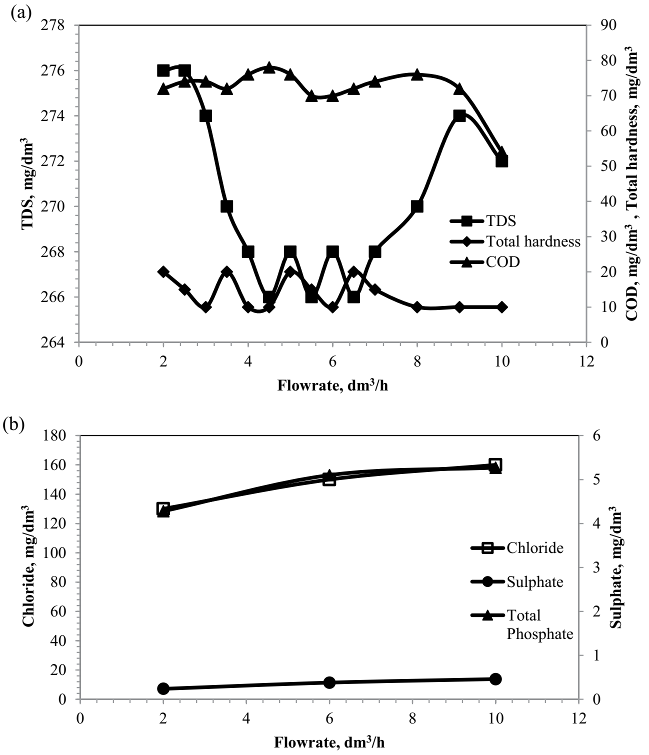


Fig. 6. Effect of flow rate on (a) removal of COD, total hardness and TDS, and (b) removal of chloride, sulphate and total phosphate of pretreated DS, COD$_i$ = 82 mg/dm^3, TDS$_i$ = 490 mg/dm^3, total hardness$_i$ = 300 mg/dm^3, chloride$_i$ = 300 mg/dm^3, sulphate$_i$ = 0.46 mg/dm^3, total phosphate$_i$ = 5.27 mg/dm^3.

5. Conclusions

The EC was found to be effective for treatment of DS. Effect of various operating parameters such as pH, current and number of plates was taken in account for treatment. At optimum operating condition pH = 8, number of plates = 6 and current = 2A (27.38 A/m^2), the initial COD 288 mg/dm^3 reduces to 62 mg/dm^3 in 20 min treatment with treatment cost = 187.54 Rs/m^2. Other pollutants such as hardness, chloride, phosphate, sulphate and TDS were also reduced significantly. The rate equation was derived using MATLAB solver which gave 1.4 order with respect to COD and 0.64 order with respect to CD. The experimental data were found close to calculated data; this shows the accuracy of the model. The EC-treated DS was further treated by IE to remove TDS and hardness. At flowrate of 10 dm^3/h of pretreated DS the COD, TDS and hardness reduced to 54 mg/dm^3, 272 mg/dm^3

and 10 mg/dm^3 from its initial value 82 mg/dm^3, 465 mg/dm^3 and 150 mg/dm^3, respectively. The treated water quality by two step is better to nearby river water located to Raipur city, Chhattisgarh, India and also better to effluent discharge norms prescribed by CPCB, India [11]. The treated water can be used for irrigation and other household purpose after chlorination. The EC followed by ion exchange could be a viable process to treat DS and its possible use.

References

[1] M. Guida, M. Mattei, C.D. Rocca, G. Melluso, S. Meriç, Optimization of alum-coagulation/flocculation for COD and TSS removal from five municipal wastewater, Desalination, 211 (2007) 113–127.

[2] R. Daghrir, P. Drogui, Coupled electrocoagulation–electro-fenton for efficient domestic wastewater treatment, Environ. Chem. Lett., 11 (2013) 151–156.

[3] J.M. Tan, G. Qiu, Y.P. Ting, Osmotic membrane bioreactor for municipal wastewater treatment and the effects of silver nanoparticles on system performance, J. Cleaner Prod., 88 (2015) 146–151.

[4] A.A. Badejo, D.O. Omole, J.M. Ndambuki, W.K. Kupolati, Municipal wastewater treatment using sequential activated sludge reactor and vegetated submerged bed constructed wetland planted with vetiveriazizanioides, Ecol. Eng., 99 (2017) 525–529.

[5] C.J. Lin, S.L. Lo, K.C.Y. Chao-Yin, C.H. Wu, Pilot-scale electrocoagulation with bipolar aluminum electrodes for on-site domestic greywater reuse, J. Environ. Eng., 131 (2005) 491–495.

[6] U. Kurt, M.T. Gonullu, F. Ilhan, K. Varinca, Treatment of domestic wastewater by electrocoagulation in a cell with Fe-Fe electrodes, Environ. Eng. Sci., 25 (2008) 153–161.

[7] F. Ozyonar, B. Karagozoglu, Operating cost analysis and treatment of domestic wastewater by electrocoagulation using aluminum electrodes, Polish J. Environ. Stud., 20 (2001) 173–179.

[8] M. Muller, F. Rabenoelina, P.B.D. Patureau, K. Lemenach, H. Budzinski, D. Barcelo, M.L.D. Alda, M. Kuster, J.P. Delgenes, G. Hernandez-Raquet, Chemical and biological analysis of endocrine-disrupting hormones and estrogenic activity in an advanced sewage treatment plant, Environ. Toxicol. Chem., 27 (2008) 1649–1658.

