

Removal of Lead Ion from Wastewater by Electrocoagulation using Iron (Fe) as a rotating electrode

Khan Rajib Hossain¹, A. Nayeem Faruqui².

¹Department of Applied Chemistry & Chemical Technology, Rajshahi University, Rajshahi Sadar, Rajshahi 6205, Bangladesh.

²Department of Applied Chemistry & Chemical Technology, Rajshahi University, Rajshahi Sadar, Rajshahi 6205, Bangladesh.

Abstract: Present study investigated the efficiency of electrocoagulation (EC) technique with sacrificial iron electrodes to remove Lead (Pb) content of battery industrial effluent at laboratory scale. The effect of voltage, effluent pH and electrolysis time on Lead (Pb) removal efficiency was examined. Optimum conditions for treating effluent were an initial battery effluent pH 3 and 15 min electrolysis time at 30V where 99.9% Lead (Pb) was removed. Effluent quality, after EC treatment, was compared with national environmental standard to discharge into surface water bodies.

Keywords: Sacrificial Electrode, Electroflocculation, Heavy Metal, Lead Poisoning, operational costs

Introduction

One of the unwanted concerns of increasing industrial growth in recent decades is the increase in metal concentrations in natural water sources, caused by the large output of industrial effluents contaminated with heavy metals. Heavy metal such lead (Pb) pollution has become one of the most serious environmental nuisances today. Lead (Pb) often present and discharged by a number of industrial processes are hazardous to the aquatic ecosystem and human health. High levels of Pb (II) can be traced to industrial discharges from variety of sources, such as batteries, paints, pigments and ammunition, petrol, cables, alloys and steels, plastics, ceramic and glass industries (Jamali et al 2007, Ghaedi et al 2006). The lead contamination is also due to effluents of vehicular traffic and the mixing of roadside run-offs (Sari and Tuzen 2009). Lead (Pb) is toxic even at low concentrations, non-degradable in the environment and can accumulate throughout the food chain and may affect variety of living species including human beings (Martins et al 2004). The presence of Pb (II) in drinkable water is known to cause various types of serious health problems (Ahmedna et al 2004). Although the inorganic form of lead is a general metabolic poison and enzyme inhibitor, organic forms are even more poisonous (Lo et al 1999). Lead (Pb) poisoning in human causes severe damage to kidney, nervous system, circulatory system, reproductive system, cardiovascular system, liver and brain (Naiyaa et al 2009). In adults, symptoms of neurological effects include dullness, irritability, poor attention span, headaches, muscular tremors, loss of memory, and hallucinations. The condition may then worsen, sometimes abruptly, to delirium, convulsions, paralysis, coma and death.

Therefore the removal of Lead (Pb) from waters and wastewaters is important in terms of protection of public health and environment. The most widely practiced methods for removing heavy metals from wastewaters include ion-exchange, chemical precipitation, filtration, reverse osmosis, evaporation, membrane filtration, pre-concentration, bio-sorption, adsorption, biological treatment etc. (Ghaedi 2006, Ghaedi et al 2007, Bailey et al 1999, Xiangliang et al 2005). Most of these methods suffer from some drawbacks, such as high capital and operational cost, generation of secondary pollutants, disposal issue of the residual metal sludge, and are not suitable for small-scale industries (Kobya et al 2005).

Electrocoagulation (EC) process has attracted a great deal of attention in treating industrial wastewaters because of its versatility and environmental compatibility. This method is characterized by simple equipment, easy operation, energy efficient, safety, selectivity, cost effectiveness, amenability to automation, a shortened reactive retention

period, a reduction or absence of equipment for adding chemicals, and decreased amount of precipitate or sludge which sediments rapidly (Mollah et al 2004, Islam et al 2011, Rahman et al 2012). Moreover, during EC, the salt content of the liquid salt content does not increase appreciably, as in the case of chemical treatment. EC is a proved efficient, effective and reliable technology used for treating various process effluents containing textile wastewater urban wastewater (Lin and Peng 1994), fluoride (Shen et al 2002; Ho et al 2005), heavy metal laden wastewater (Lai and Lin 2003), (Islam et al 2011), COD (Rahman et al 2012), textile dyes (Islam et al 2011, Can et al 2003; Daneshvar et al 2003), nitrate (Koparal and Ogutveren 2002), oil mill wastewater (Inan et al 2004), restaurant wastewater (Chen et al 200), arsenic (Kumar et al 2004), phenolic compounds (Adhoum and Monser 2004), latex particles (Larue et al 2003), poly-aromatic wastes (Panizza et al 2000), tannery effluent (Muruganathan et al 2004), aqueous suspensions containing kaolinite, bentonite, and ultra fine particles (Matteson et al 1995), landfill leachate (Tsai et al 1997), saline wastewater (Lin et al 1998), tar sand and oil shale wastewater (Renk 1988), laundry wastewater (Ge et al 2004), potable water (Vik et al 1984), potato chips wastewater (Kobyas et al 2006), poultry slaughterhouse wastewater (Bazrafshan et al 2012), boron containing water (Xu et al 2009), alcohol distillery wastewater (Yavruz 2006), sulphide (Muruganathan et al 2004), olive oil wastewater (Adhoum et al 2004), egg process wastewater (Xu et al 2002), oily wastewater (Chen et al 2002), heavy metals workers (Kongsricharoern and Polprasert 1995; Adhoum et al 2004; Gao et al 2005) etc. But there are no literatures to treat real battery effluent for removal of Lead (Pb) by EC. Thus the goal of present research was to assess the performance of EC, using sacrificial iron electrodes, on the removal of Lead(Pb) from battery effluent of Panna Battery Limited (PBL) industry, by exploring the effects of various process parameters such as voltage, pH and reaction time.

