Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25971

197 (2020) 67–75
September

Study of flow dynamic behavior of electrochemical reactor for treating liquid biomedical wastewater

Mohamed Yacin Sikkandar[a,*], S. Sabarunisha Begum[b], N.M. Sudharsan[c], N.B. Prakash[d]

[a]*Department of Medical Equipment Technology, CAMS, Majmaah University, Al Majmaah 11952, Saudi Arabia, email: m.sikkandar@mu.edu.sa (M.Y. Sikkandar)*
[b]*Department of Chemical Engineering, Sethu Institute of Technology, Virudhunagar, India, email: sabarunisha@sethu.ac.in (S.S. Begum)*
[c]*Department of Mechanical Engineering, Rajalakshmi Engineering College, Chennai, India, email: sudharsan.nm@rajalakshmi.edu.in (N.M. Sudharsan)*
[d]*Department of Electrical and Electronics Engineering, National Engineering College, Kovilpatti, India, email: nbprakas@gmail.com (N.B. Prakash)*

Received 4 December 2019; Accepted 9 April 2020

A B S T R A C T

In this paper, the flow dynamic behavior of the filter press electrochemical reactor (FPECR) has been investigated for the treatment of liquid biomedical wastewater. The residence time distribution is utilized as a tool to investigate the flow dynamic behavior of the electrolyte within the reactor. The reactor is operated at different current densities of 2, 4, 6, 8, and 10 A/dm^2 with RuO_2/Ti as an electrode by varying flow rates such as 20, 40, 60, 80, and 100 L/h. Impacts of various flow rates on flow dynamics were examined. The outcomes of this study demonstrate the presence of a dead volume and short-circuiting in the reactor were reduced for the lowest flow rate of 20 L/h in the reactor at 10 A/dm^2. The potential of the FPECR was experimentally validated by analyzing the chemical oxygen demand (COD) removal efficiency, total dissolved solids, and total suspended solids emanating from the wastewater. Findings of this study reveal that maximum COD reduction of about 94% was achieved with a maximum current efficiency of 18.47% at a flow rate of 20 L/h which has good mixing and less back mixing condition inside the reactor. The experimental findings prove that the FPECR can be used for the treatment of pharmaceutical-based liquid biomedical waste and can achieve the quality of the standards prescribed for reuse of biomedical wastewater.

Keywords: Electrochemical reactor; Flow dynamics; Residence time distribution; Liquid biomedical wastewater; Chemical oxygen demand

1. Introduction

Biomedical waste is the one which are generated in the form of swabs, discarded syringes, plastics, unused specimens, etc., from the hospitals or any other healthcare facilities. These wastes may be either in the form of solid or liquid which are produced by means of diagnosis, immunization, and/or treatment of human beings or animals; and also, may be as a result of research or testing of animals, etc., [1]. Liquid biomedical waste is mostly from the points such as operation theatre, labor ward, laboratory, restaurant, washrooms, lavatory, etc. Some of the hospitals and health care centers that are not having effluent treatment plants (ETPs) are just separating these wastes and discharges as effluent into a drainage system. This biomedical liquid waste effluent contains a lot of infections and disease-causing pathogens which will affect the people if it is left to run out into local bodies of water such as rivers, lakes, ponds, etc. Of all other biomedical waste, it is generally considered that

* Corresponding author.

liquid waste would possesses major threat to human health and surroundings because of its potential to pass into the water bodies and pollute them [2].

It is clearly mentioned in the BioMedical Waste (Management and Handling) Rules of India, 1998, that wastewater can be reused by establishing ETPs in the hospitals or healthcare facilities itself [3]. Also, the rule states that hospitals that are not owning their ETPs should treat the wastewater chemically and to be discharged into the public drainage system provided it should be linked to the water treatment plant of local government bodies. This discharged wastewater contains organic/inorganic solids and microbial contaminants which can be measured by the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) tests. The permissible limit of liquid biomedical wastewater coming out of a health care facility/hospital as effluent should adhere to certain standards: pH 6.5–8.5; total suspended solids (TSS) 110 mg/L; oil and grease 15 mg/L; BOD 35 mg/L; COD 260 mg/L [4].

Most existing systems and technologies being used in handling liquid biomedical waste are failing to address the problem of effective management of liquid waste. Emerging technologies include mechano-chemical treatment, plasma pyrolysis, sonic technology, alkaline hydrolysis, solvated electron technology, electrochemical technologies, and phyto-technology [5]. Of the other emerging treatment technologies, electrochemical technology provides an ideal solution to address the environmental problems caused by biomedical waste which leaves no secondary pollutants after treatment. Several electro-chemical reactors such as cylindrical and tubular type, plate and frame filter press type, rotating cells, tank reactors, three-phase electrochemical reactors of fixed bed, fluidized bed, etc., are used for treating wastewater [6]. Electrochemical oxidation technology has been explored for various wastewater treatment processes such as textile, diary, tannery, oil refinery, petrochemical, pharmaceutical effluents, etc., by many researchers using different electrochemical reactors [7,8]. Out of all other electrochemical reactors, the most ideal type which can be used for treating liquid biomedical waste is a filter press type electrochemical reactor (FPECR) in which the fluid flow inside FPECR can often assumed as dispersed plug flow of fluid. FPECR has higher mass transfer coefficients even at low axial flow rates thereby showing improvement in the pollutant removal rate with high current efficiency.