[9] R. Katal, H. Pahlavanzadeh, Influence of different combinations of aluminum and iron electrode on electrocoagulation efficiency: application to the treatment of paper mill wastewater, Desalination, 265 (2011) 199–205.

[10] A.K. Sharma, A.K. Chopra, Removal of nitrate and sulphate from biologically treated municipal wastewater by electrocoagulation, Appl. Water Sci., 7 (2017) 1239–1246.

[11] CPCB, General Standards for Discharge of Environmental Pollutants Part-A: Effluents, The Environment (Protection) Rules, Schedule – VI, pp. 545–548, 1986.

[12] https://www.researchgate.net/figure/chemical-composition-of-AISI-304-stainless-Steel.

[13] O.P. Sahu, P.K. Chaudhari, Electrochemical treatment of sugar industry wastewater: COD and color removal, J. Electroanal. Chem., 739 (2015) 122–129.

[14] Standard Method for the Examination of Water and Wastewater, 22nd edition, (APHA) American Public Health Association, Washington, D.C., 2012.

[15] S. Mahesh, B. Prasad, I.D. Mall, I.M. Mishra, Electrochemical degradation of pulp and paper mill wastewater Part-2 Characterization and analysis of sludge, Ind. Eng. Chem. Res., 45 (2006) 5766–5774.

[16] O.T. Can, M. Kobya, E. Demirbas, M. Bayramoglu, Treatment of the textile wastewater by combined electrocoagulation, Chemosphere, 62 (2006) 181–187.

[17] H.S. Peavy, D.R. Rowe, G. Tchobanoglous, Environmental Engineering, McGraw-Hill Higher Education, New York, 2009.

[18] R.K. Choudhary, P.K. Chaudhari, Removal of pollutants of coking wastewater by adsorption, Desal. Wat. Treat., 75 (2017) 45–57.

[19] A. Gurses, M. Yalcin, C. Dogˇar, Electrocoagulation of some reactive dyes: a statistical investigation of some electrochemical variables, Waste Manage., 22 (2002) 491– 499.

[20] M. Saleem, A.A. Bukhari, M.N. Akram, Electrocoagulation for the treatment of wastewater for reuse in irrigation and plantation, J. Basic Appl. Sci., 7 (2011) 1814–8085.

[21] K.A. Vakil, M.K. Sharma, A. Bhatia, A.A. Kazmi, S. Sarkar, Characterization of greywater in an indian middle-class household and investigation of physicochemical treatment using electrocoagulation, Sep. Purif. Technol., 130 (2014) 160–166.

[22] P.K. Chaudhari, S. Chand, I.M. Mishra, Kinetics of catalytic thermal treatment (catalytic thermolysis) of biodigester effluent of an alcohol distillery plant, Chem. Eng. Comm., 199 (2012) 874–888.

[23] A.D. Dhale, V.V. Mahajani, Treatment of distillery wastewater after bio gas generation: wet oxidation, Indian J. Chem. Technol., 7 (2000) 11–18.

[24] O.P. Sahu, P.K. Chaudhari, Removal of color and chemical oxygen demand from sugar industry wastewater using thermolysis processes, Desal. Wat. Treat., 56 (2015) 1756–1767.

[25] K.A. Gavhane, Chemical Reaction Engineering I, 8th edition, Nirali Publication, Pune, India, 2007.

[26] G. Jyoti, S. Bhoi, D.K. Sahu, Production and isolation of n-butyl acrylate using pervaporation-aided esterification reaction: kinetics and optimization, Chem. Eng. Technol., 42 (2019) 617–627.

[27] S. Gondudey, P.K. Chaudhari, Influence of various electrode materials in electrocoagulation: application in treatment of sugar industry effluent, Sugar Technol., (2019) 1–13.

[28] O.P. Sahu, V. Gupta, P.K. Chaudhari, V.C. Shrivastava, Electrocoagulation treatment of actual sugar industry wastewater using aluminum electrode, Int. J. Environ. Sci. Technol., 12 (2015) 3519–3530.

[29] G. Guven, A. Perendeci, A. Tanylac, Electrochemical treatment of simulated beet sugar factory wastewater, Chem. Eng. J., 151 (2009) 149–159.

[30] P.I. Omwene, M. Kobya, Treatment of domestic wastewater phosphate by electrocoagulation using Fe and Al electrodes: a comparative study, process safety and environmental protection, 116 (2018) 34–51.

[31] P.I. Omwene, M. Kobya, O.T. Can, Phosphorus removal from domestic wastewater in electrocoagulation reactor using aluminum and iron plate hybrid anodes, Ecol. Eng., 123 (2018) 65–73.

[32] https://www.india-briefing.com/news/industrial-power-rates-india-11062.html, 05/12/2018.

[33] https://www.steelplates.in, /20/10/2018.

[34] www.mattenplant.com/ion-exchange-ix/overview/types-of-resins/

[35] R. de. A. Domingos, F.V. da. Fonseca, Evaluation of adsorbent and ion exchange resin for removal of organic matter from petroleum refinery wastewater aiming to increase water reuse. J. Environ. Manage., 214 (2018) 362–369.

[36] A. Vasileva, Ion Exchange for Natural Organic Matter Removal, B.Tech Thesis, Helsinki Metropolia University of Applied Sciences, Finland, 2014.

[37] B. Bolto, D. Dixon, R. Eldridge, S. King, K. Linge, Removal of natural organic matter by ion exchange, Water Res., 36 (2002) 5057–5065.

[38] www.alibaba.com, 05/12/2018.