Electrocoagulation Mechanism

EC is a complicated process involving many chemical and physical phenomena that use consumable electrodes to supply ions into the wastewater stream. In an EC process the coagulating ions are produced 'in situ' and it involves three successive stages: (i) formation of coagulants by electrolytic oxidation of the 'sacrificial electrode', (ii) destabilization of the contaminants, particulate suspension, and breaking of emulsions, and (iii) aggregation of the destabilized phases to form flocs (Mollah et al 2004). The destabilization mechanisms of the contaminants, particulate suspension, and breaking of emulsions have been described in broad steps and may be summarized as follows: (a) Compression of the diffuse double layer

around the charged species by the interactions of ions generated by oxidation of the sacrificial anode, (b) Charge neutralization of the ionic species present in wastewater by counter ions produced by the electrochemical dissolution of the sacrificial anode. These counter ions reduce the electrostatic inter-particle repulsion to the extent that the van der Waals attraction predominates, thus causing coagulation. A zero net charge results in the process, (c) Floc formation; the floc formed as a result of coagulation creates a sludge blanket that entraps and bridges colloidal particles still remaining in the aqueous medium (Mollah et al 2004). The solid oxides, hydroxides and oxyhydroxides provide active surfaces for the adsorption of the polluting species.

Materials and Methods

Sampling and Sample analysis

Untreated battery Effluent samples were collected from Effluent Treatment Plant (ETP) of Panna Battery Limited (PBL) located in 43, West Rasulpur (Geographic Location), Kamrangirchar, Dhaka-1211, Bangladesh (Figure 1). Panna Battery Limited (PBL) produces and markets a wide range of industrial batteries which are used in automotive, motorcycle, telecommunication, power station, railways, electric vehicles, forklifts, ships, buoy lighting, UPS, inverter and solar power systems. Before discharging the effluent in the environment, PBL treats the effluent chemically. But plant requires high amount chemicals and after treatment, Pb concentration level remains higher than the standard level (100µg/l). But the level must be lower than the permissible level before discharging in the environment. Glass bottles of 500 ml capacity were used for sampling and prior to sampling these containers were washed with 10% (V/V) HNO₃ solution and then rinsed thoroughly with de-ionized water. The containers were completely filled with sample effluent, sealed carefully, labelled with specific code number tightly and transported to the laboratory immediately using an ice box maintaining temperature between 4°C to 6°C. Physico-chemical parameter of samples such as total suspended solids (TSS), total dissolved solids (TDS), dissolved oxygen (DO), pH and the conductivity were determined using APHA method, TDS meter (HANNA H18734), DO meter (Cyber Scan DO 110) pH meter (EcoScan Ion 6), respectively.

EC Experimental Set Up

The experiments were performed at a laboratory bench scale (Figure 2) by employing effluent from battery industry. A 250 ml pyrex glass beaker was used as a reactor or EC cell where a regulated DC power supply was employed to supply the external electricity. The

low-cost iron plates were used as the sacrificial electrodes with the distance between each plate fixed at approximately 4cm. The initial pH of the raw water was 1 and hence post adjustment was required using NaOH and monitored by pH meter. The experiment was carried out at different pH (1, 3, 5, 7 and 9), voltage (15, 30 and 45V) and electrolysis time (15, 30, 45 and 60 min). The purity of the iron electrodes used was about 99.8%. Before use, the electrodes were cleaned manually by abrading with sand papers and then washed with dilute acid to remove impurities on the metal surface. At the end of the run, the solution was filtered and then the filtrate was analyzed, the electrodes were washed thoroughly with water to remove any solid residues on the surfaces, dried, and reweighed.

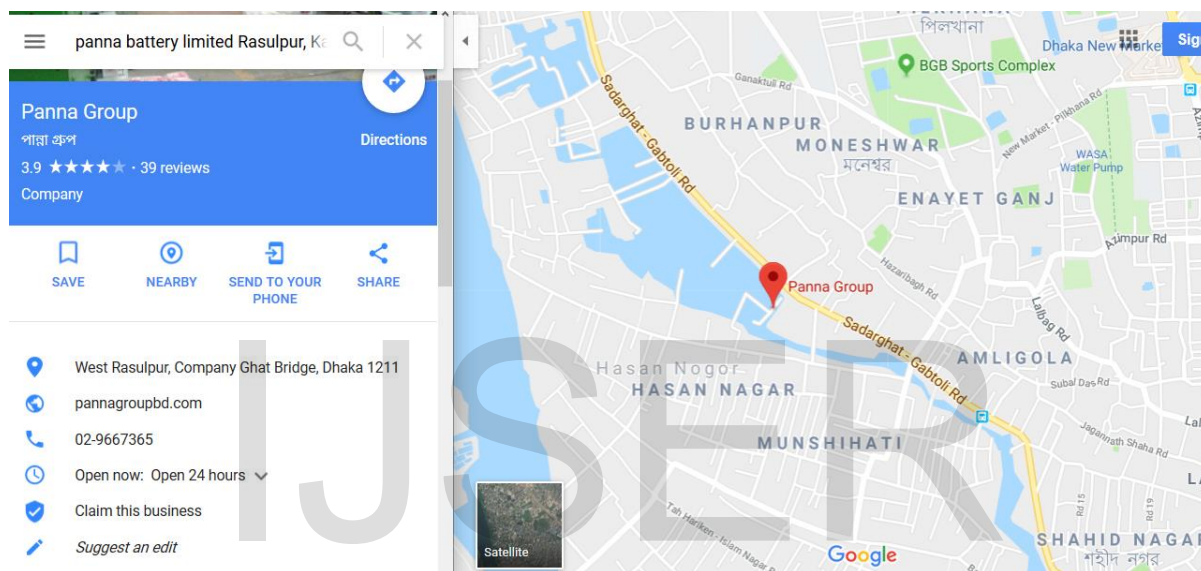


Figure 1: Location of study area.

Instrumental Analysis for Lead Determination

Lead (Pb) concentration of before and after treatment were measured by Inductively Coupled Plasma Mass Spectrometry (Varian, Australia), Flame Atomic Absorption Spectrometry (Varian, AA 240 FS) and Graphite Furnace Atomic Absorption Spectrometry (Varian, AA 240Z). Lead removal efficiency (% RE) by EC was calculated as Equation 1.

$$\% RE = (C_o - C_f) / C_o \times 100 \dots\dots\dots(1)$$

Where C_o and C_f are the concentrations of Lead (Pb) before and after the experiment, respectively.