In the electrochemical reactor system, effluents containing oxidizable species as pollutants are the one which are much suitable for treating under electro-oxidation process [9]. Electron is the main reagent used in the electrochemical system which avoids the addition of other reagents and production of secondary pollutant after the treatment process while the other treatment technologies does [10,11]. During the process, the pollutants are broken down by direct or indirect anodic oxidation methods. In the direct electro-oxidation process, the pollutants get adsorbed on the surface of the anode and devastated by the electron transfer reaction at the anode. In the indirect electro-oxidation method, strong oxidants such as ozone, hypochlorite/chlorine, and hydrogen peroxide are generated electrochemically and destroy pollutants in the effluent [12,13]. Many researchers have investigated various electrochemical treatment technologies for treating effluents from dairy, pharmaceutical, textile, leather, oil refinery, etc., [14–19]. But it's hard to find literature on electrochemical treatment of biomedical liquid wastewater.

In the electrochemical reactor system, the efficiency of organics degradation during electro-oxidation process depends on the optimum time spent by the wastewater in the reactor [20]. Analyzing the mixing characteristics of the fluid in the treatment system plays a vital role as it affects both the efficiency of the treatment process and the hydrodynamic behavior of the reactor [21]. Studying the hydrodynamic behavior of the liquid flow helps to determine the residence time and distribution of fluid flow inside the reactor [22]. Good mixing promotes the degradation rate making the reactor system to approach ideal state [23]. In order to achieve a good electrochemical reactor design, it is important to study the flow characteristics of the fluid during the electro treatment process. To overcome the limitation that occurred in the real reactors, it is essential to design a reactor with less non-ideal effects such as channeling of fluid elements, back mixing, short-circuiting and dead, or stagnant zones. These non-ideal defects lower the performance of the reactor in either pilot plant or industrial scale [24,25].

In this research work, all these non-ideal defects are eliminated by studying the flow dynamics of the reactor thereby evaluating residence time distribution (RTD) and degree of dispersion of flow elements inside the FPECR. The reactor performance was evaluated for treating liquid biomedical wastewater during electro-oxidation process. The flow characterization inside the reactor was done for various flow rates such as 20, 40, 60, 80, and 100 L/h. The biomedical wastewater degradation experiments were carried out in FPECR using Ti/RuO_2 anode with same flow rates (20, 40, 60, 80, and 100 L/h) and different current densities (2, 4, 6, 8, and 10 A/dm^2) and reported the reductions in COD, total dissolved solids (TDS), SS, pH, and current efficiency during the process of electrochemical treatment. Thus, our present study has been attempted to investigate the flow dynamic behavior of FPECR and study the experimental validation for the treatment of liquid biomedical wastewater.

2. Experimental section

2.1. Materials

Pharmaceutical based biomedical wastewater was collected from a hospital ETP unit in Chennai, India. The composition of the wastewater is determined using APHA Standard Methods [26] and are presented in Table 1.

2.2. Experimental set up

The schematic representation of a benchtop filter press electrochemical reactor (FPECR) for performing the treatment of liquid biomedical wastewater experiments is shown in Fig. 1. The experimental set up consists of two parts, one is fluid flow circuit consists of a magnetically driven self-priming centrifugal pump, a flow meter, and the electrolytic cell and the other is electrical circuit consists of a regulated direct current power supply, ammeter, and the

Table 1
Characteristics of pharmaceutical based liquid biomedical wastewater

Parameters	Raw effluent
Color	Black
Odour	Organic smell
COD (mg/L)	1,636
TDS (mg/L)	1,200
TSS (mg/L)	230
pH	6.1

cell with the voltmeter connected in parallel to the reactor. Experiments were conducted under various current densities (2, 4, 6, 8, and 10 A/dm^2) and different flow rates (20, 40, 60, 80, and 100 L/h) using ruthenium oxide (RuO_2) coated on titanium mesh (Ti) as anode and stainless-steel acting as a cathode. The length and breadth of the electrode plates (stainless steel cathode and RuO_2 coated Ti mesh anode) are 7 cm each. The thickness of the electrode is 0.12 cm. The RuO_2/Ti anode has 60% perforation which resulted in an effective anode area of 39.2 cm^2. The anode and cathode plates are organized like filter press type arrangement and are mounted in between cell frames. In FPECR, batch recirculation operation was performed, and the reactor holdup is 0.352 L. The FPECR is fixed with a rigid frame, and the electrodes are connected to a power supply made of AE Rectifier (230 V input, 0–50 V output, 100 A). DC power is supplied to the electrodes and the experiments are carried out under various current densities (2, 4, 6, 8, and 10 A/dm^2) and different flow rates (20, 40, 60, 80, and 100 L/h).

2.3. Electrode (RuO_2/Ti) preparation

Thin RuO_2 film coated on Ti electrode, commonly known as dimensionally stable anodes (DSAs), are the most widely utilized anodes for the electrochemical treatment due to their excellent stability. These electrodes have excellent corrosion resistance and high electrocatalytic activity. RuO_2/Ti is prepared by thermal decomposition technique, in which the following steps are involved: dissolution in isopropanol of the coating component ($RuCl_3$) and application on the pretreated titanium substrate by brush, drying at 80°C, thermal decomposition at high temperature (~500°C), cooling, and repeating the above operation until the desired amount of coating is reached (~35 g/m^2), finally post-heat treatment at 550°C for 1 h.

2.4. Experimental procedure

2.4.1. RTD experiment

All RTD experiments were carried in FPECR out with water as an electrolyte and HCl acting as a tracer in room temperature conditions. At different inlet flow rates (20, 40, 60, 80, and 100 L/h) water from the effluent reservoir was allowed to pass into the reactor. In the pulse input mode, 5 mL of HCl was injected into the reactor entrance in continuous operation. The time and conductivity of the water were noted at regular intervals of time (30 s) at the reactor outlet. The experiment was about to end when the conductivity reduced to the level of normal water. The experimental value of exit age distribution $E(t)$ was determined to optimize the flow characterization and performance of the reactor.