Operational Cost Estimation

For EC main operational costs included electricity and electrodes price and in present work the overall operational costs were calculated using Equation 3 to 4 (after Ghosh et al 2008).

$$\text{Operating Cost} = aC_{\text{energy}} - bC_{\text{electrode}} \dots\dots (2)$$

$$C_{\text{energy}} = UIt_{\text{EC}}/v \dots\dots\dots (3)$$

$$C_{\text{electrode}} = M_W It_{\text{EC}}/zFv \dots\dots\dots (4)$$

where, U is cell voltage (V), I is current (A), t_{EC} is time of EC (h), v is volume of sample (m^3), F is the Farady’s constant (96487 C/mol), M_W is molecular weight of iron (55.85 g/mol), z is number of electron transferred ($z = 1$), a is electricity energy price (2.64 taka/kWh) and b is electrode material price (50 taka/kg iron).

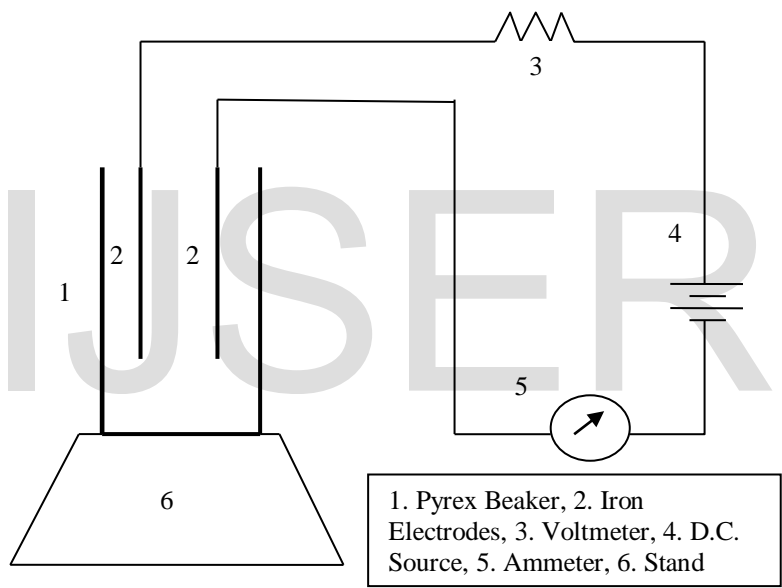


Figure 2: Schematic diagram of the EC cell (1. Pyrex Beaker, 2. Iron Electrodes, 3. Voltmeter, 4. D.C. Source, 5. Ammeter and 6. Stand)

Results and Discussion

Characteristics of raw battery effluent are shown in Table 1. Effluent was strongly acidic in nature with suspended materials. Several operating parameters, such as initial pH, voltage and electrolysis time was investigated in order to evaluate the efficiency of EC for Lead (Pb) removal.

Table 1: Physicochemical characteristics of battery effluent

Parameter	Unit	Effluent Value	DoE Standard (DoE, 2003)
pH		1	6-9
TSS	mg/l	36	150-500
TDS	mg/l	7480	2100
DO	mg/l	7.80	4.5-8
EC	µs/cm	14023	1200
Pb	µg/l	4600	100

Effect of Voltage and Electrolysis Time on pH

With the increased electrolysis time and voltage, pH value was reached to maximum 5.28 at initial effluent pH 1(Figure 3). But this was lower than the standard value to discharge in the environment. Therefore post adjustment of pH was required to the desired pH 3, 5, 7 and 9 using NaOH. The effect of the operating time on pH was noted. pH increased as the operating time was increased (Figure 4). This was due to the OH⁻ ion accumulation in aqueous solution during the process. Increase of pH at acidic condition was attributed to hydrogen evolution at cathodes (Nabil et al 1998).

Effect of Initial pH on Lead Removal

When EC proceeds in aqueous solution, the pH of the medium has a considerable effect on its performance as well as on the solubility of the analytic (Escobar et al 2005; Casqueira et al 2006). To improve the efficiency of lead removal, the effect of the initial wastewater pH was also explored in the range of 1-9 at various electrolysis times. With increased pH at various electrolysis times, the removal efficiency of lead also increased (Figure 5). Subsequently, when EC was applied to the wastewater with a high initial pH, the degree of removal of metals increased rapidly to their maximum because, at high initial pH, the structures of ferrous ions in the system were in the monomeric (Fe(OH)₃) form and polyhydroxyl iron (III) complexes such as Fe(OH)²⁺, Fe(OH)₂⁺, Fe(H₂O)₅OH²⁺ and Fe(H₂O)₄(OH)₂⁺ which can combine with the metal ion molecules causing the coagulation (Adhoum et al 2004) and the reduction of heavy metals occurred.

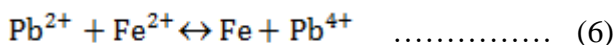
Effect of Voltage on Lead Removal

The Lead (Pb) removal efficiency was fluctuated with increased voltage at different electrolysis time (Figure 6). In high voltages, size and growth rate of produced flocs increase and this in turn affects the efficiency of the process (Kim et al 2002; Zhu et al 2005). At constant time 45min and 60min, the removal efficiency increased with increased voltage and reached above 99%.

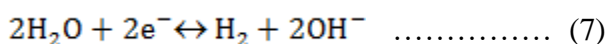
Effect of Electrolysis Time

Increase in retention time in the case of constant voltage and pH, increases the efficiency of Lead (Pb) removal due to precipitation of metal from effluent by forming flocs. The removal efficiency of Lead (Pb) increased with increasing electrolysis time with change of pH 1,3,5,7 and 9 and voltage 15, 30 and 45V (Figure 7). This is expected since a high applied current over a long electrolysis time will generate a large amount of coagulant according to Faraday's law, leading to lower amount of heavy metals in the treated wastewater (Chaloempan 2009). With the formation of coagulants, during the treatment process, hydrogen gas was released from the cathode which can help to float the flocculated particles out of the water, a process which is sometimes called electro flocculation (Chen 2004). The main reactions were as Equation 5-10:

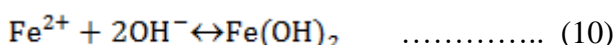
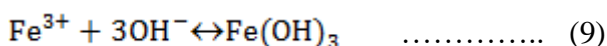
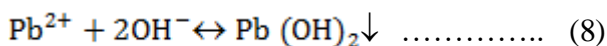
Anode reaction (oxidation):



Cathode reaction (reduction):



Co-precipitation:



In the presence of iron electrodes, the ferric ions generated by the electrochemical oxidation of the iron electrode, according to Equation (5), may form monomeric species, such as $\text{Fe}(\text{OH})^{2+}$, $\text{Fe}(\text{OH})_2^+$, $\text{Fe}(\text{H}_2\text{O})_5\text{OH}^{2+}$, $\text{Fe}(\text{H}_2\text{O})_4\text{OH}_2^+$, $\text{Fe}(\text{OH})_3$, and $\text{Fe}(\text{OH})_4$, and polymeric species, such as $\text{Fe}_2(\text{H}_2\text{O})_8\text{OH}_2^{4+}$ and $\text{Fe}_2(\text{H}_2\text{O})_6\text{OH}_4^{2+}$, depending on the pH of the aqueous medium in the electrocoagulation process (Kobyas 2008, Gomes et al 2007). These complex

molecules can act as adsorbents and/ or traps for Lead (Pb) ions and so eliminate them from wastewater.

The treated effluent quality was compared with wastewater reuse quality standards for inland surface water (Table 2). Comparison allows judging the effectiveness of EC process for the treatment of battery effluent at Panna Battery Limited (PBL). After EC treatment all parameters of effluent except electrical conductivity were within standard of Department of Environment, Bangladesh (DoE 2003). The final pH of treated effluent was varied from 3.62 to 14. At pH 3 and 15min electrolysis time; at pH 5 and 15min and 30min electrolysis time and at pH 7 and 15min electrolysis time, the final pH of effluent was within allowable limit.

Table 2: Comparison of studied treated wastewater quality with various wastewater quality standards

Parameter	Unit	After Treatment			DoE Standard (DoE, 2003)
		Minimum	Maximum	Mean	
TDS	mg/l	470	1450	640	2100
TSS	mg/l	2.74	97.4	50.7	150
pH	-	3.62	14	8.81	6-9
EC	µs/cm	960	3220	2090	1200
DO	mg/l	5.10	8.48	6.79	4.5-8
Pb	µg/l	0.03	37.9	19	100

Conclusion

From the experiments at laboratory bench scale, EC was found effective process for treating battery effluent containing heavy metal such as lead, but the removal efficiency was significantly influenced by various parameters including the voltage, initial effluent pH and electrolysis time. In all working conditions Lead (Pb) removal efficiency was above 90% but the optimum conditions in batch experiment were a battery effluent pH 3 and 15 min electrolysis time at 30V. After EC treatment Lead (Pb) concentration reached at 0.03-37.9 µg/l which was within the permissible limit for discharging at inland surface water (100µg/l) and removal efficiency was about 99.90%. Therefore, EC is significantly underused technique and would be a revolutionary technology in battery effluent treatment which is an excellent, cost effective technology to treat battery effluent focusing Lead (Pb) removal.

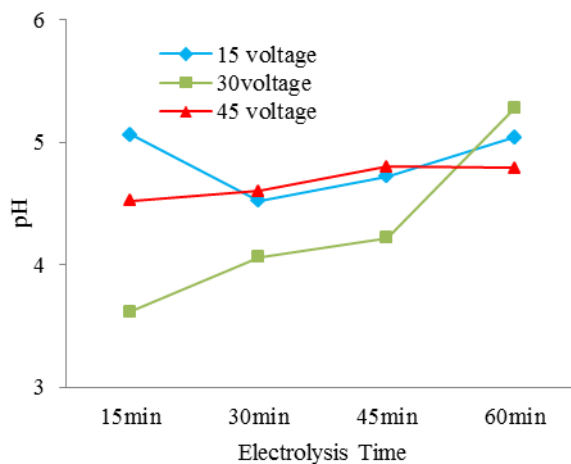


Figure 3: Effect of voltage and electrolysis time on initial wastewater pH (at pH=1)

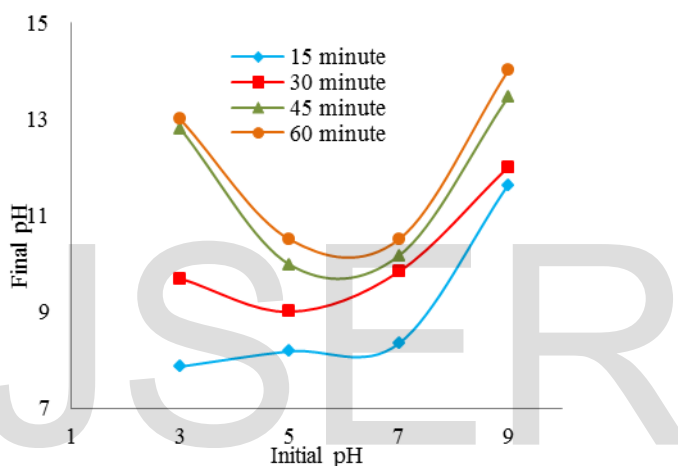


Figure 4: Variation of pH at various times on electrolysis times at constant voltage 30V