2.4.2. Treatment of liquid biomedical wastewater

For treating the pharmaceutical-based biomedical wastewater, the experiments were performed in filter press type electrochemical reactor (Fig. 1). One liter of effluent per batch of electrolysis is electrolyzed by passing different current densities (2, 4, 6, 8, and 10 A/dm^2) and the process of electrolysis is carried out at various flow rates (20, 40, 60, 80, and 100 L/h) of electrolyte. To verify the destruction of COD, samples were drawn at predetermined intervals to measure the values of COD. All the experiments were conducted in triplicate for each experimental condition to get the mean concordant value. Statistical analysis was done to find mean, variance standard deviation, standard error, etc., and incorporated in the Figures of results and discussion section.

2.5. RTD profiles and its design parameters

The experimental determination of RTD was done by using the method of tracer response. $E(t)$ curve is obtained

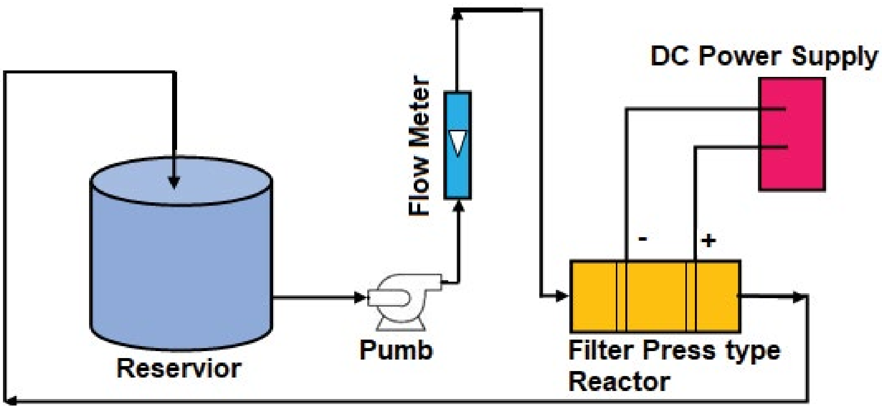

Fig. 1. Schematic representation of filer press type electrochemical reactor (FPECR) set up.

by dividing the concentration of the tracer $C(t)$ to its integral at time t. Using the following equation, $E(t)$ curve can be evaluated [27]:

$$E(t)=\frac{C(t)}{\left[\int_0^\infty C(t)dt\right]} \quad (1)$$

The characteristic RTD design parameters of fluid flow characteristics inside the reactor system can be determined from the below relations:

$$t_m=\int_0^\infty tE(t)dt \quad (2)$$

$$\tau=\frac{V_r}{Q} \quad (3)$$

$$\sigma^2=\int_0^\infty (t-t_m)^2 E(t)dt \quad (4)$$

For the closed vessel configuration, the dispersion number $N_d=\frac{D}{uL}$ can be calculated by trial and error procedure using Eq. (5) by the trial and error method, when the dispersion number is less than one [28].

$$\left(\frac{\sigma^2}{t_m^2}\right)=2\left[\frac{D}{(uL)}\right]-2\left[\frac{D}{(uL)}\right]^2\left(1-e^{[(uL)/D]}\right) \quad (5)$$

where σ^2 is the variance in min^2; t_m is the mean residence time in min; D is the diffusion coefficient in (m^2/s); u is the fluid flow velocity in m/s; L is the length of the reactor in m; V_r is the reactor volume in L; and Q is the volumetric flow rate of the fluid in (L/h).

To analyze the relationships between various RTD design parameters such as peak time (t_p), hydraulic total residence time (τ), and mean residence time (t_m), the following relations were used [21,25]:

$$\text{Plug flow index}=\frac{t_p}{\tau} \quad (6)$$

$$\text{Dead zone index}=\frac{t_m}{\tau} \quad (7)$$

$$\text{Short circuiting index}=1-\left(\frac{t_p}{t_m}\right) \quad (8)$$

2.6. Analytical procedure for degradation experiments

The wastewater analyses such as pH, conductivity, COD, TDS, and TSS were carried out in agreement with the American Public Health Association (APHA) standard methods for examination of water and wastewater [26]. The samples withdrawn during experimental runs were titrated with concentrated sulfuric acid to arrest the variation of COD and analysis of COD is carried out as per standard methods. The removal efficiency of COD (R) was calculated using the following equation:

$$R=\left[\frac{Y_0-Y}{Y_0}\right]100 \quad (9)$$

where Y_0 and Y were initial and final values of COD measured during experimental runs.

3. Results and discussion

3.1. Effect of flow rates on flow dynamics

The effect of fluid flow characteristics in FPECR was analyzed by evaluating various flow rates such as 20, 40, 60, 80, and 100 L/h. The effect of flow rates was found to be significant on the obtained RTDs and on the fluid flow behavior in the FPECR. Fig. 2 shows the exit age distribution $E(t)$ curve for various flow rates. The non-symmetrical $E(t)$ curve shows the presence of short-circuiting or bypassing along the reactor [25]. From Fig. 2, it was found that on increasing the flow rate, the peak points in $E(t)$ curve reached the highest value of 0.91 for the flow rate of 20 L/h which has good mixing condition and lack of back mixing characteristics. Thus, the flow behavior for the flow rate of 20 L/h indicates less non-ideality conditions. The $E(t)$ curve also approached near symmetrical for 20 L/h depicting much less short-circuiting condition along the reactor length and thus the flow in FPECR tends to approach the condition of plug flow.