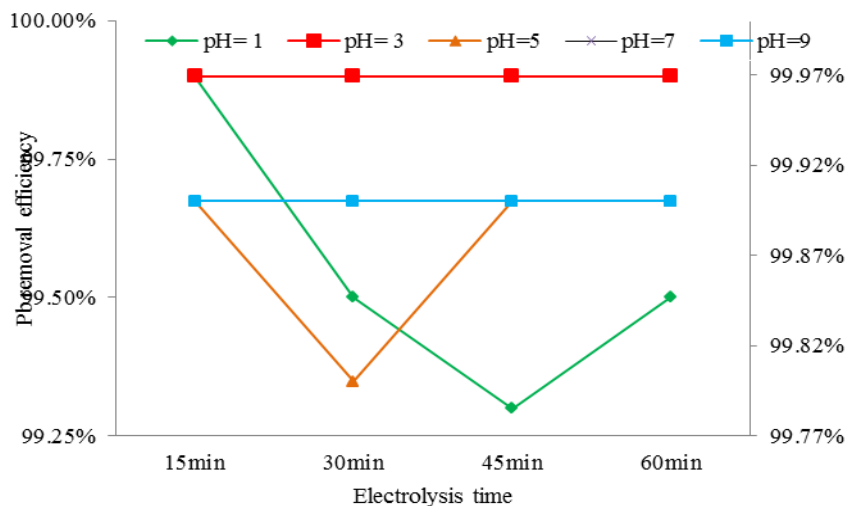


Figure 5: Removal of lead as a function of time at different pH at 30V

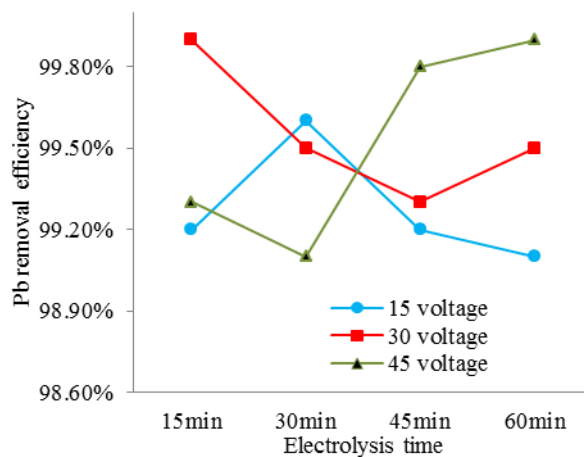


Figure 6: Removal of lead as a function of time at various voltages at constant pH 1

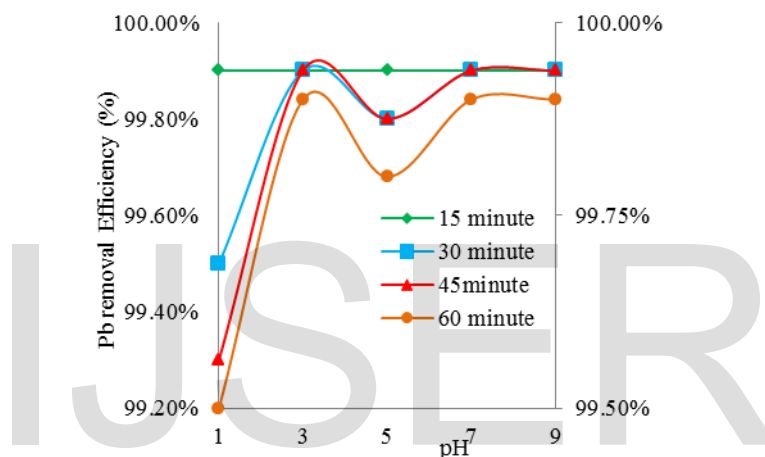


Figure 7: Removal percentage of lead as a function of pH with different electrolysis time at constant voltage 30V.

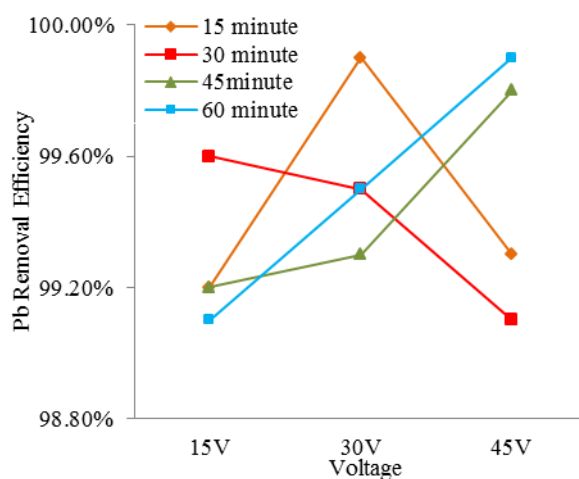


Figure 8: Removal percentage of lead as a function of voltage with different electrolysis time at constant pH= 1.

References

Chen X., Chen G. and Yue P.L., 2000. Separation of pollutants from restaurant wastewater by electrocoagulation, *Sep. Purif. Technol.* 19, 65–76.

X. Chen, G. Chen, P.L. Yue, Separation of pollutants from restaurant wastewater by electrocoagulation, *Sep. Purif. Technol.* 19 (2000) 65–76.

X. Chen, G. Chen, P.L. Yue, Electrocoagulation and electroflotation of restaurant wastewater, *J. Environ. Eng.* 126 (2000) 858–863.

Sheng H. Lin, Chi F. Peng Treatment of textile wastewater by electrochemical method, Water Research, Volume 28, Issue 2, February 1994, Pages 277–282

Y. Xua, Jia-Qian Jianga*, K. Quillb, J. Simonb, K. Shettleb Electrocoagulation: a new approach for the removal of boron containing wastes *Desalination and Water Treatment* 2 (2009) 131–138

Adhoum N. and Monser L., 2004. Decolourization and removal of phenolic compounds from olive mill wastewater by electrocoagulation. *Chem. Eng. Process.* 43, 1281–1287.

Adhoum N., Monser L., Bellakhal N. and Belgaied J.E., 2004. Treatment of electroplating wastewater containing Cu^{2+} , Zn^{2+} and Cr(VI) by electrocoagulation, *J. Hazard. Mater.* B112, 207–213.

Can O.T., Bayramoglu M. and Kobya M., 2003. Decolorization of reactive dye solutions by electrocoagulation using aluminum electrodes, *Ind. Eng. Chem. Res.* 42, 3391–3396.

Chen G., 2004. *Sep. Purif. Technol.*, 38, 11.

Casqueira R.G., Toren M.L and Kohler H.M., 2006. The removal of zinc from liquid streams by electroflotation, *Miner. Eng.* 19, 1388–1392.

Chaloempan P., Petsriprasit C. and Namboonmee J. and Hunsom M. 2009. Application of the electrocoagulation technique for treating heavy metals containing wastewater from the pickling process of a billet plant. *Korean Journal Chemical Engineering*, **27**(3): 854-861.

Daneshvar N., Ashassi-Sorkhabi H. and Tizpar A., 2003. Decolorization of orange II by electrocoagulation method, *Sep. Purif. Technol.* 31, 153– 162.

Escobar C., Soto-Salazar C. and Toral M. I., 2005. Optimization of the electrocoagulation process for removal of copper, lead and cadmium in natural waters and simulated wastewater, *J. Environ. Manage.* 81, 384–391.

Faghihian H., Ghannadi-Marageh M. and Kazemian H., 1999. The use of clinoptilolite of radioactive cesium and strontium from nuclear waste water and lead, nickel, cadmium, barium from municipal waste water. *Sep Sci Technol* 34(12):2275–92.

Gao P., Chen X., Shen F. and Chen G., 2005. Removal of chromium(VI) from wastewater by combined electrocoagulation–electroflotation without a filter, *Sep. Purif. Technol.* 43 (2): 117–123.

Gomes J.A.G., Daida P., Kesmez M., Weir M., Moreno H., Parga J.R., Irwin G., McWhinny H., Grady T., Peterson E., and D., 2007. *J. Hazard. Mater. B*, 139, 220.

Hewitt CN, Metcalfe PJ, Street RA., 1991. Method for the sampling and removal of ionic alkyl-lead compounds from aqueous solution using ion-exchange media. *Water Res* 25(1):91–4.

Hu C.Y., Lo S.L., Kuan W.H. and Lee Y.D., 2005. Removal of fluoride from semiconductor wastewater by electrocoagulation–flotation, *Water Res.* 39, 895–901.

Kongsricharoen N. and Polprasert C., 1995. Electrochemical precipitation of chromium (Cr^{6+}) from an electroplating wastewater, *Water Sci. Technol.* 31 (9): 109–117.

Kim T.K., Perk's Shin.E.B. and Kim S. 2002. Dechlorination of disperse and reactive dyes by continuous electro coagulation process, *Desalination*, 150, 165-175.

Koparal A.S. and Ogutveren U.B., 2002. Removal of nitrate from water by electroreduction and electrocoagulation, *J. Hazard. Mater.* B89, 83–94.

Kumar P.R., Chaudhari S., Khilar K.C. and Mahajan S.P., 2004. Removal of arsenic from water by electrocoagulation, *Chemosphere* 55, 1245–1252.

M. Koby M., C. Ciftci C., M. Bayramoglu M. and M. T. Sensoy M.T., 2008. *Sep. Purif. Technol.*, 60, 285.

Laumakis MT, Martin PJ, Pamucku S and Owens K., 1995. *Proceeding of the International Conference on Hazard Waste Management.* New York: ASCE p. 528–35.

Larue O., Vorobiev E., Vu C. and Durand B., 2003. Electrocoagulation and coagulation by iron of latex particles in aqueous suspensions, *Sep. Purif. Technol.* 31, 177–192.

Muruganathan M., Raju G.B and Prabhakar S., 2004. Separation of pollutants from tannery effluents by electro-flotation, *Sep. Purif. Technol.* 40, 69–75.

Niu H, Xu Xue S, Wang JH and Volesky B., 1993. Removal of lead from aqueous solutions by penicillium biomass. *Biotechnol Bioeng* 42, 785–7.

Namasivayam C and Ranganathan K., 1995. Removal of Cd(II) from waste water by adsorption on waste FeIII/CrIII hydroxide. *Water Res* 29(7):1737–44.

Nabil S. A.; Alaadin A. B. and Zakariya M. A, 1998. Removal of bentonite causing turbidity by electrocoagulation. *Journal Environmental Science. Health, Part A.* 33(7): 1341-1358.

Pansini M and Collella C., 1990. Dynamic data on lead uptake from water by chabazite. *Desalination* 78(2):287–95.

Petruzzelli D, Pagano M, Triavanti G and Passino R., 1999. Lead removal and recovery from battery waste waters by natural zeolite clinoptilolite. *Solvent Extr Ion Exchang* 17(3):677–94.

Park KH, Park MA, Jang H, Kim EK and Kim YH., 1999. Removal of heavy metals, cadmium II and lead II ions in water by sargassum. *Anal Sci Technol* 12(3):196–202.

Panizza M., Bocca C. and Cerisola G., 2000. Electrochemical treatment of wastewater containing polyaromatic organic pollutants, *Water Res.* 34 (9): 2601–2605.

Reed BE, Arunachalam S, Thomas B., 1994. Removal of lead and cadmium from aqueous streams using granular activated carbon columns. *Environ Progr* 13(1):60–4.

Srivastav RK, Gupta SK, Nigam KDP and Vasudevan P, 1993. Use of aquatic plants for the removal of heavy metals from waste waters. *Int J Environ Stud* 45(1):43–50.

Shen F., Chen X., Gao P. and Chen G., 2003. Electrochemical removal of fluoride ions from industrial wastewater, *Chem. Eng. Sci.* 58, 987–993.

Vecchio A, Finoli C, Di-Simine D and Andreoni V., 1998. Heavy metal biosorption by bacterial cells. *Fresenius J Anal Chem* 361(4):338–42.