Table 2 shows the various design parameters evaluated using RTD experiments and depicts the value of plug flow index upon increasing the flow rate of the effluent; it approached a higher value of 0.93 for the minimal flow

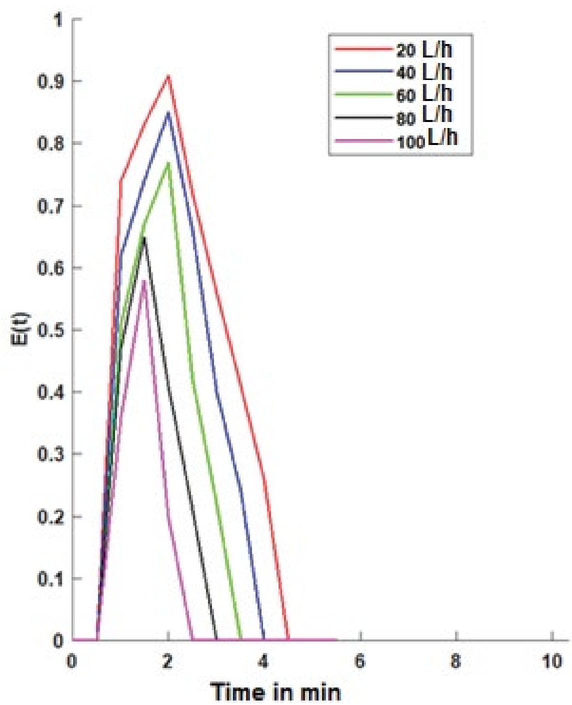

Fig. 2. Exit age distribution $E(t)$ curve for different flow rates

Table 2
Parameters obtained using the data of RTD experiments

Flow rate (L/h)	τ (min)	t_m (min)	t_p (min)	σ^2 (min)^2	$[D/(uL)]$	Plug flow index, t_p/τ	Dead zone index, t_m/τ	Short circuiting index, $1-(t_p/t_m)$
20	2.2	0.82	2	0.243	0.140	0.91	0.370	–
40	2.5	1.40	2	0.282	0.223	0.79	0.558	–
60	2.9	2.38	2	0.845	0.313	0.69	0.821	0.159
80	3.6	3.56	1.5	5.069	0.428	0.42	0.988	0.578
100	4.0	4.88	1.5	17.610	0.879	0.38	1.220	0.693

rate of 20 L/h. This shows that the liquid flow behavior of FPECR approaches to plug flow conditions to a greater extent with the existence of mesh type RuO_2/Ti electrode. The calculation depicts the occurrence of a dead or stagnant zone was found to be less and the effect of short-circuiting is removed at flow rate of 20 L/h. The dispersion number is shown in Table 2 also supports the results.

The fluid flow behavior in FPECR shows the lowest deviation from plug flow [$(D/(uL) = 0.140$] only at the inlet flow rate of 20 L/h on comparing with other flow rates. The variance (σ^2) and dispersion (D) influence on the efficiency of the electrochemical reactor to degrade the effluent. RTD data discussed above have been compared with the experimental results of the biomedical wastewater degradation studies carried out with the same set of inlet flow rates of the effluent. The plug flow behavior of the flow rate (20 L/h) from the RTD analysis matches well with the experimental degradation studies in FPECR producing a higher percentage of COD removal.

3.2. *Effect of flow rates on COD removal*

Optimization of flow rate is important in investigating the efficiency of wastewater treatment in the electrochemical reactor. The effect of flow rate on the removal efficiency of COD was studied by carrying out experiments at various flow rates such as 20, 40, 60, 80, and 100 L/h at a current density of 10 A/dm^2. COD analysis was carried out for samples collected at regular intervals of experimental runs operated for various flow rates (20, 40, 60, 80, and 100 L/h). Keeping the initial COD of the sample in the range of 1,630–1,650 mg/L, the electro-oxidation process was done to attain the final COD after 8 h of electrolysis time. Fig. 3a shows the degradation of COD with standard error bars for various flow rates from its initial value to a final level concerning to the electrolysis time.

The COD removal efficiency was calculated for all flow rates and are shown in Fig. 3b. It was found that COD removal efficiency was found to be very high with 94% for the flow rate of 20 L/h. Results showed that higher COD reduction occurred at 20 L/h at which the fluid flow characteristics of FPECR approach to plug flow behavior with effective removal of short-circuiting and avoiding the presence of stagnant zones to a greater extent.

3.3. *Effect of current density on COD removal*

Figs. 4 and 5 show the effect of current density on COD reductions for different current densities such as 2, 4, 6, 8, and 10 A/dm^2. Experiments were conducted by varying current densities at the flow rate of 20 L/h which showed higher COD reductions with plug flow behavior inside the reactor. Fig. 4 shows that the COD reductions were found to high from 1,636 to 94 mg/L at a higher current density of 10 A/dm^2. Thus, by increasing the current densities, the percentage reduction of COD also gets increased and attained to a higher percentage of 94% for 10 A/dm^2 as shown in Fig. 5. This might be due to the generation of electron transfer mediators at fairly high current densities so that a steady-state concentration available to bring about oxidation of the organic compounds present in the biomedical liquid wastewater.

Similarly, Fig. 5 also shows the effect of applied current on the percentage reduction of COD of the biomedical wastewater as a function of time. COD reduction (%) was found to be high (94%) at current 3.9 A applied to the process. Higher the current employed to the process, the percentage reduction of COD also gets increased which might be due to greater evolution of O_2 on the electrode surface causing improved mass transfer rates which could affect the by-product formation.