Edris Bazrafshan¹, Ferdos Kord Mostafapour¹, Mehdi Farzadkia², Kamal Aldin Ownagh¹, Amir Hossein Mahvi^{2,3,4*} Slaughterhouse Wastewater Treatment by Combined Chemical Coagulation and Electrocoagulation Process June 2012 | Volume 7 | Issue 6 | e40108 plos one

S.E. Bailey, T.J. Olin, R.M. Bricka, D.D. Adrian. A review of potentially low-cost sorbents for heavy metals. *Water Res.*, 33 (1999), pp. 2469–2479

M. Ahmedna, W.E. Marshall, A.A. Hussein, R.M. Rao, I. Goktepe
The use of nutshell carbons in drinking water filters for removal of trace metals
Water Res., 38 (2004), pp. 1062–1068

M. Ghaedi, E. Asadpour, A. Vafaie. Simultaneous preconcentration and determination of copper, nickel, cobalt, lead, and iron content using a surfactant-coated alumina. *Bulletin Chem. Soc. Jpn.*, 79 (2006), pp. 432–436

M. Ghaedi, M. Montazerzohori, M. Soylak. Solid phase extraction method for selective determination of Pb(II) in water samples using 4-(4-methoxybenzylideneimine) thiophenole. *J. Hazard. Mater.*, 142 (2007), pp. 368–373

M. Ghaedi, Pyrimidine-2-thiol as selective and sensitive ligand for preconcentration and determination of Pb²⁺, *Chemia Analityczna*, 51 (2006), pp. 593–602

M. Kobya, E. Demirbas, E. Senturk, M. Ince. Adsorption of heavy metal ions from aqueous solutions by activated carbon prepared from apricot stone. *Bioresour. Technol.*, 96 (2005), pp. 1518–1521

M.K. Jamali, T.G. Kazi, M.B. Arain, H.I. Afridi, N. Jalbani, A.R. Menon Heavy metal contents of vegetables grown in soil, irrigated with mixtures of wastewater and sewage sludge in Pakistan, using ultrasonic assisted pseudo-digestion *J. Agronomy Crop Sci.*, 193 (3) (2007), pp. 218–228

M. Kobya, H. Hiz, E. Senturk, C. Aydinler, E. Demirbas · **Treatment of potato chips manufacturing wastewater by electrocoagulation** *Desalination, Volume 190, Issues 1–3*, 15 April 2006, Pages 201–211

Yusuf Yavuz **EC and EF processes for the treatment of alcohol distillery wastewater** *Separation and Purification Technology, Volume 53, Issue 1*, 15 February 2007, Pages 135–140

Sheng H. Lin, Ching T. Shyu, Mei C. Sun **Saline wastewater treatment by electrochemical method** *Water Research, Volume 32, Issue 4*, April 1998, Pages 1059–1066

Eilen A. Vik¹, Dale A. Carlson², Arild S. Eikum¹, Egil T. Gjessing¹ **Electrocoagulation of potable water** *Water Research* Volume 18, Issue 11, 1984, Pages 1355–1360

Chen L Lai, Sheng H Lin Electrocoagulation of chemical mechanical polishing (CMP) wastewater from semiconductor fabrication *Chemical Engineering Journal, Volume 95, Issues 1–3*, 15 September 2003, Pages 205–211

H. Inan, A. Dimoglu, H. Simsek, M. Karpuzcu, Olive oil mill wastewater treatment by means of electrocoagulation, *Sep. Purif. Technol.* 36 (2004) 23–31.

X. Chen, G. Chen, P.L. Yue, Novel electrode system for electroflotation of wastewater, *Environ. Sci. Technol.* 36 (2002) 778–783.

J.G. Ibanez, M. Takimoto, R. Vasquez, K. Rajeshwar, S. Basak, Laboratory experiments on electrochemical remediation of the environment: electrocoagulation of oily wastewater, *J. Chem. Educ.* 72 (1995) 1050–1052.

W. Lo, H. Chua, K.H. Lam, S.P. Bi A comparative investigation on the biosorption of lead by filamentous fungal biomass *Chemosphere*, 39 (1999), pp. 2723–2736

T.K. Naiyaa, A.K. Bhattacharya, S. Mandal, S.K. Das. The sorption of lead(II) ions on rice husk ash. *J. Hazard. Mater.*, 163 (2009), pp. 1254–1264

Ahmet Sari, Mustafa Tuzen Kinetic and equilibrium studies of biosorption of Pb(II) and Cd(II) from aqueous solution by macrofungus (*Amanita rubescens*) biomass
Journal of Hazardous Materials, Volume 164, Issues 2–3, 30 May 2009, Pages 1004–1011

R.J.E. Martins, R. Pardo, R.A.R. Boaventura Cadmium(II) and zinc(II) adsorption by the aquatic moss *Fontinalis antipyretica*: effect of temperature, pH and water hardness *Water Res.*, 38 (2004), pp. 693–699

L.J. Xu, B.W. Sheldon, D.K. Larick, R.E. Carawan, Recovery and utilization of useful by-products from egg processing wastewater by electrocoagulation, *Poultry Sci.* 81 (2002) 785–792.

H Inan, Anatoly Dimoglo, H Şimşek, M Karpuzcu Olive oil mill wastewater treatment by means of electro-coagulation
Separation and Purification Technology, Volume 36, Issue 1,
April 2004, Pages 23–31

Michael J. Matteson, Regina L. Dobson, Robert W. Glenn Jr., Nagesh S. Kukunoor, William H. Waits III, Eric J. Clayfield **Electrocoagulation and separation of aqueous suspensions of ultrafine particles** Water Research Volume 31, Issue 12, December 1997, Pages 3073–3081

C.T. Tsai¹, S.T. Lin, Y.C. Shue¹, P.L. Su¹ **Electrolysis of soluble organic matter in leachate from landfills** Separation and Purification Technology, Volume 36, Issue 1, April 2004, Pages 33–39

Jiantuan Ge, Jiuhui Qu, Pengju Lei, Huijuan Liu **New bipolar electrocoagulation–electroflotation process for the treatment of laundry wastewater** Journal of Hazardous Materials, Volume 109, Issues 1–3, 2004, 37–44

M. Murugananthan, G.Bhaskar Raju, S. Prabhakar Removal of sulfide, sulfate and sulfite ions by electro coagulation. Journal of Hazardous Materials, Volume 109, Issues 1–3, 18 June 2004, Pages 37–44

P. Xiangliang, W. Jianlong, Z. Daoyong. Biosorption of Pb(II) by *Pleurotus ostreatus* immobilized in calcium alginate gel. Process Biochem., 40 (2005), pp. 2799–2803

Zhu B., Clifford D.A. and Chellam S., 2005. Comparison of electro coagulation and chemical coagulation pre treatment for enhanced virus removal using microfiltration membranes, Water Resource, 39(20) :3098 – 3108.