Thus, under the ideal plug flow conditions with less dead zone and no short-circuiting at the current density of 10 A/dm^2 with 3.9 A and flow rate of 20 L/h, the overall current efficiency was found to reach a higher value of 18.47% when compared to other current densities and is shown in Fig. 6. Lower the consumption of current during the operation in FPECR reduces the operational cost of the system. As a result, FPECR system approach the plug flow behavior with less utilization of power.

3.4. *Variation of pH on COD removal*

Variation in pH often controls the charge on the products of hydrolysis and metal hydroxides precipitation during the electrolysis process [29]. To analyze its variation effects during the treatment of biomedical wastewater, pH was monitored at regular intervals, and the results are shown in Fig. 7. The initial pH of the wastewater was 6.1 at the start of electrolysis process and it reached to alkaline value of 8.1 at the end of treatment process. In acidic conditions, or at an initial pH of 6.1, hydrogen gas was generated at the cathode according to Eq. (10). In neutral or alkaline conditions, or at final pH value of 8.1 at the end of electrolysis, a reduction reaction produced hydrogen gas, as in Eq. (11) [30].

$$2\,H^+_{(aq)} + 2e \rightarrow H_{2(g)} \tag{10}$$

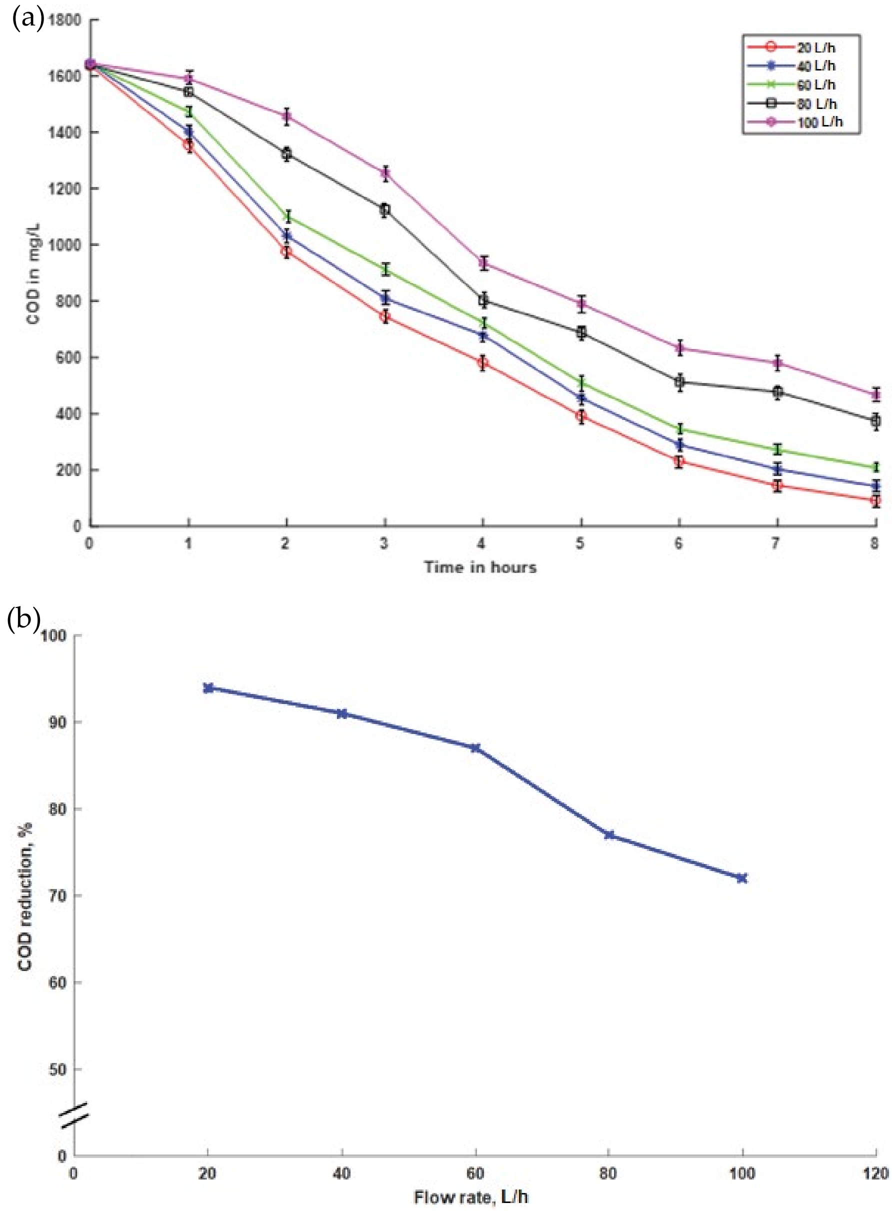

Fig. 3. (a) Reduction of COD vs. time for various flow rates at current density 10 A/dm^2. (b) COD reduction (%) for various flow rates (L/h).

$$2\,H_2O_{(l)} + 2e^- \rightarrow 2H_{2(g)} + 2OH^-_{(aq)} \tag{11}$$

It was found that the COD reduced to a greater extent when the electrolysis system approached neutral and alkaline pH. The formation of strong hypochlorite/chlorine oxidants at neutral and alkaline pH in the electrolyte removes COD at a greater extent. These oxidants are generated electrochemically *in situ* and are utilized immediately for destroying the pollutants in the electrolyte by electro-oxidation process [12,13].

3.5. Physiochemical analysis of treated biomedical wastewater

The liquid biomedical wastewater was initially characterized for its physiochemical parameters as per APHA standard methods and it was then treated with FPECR [26]. Table 3 shows the physiochemical characteristics of the treated wastewater. The pH of treated wastewater was found to be 8.1 which showed that the treatment had changed the acidic nature of wastewater to above neutral. COD, TDS, and TSS in the wastewater were measured and the percentage of removal was found to be 94%, 92%, and 95%,

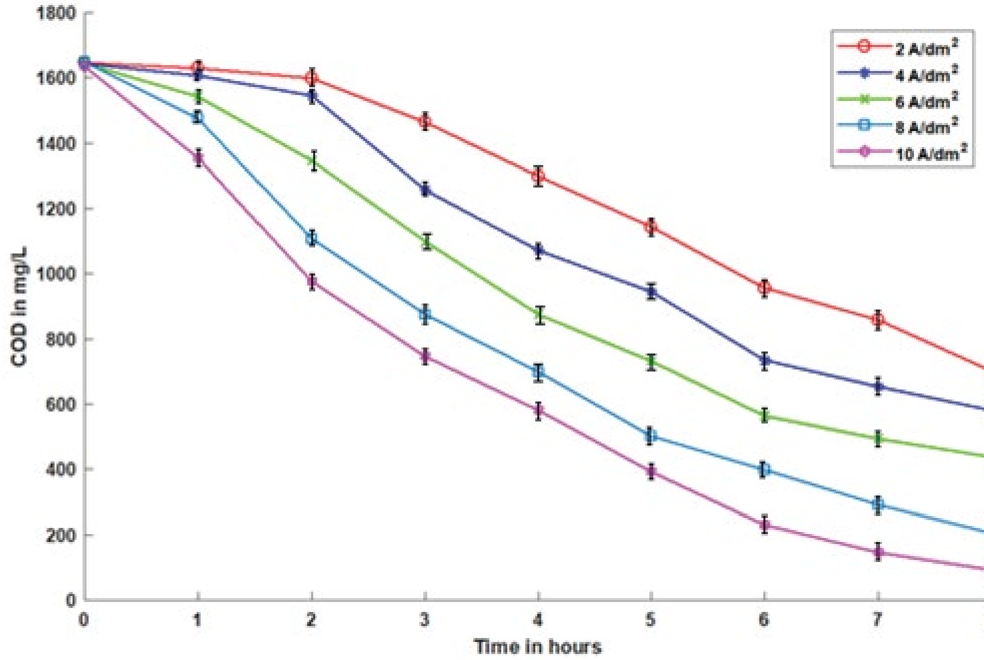

Fig. 4. COD reductions with respect to time for different current densities at 20 L/h.

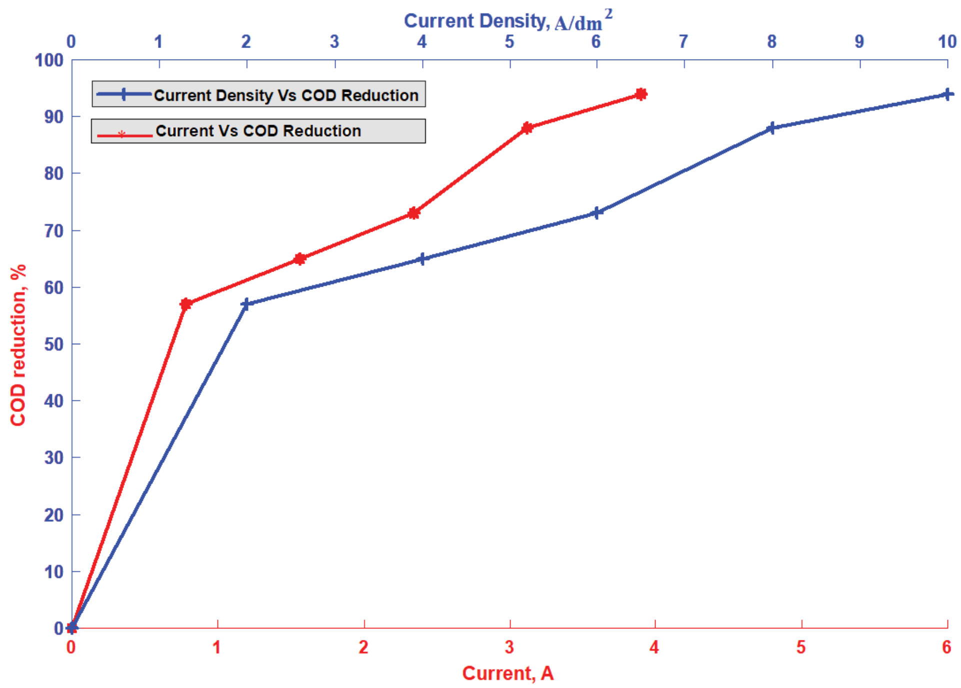

Fig. 5. Percentage reduction of COD vs. current density and current for the flow rate of 20 L/h.

respectively, and were found to be well below the prescribed standard limits of biomedical waste reuse system [2,4].