T. M. Adyel, S. H. Rahman, S. M. N. Islam, H. M. Sayem, M. Khan, and M. M. Zaman, “Geo-engineering potentiality of electrocoagulated metal hydroxide sludge (EMHS) from textile industry and EMHS amended soil for using as building material,” International Journal of Current Research, vol. 4, no. 2, pp. 21–25, 2012.

T. M. Adyel, S. H. Rahman, S. M. N. Islam, H. M. Sayem, M. Khan, and M. A. Gafur, “Characterization of brick making soil: geo-engineering, elemental and thermal aspects,” Jahangirnagar University Journal of Science, vol. 35, no. 1, pp. 109–118, 2012.

T. M. Adyel, S. H. Rahman, M. Khan, and S. M. N. Islam, “Analysis of heavy metal in electrocoagulated metal hydroxide sludge (EMHS) from textile industry by energy dispersive X-ray fluorescence (EDXRF),” *Metals*, vol. 2, no. 4, pp. 478–487, 2012.

A. K. Golder, A. N. Samanta, and S. Ray, “Anionic reactive dye removal from aqueous solution using a new adsorbent-sludge generated in removal of heavy metal by electrocoagulation,” *Chemical Engineering Journal*, vol. 122, no. 1-2, pp. 107–115, 2006.

S. H. Rahman, S. M. N. Islam, N. Kaiser, and M. M. Rahman, “Electrocoagulation (EC) for reduction of chemical oxygen demand (COD) of surface water,” *Bangladesh Journal of Scientific and Industrial Research*, vol. 47, no. 1, pp. 77–82, 2012.

S. M. N. Islam, S. H. Rahman, T.M. Adyel et al., “Electrocoagulation (EC) technique for color removal from orange II dye,” *Bangladesh Journal of Environmental Research*, vol. 9, pp. 45–52, 2011.

S. M. N. Islam, S. H. Rahman, M.M. Rahman et al., “Excessive turbidity removal from textile effluents using electrocoagulation (EC) technique,” *Journal of Scientific Research*, vol. 3, no. 3, pp. 557–568, 2011.

M. Y. A. Mollah, R. Schennach, J. R. Parga, and D. L. Cocke, “Electrocoagulation (EC)—science and applications,” *Journal of Hazardous Materials*, vol. 84, no. 1, pp. 29–41, 2001.

M. Y. A. Mollah, P. Morkovsky, J. A. G. Gomes, M. Kesmez, J. Parga, and D. L. Cocke, “Fundamentals, present and future perspectives of electrocoagulation,” *Journal of Hazardous Materials*, vol. 114, no. 1–3, pp. 199–210, 2004.

A. Amirtharajah and K. M. Mills, “Rapid-mix design for mechanisms of alum coagulation,” *Journal / American Water Works Association*, vol. 74, no. 4, pp. 210–216, 1982.

S. H. Rahman, D. Khanam, T. M. Adyel, M. S. Islam, M. A. Ahsan, and M. A. Akbor, “Assessment of heavy metal contamination of agricultural soil around Dhaka export

processing zone (DEPZ), Bangladesh: implication of seasonal variation and indices,” *Applied Sciences*, vol. 2, no. 3, pp. 584–601, 2012.

Casillas, H.A.M., Cocke, D.L., Gomes, J.A.G., Morkovsky, P., Parga, J.R. and Peterson, E. (2007) ‘Electrocoagulation mechanism for COD removal’, *Separation and Purification Technology*, Vol. 56, pp.204–211.

Centkin, V.E. and Belevtsev, A.N. (1985) ‘Electrochemical treatment of industrial waste water’, *Effluent and Water Treatment Journal*, Vol. 11, pp.243-249.

Islam, S.M.N., Rahman, S.H., Adyel, T.M., Ahmed, M.S., Yesmin, R.A., Kaiser, N. and Rahman, M.M. (2011) ‘Electrocoagulation (EC) Technique for Color Removal from Orange II Dye’, *Bangladesh Journal of Environmental Research*, Vol. 9, pp.45-52.

Islam, S.M.N., Rahman, S.H., Rahman, M.M., Adyel, T.M., Yesmin, R.A., Ahmed, M.S. and Kaiser, N. (2011) ‘Excessive turbidity removal from textile effluents using electrocoagulation (EC) technique’, *Journal of Scientific Research*, Vol. 3, pp.557-568.

Mollah, M.Y.A., Schennach, R., Parga, J.R. and Cocke, D.L. (2001) ‘Electrocoagulation (EC)-science and applications’, *Journal of Hazardous Materials*, Vol. 84, pp.29–41.

Mollah, M.Y.A., Morkovsky, P., Gomes, J.A.G., Kesmez, M., Parga, J.R. and Cocke, D.L. (2004) ‘Fundamentals, present and future perspectives of electrocoagulation’, *Journal of Hazardous Materials*, Vol. 114, pp.199–210.

Mollah, M.Y.A., Gomes, J.A.G., Das, K.K. Cocke, D.L. (2010) ‘Electrochemical treatment of Orange II dye solution-use of aluminum sacrificial electrodes and floc characterization’, *Journal of Hazardous Materials*, Vol. 174, pp.851–858.

--- End ---