4. Conclusion

In this research work, the electrochemical oxidation process was investigated for the treatment of liquid biomedical wastewater and the flow dynamics were studied in FPECR. The RTD method was used to understand the flow dynamic behavior of the electrolyte within the reactor for various flow rates such as 20, 40, 60, 80, and 100 L/h. The results showed that the plug flow index approached a higher value of 0.91 and the dispersion number $[D/(uL)]$ to a lower value of 0.140 for the flow rate of 20 L/h when compared to other flow rates. This shows the flow behavior of FPECR approaches to plug flow conditions to a greater

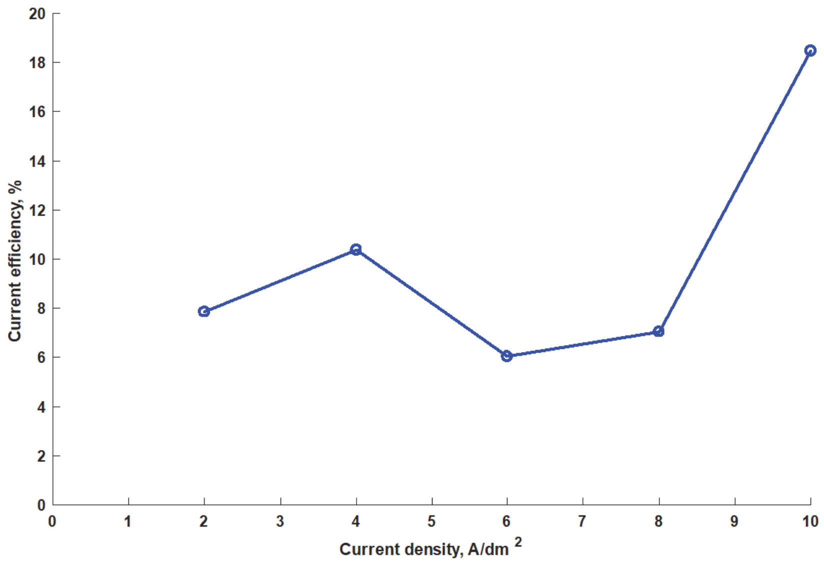

Fig. 6. Current efficiency vs. current densities at 20 L/h.

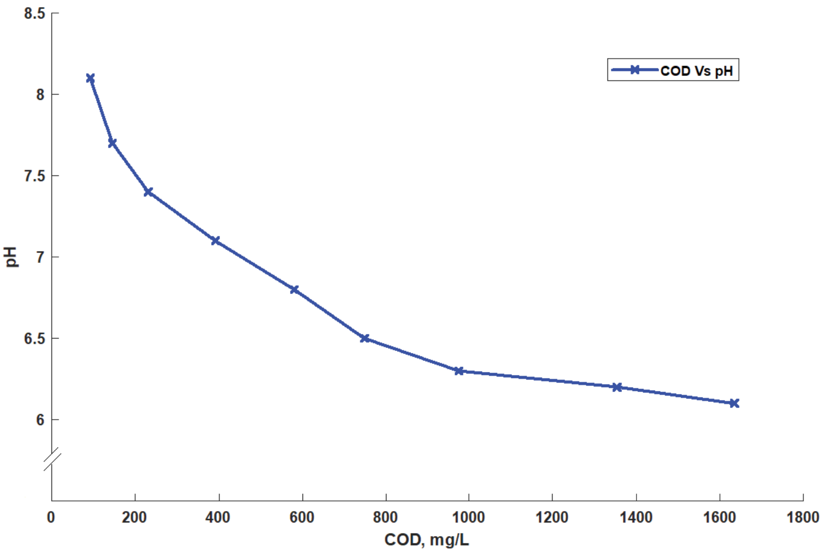

Fig. 7. Variation of pH vs. COD for the flow rate 20 L/h at 10 A/dm^{2}.

Table 3
Physiochemical characteristics of liquid biomedical wastewater before and after treatment using FPECR

Parameters	Liquid biomedical wastewater			Prescribed standard limit
	Untreated	Treated	% Removal	
Color	Black	Light brown	–	–
Odor	Organic smell	Smell less	–	–
COD (mg/L)	1,636	92	94	<260
TDS (mg/L)	1,200	96	92	<1,000
TSS (mg/L)	230	12	95	<110
pH	6.1	8.1	–	6.5–8.5

extent for the flow rate of 20 L/h with less dead zone and almost no short-circuiting inside the reactor. The plug flow behavior of the flow rate (20 L/h) from the RTD analysis matches well with the experimental wastewater treatment studies in FPECR producing a higher percentage of COD removal (94%) under the current density of 10 A/dm^2. The current efficiency was also found to be high for the flow rate operated at 10 A/dm^2 with the effective removal of color, odor, TDS (92% removal), and SS (95% removal) within the short residence period of wastewater in the reactor. In our future study, energy consumption can be optimized for large scale units and to implement computational fluid dynamics studies to study the reactor performance and to identify the defects in fluid dynamics in the reactor.

Acknowledgments

The authors extend their appreciation to the Deanship of Scientific Research at Majmaah University for funding this work under Project Number RGP-2019–33.

Reference

[1] Y. Chartier, J. Emmanuel, U. Pieper, A. Pruss, P. Rushbrook, R. Stringer, W. Townend, S. Wilburn, R. Zghondi, Eds., Safe Management of Wastes from Health-Care Activities, 2nd ed., WHO Blue Book, Geneva, Switzerland, 2014.
[2] M.R. Capoor, K.T. Bhowmik, Current perspectives on biomedical waste management: rules, conventions and treatment technologies, Indian J. Med. Microbiol.,35 (2017) 157–164.
[3] D. Priya, K.M. Gursimran, C. Jagnis, Biomedical waste management in India: critical appraisal, J. Lab. Physicians, 10 (2018) 6–14.
[4] S. Biswal, Liquid biomedical waste management: an emerging concern for physicians – review, Muller J. Med. Sci. Res., 4 (2013) 99–106.
[5] J. Emmanuel, Non-Incineration Medical Waste Treatment Technologies, Health Care without Harm, Washington, DC, 2001.
[6] G. Chen, Electrochemical technologies in wastewater treatment, Sep. Purif. Technol., 38 (2004) 11–41.
[7] J. Wang, T. Li, M. Zhou, X. Li, J. Yu, Characterization of hydrodynamics and mass transfer in two types of tubular electrochemical reactors, Electrochim. Acta, 173 (2015) 698–704.
[8] H. Afanga, H. Zazou, F.E. Titchou, Y. Rakhila, R.A. Akbour, A. Elmchaouri, J. Ghanbaja, M. Hamdani, Integrated electrochemical processes for textile industry wastewater treatment: system performances and sludge settling characteristics, Sustainable Environ. Res., 30 (2020) 487–492.
[9] C. Comninellis, G.P. Vercesi, Characterization of DSA type oxygen evolving electrodes: choice of a coating, J. Appl. Electrochem., 21 (1991) 335–345.
[10] K. Rajeshwar, J.G. Ibanez, Environmental Electrochemistry: Fundamentals and Applications in Pollution Abatement, Academic Press, Inc., San Diego, CA, 1997.
[11] K. Rajeshwar, J.G. Ibanez, G.M. Swain, Reviews of electrochemistry: electrochemistry and the environment, J. Appl. Electrochem., 24 (1994) 1077–1091.
[12] R. Priambodo, Y.-J. Shih, Y.-J. Huang, Y.-H. Huang, Treatment of real wastewater using semi batch (photo)-electro-Fenton method, Sustainable Environ. Res., 21 (2011) 389–393.
[13] A.R. Rahmani, K. Godini, D. Nematollahi, G. Azarian, Electrochemical oxidation of activated sludge by using direct and indirect anodic oxidation, Desal. Water Treat., 56 (2014) 1–12.
[14] B. Borbon, M.T. Oropeza-Guzman, E. Brillas, I. Sires, Sequential electrochemical treatment of dairy wastewater using aluminum and DSA-type anodes, Environ. Sci. Pollut. Res. Int., 21 (2014) 8573–8584.
[15] J.R. Dominguez, T. Gonzalez, P. Palo, Electrochemical degradation of a real pharmaceutical effluent, Water Air Soil Pollut., 223 (2012) 2685–2694.
[16] E. Gil Pavas, P. Arbeláez-Castano, J. Medina, D.A. Acosta, Combined electrocoagulation and electro-oxidation of industrial textile wastewater treatment in a continuous multistage reactor, Water Sci. Technol., 76 (2017) 2515–2525.
[17] B.M.B. Ensano, L. Borea, V. Naddeo, V. Belgiorno, M.D.G. De Luna, F.C. Ballesteros Jr., Removal of pharmaceuticals from wastewater by intermittent electro-coagulation, Water, 9 (2017) 85.
[18] J.H. Naumczyk, M.A. Kucharska, Electrochemical treatment of tannery wastewater—raw, coagulated, and pretreated by AOPs, J. Environ. Sci. Health., Part A, 52 (2011) 649–664.
[19] L. Candido, J.A.C. Ponciano Gomes, H.C.M. Jambo, Electrochemical treatment of oil refinery wastewater for NH_3–N and COD removal, Int. J. Electrochem. Sci., 8 (2013) 9187–9200.
[20] P. Maloszewski, P. Wachniew, P. Czuprynski, Hydraulic characteristics of a wastewater treatment pond evaluated through tracer test and multi-flow mathematical approach, Pol. J. Environ. Stud., 15 (2006) 105–110.
[21] Y. Wang, U.C. Sanly, M. Brannock, G. Leslie, Diagnosis of membrane bioreactor performance through residence time distribution measurements - a preliminary study, Desalination, 236 (2009) 120–126.
[22] E.B. Nauman, Chemical Reactor Design, Optimisation, and Scaleup, McGraw-Hill Publishers, New York, NY, 2002.
[23] J. Su, H. Lu, H. Xu, J. Sun, J. Han, H. Lin, Mass transfer enhancement for mesh electrode in a tubular electrochemical reactor using experimental and numerical simulation method, Russ. J. Electrochem., 47 (2011) 1293–1298.
[24] W. Djoudi, F. Aissani-Benissad, P. Ozil, Flow modeling in electrochemical tubular reactor containing volumetric electrode: application to copper cementation reaction, Chem. Eng. Res. Des., 90 (2012) 1582–1589.
[25] S.I. Dhorgham, C. Veerabahu, R. Palani, S. Devi, N. Balasubramanian, Flow dynamics and mass transfer studies in a tubular electrochemical reactor with a mesh electrode, Comput. Fluids, 73 (2013) 97–103.
[26] APHA-AWWA-WEF, Standard Methods for the Examination of Water and Wastewater, 20th ed., American Public Health Association, American Water Works Association, Water Environment Federation, Washington DC, 1998.
[27] H.S. Fogler, Elements of Chemical Reaction Engineering, 4th ed., Pearson Education Inc., USA, 2006.
[28] O. Levenspiel, Chemical Reaction Engineering, 3rd ed., John Wiley & Sons Pvt. Ltd., Singapore, 2004.
[29] K. Thirugnanasambandham, V. Sivakumar, Removal of ecotoxicological matters from tannery wastewater using electro coagulation reactor: modelling and optimization, Desal. Water Treat., 57 (2016) 3871–3880.
[30] P. Yodhor, P. Choeisai, K. Choeisai, K. Syutsubo, Effect of pH on electrochemical treatment using platinum coated titanium mesh electrodes for post treatment of anaerobically treated sugarcane vinasses, Eng. Appl. Sci. Res., 44 (2017) 39–42.