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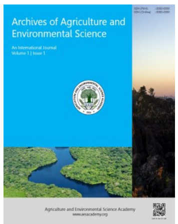

REVIEW ARTICLE

A review on the feasibility of electrolytic treatment of wastewater: Prospective and constraints

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ABSTRACT

Electrolytic treatment of wastewater utilizes the electric energy to remover the pollutants from the wastewater. Considerable efforts have been made to purify the different types of wastewater using various electrolytic treatment devices, apparatus and reactors. The present review focuses on the recent development in the electrolytic treatments considering the views of the past work in this field. Most studies have been performed on iron, steel, aluminium and zinc electrodes using various current densities and electrolysis time. Moreover, these studies have been carried out on the removal of different physico-chemical, heavy metals and microbiological parameters using different types of wastewater. In this review the main emphasis has been given to the removal of physico-chemical parameters viz., colour, turbidity, EC, TSS, BOD, COD and heavy metals of the wastewater. The literature on the electrolytic treatment methods using different types of wastewater is surveyed and physico-chemical parameters of wastewater are reviewed. Besides this impact of current density, electrode types, time of electric current application along with the removal efficiency are also discussed in the present review. Additionally, various aspects of the electrolytic treatment of wastewater like impact of temperature, coagulation and flocculation rate are also discussed to make the literature more specific and generalization to understand the electrolytic treatment of wastewater. Therefore, the future directions of the research could be focused on the more efficient removal of pollutants from the wastewater using electrolytic technology in order to achieve the safe limits of wastewater for the reuse and discharge as per water quality standards.

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INTRODUCTION

Disposal of wastewater has become a global problem due to generation of huge volume of the wastewater through a number of sources mainly domestic and industrial (Kumar and Chopra, 2011a, b; Pathak *et al.,* 2011; Kumar *et al.,* 2016). The wastewater contains a wide range of nutrients, heavy metals and microorganisms. Discharge of untreated or partially treated wastewater deteriorates the quality of the receiving soil or aquatic environment (Rahmani, 2008; Kumar and Chopra, 2011a, b). Most of the rivers, lakes, streams, ponds etc. are on potential risk of water pollution due to discharge of untreated or partially treated wastewater. Therefore, these resources are rapidly converting into the dumping sites for the wastewater (Chopra *et al.,* 2011b; Kumar *et al.,* 2016). Globally scientists are making efforts to get rid of this worse problem to save the aquatic resources for the present and future use. World-wide extensive efforts have been made to treat the wastewater through different methods like, filtration, sedimentation, aeration, coagulation, flocculation, and phytoremediation (Cerqueira and Marques, 2012; Kumar and Chopra, 2016). Some of these methods are found to be feasible in the reduction of pollution load of wastewater but at the same time they are very costly and can not be used for the large scale treatment of wastewater (Kumar and Chopra, 2011a; Chaturvedi, 2013). Therefore, scientists are looking to develop new cost-effective and more reliable treatment technologies for the treatment of wastewater. They are now focusing on the scope of electrolytic treatment of wastewater (Chopra *et al.,* 2011a; Cerqueira and Marques, 2012). The electrolytic treatment of wastewater is based on the application of electricity in the electrodes to neutralize the pollutants present in the ionic forms in the aqueous state (Edwards *et al.,* 2006;

Chaturvedi, 2013). Electrocoagulation (EC) is likely to be suggested as an advanced alternative to chemical coagulation in pollutant removal from raw waters and wastewaters. In this technology, metal cations are released into water through dissolving metal electrodes (Chopra *et al.,* 2011a; Chaturvedi, 2013). Chemical coagulation and flocculation are commonly used as a part of the water purification systems for the removal of pollutants from raw waters and wastewaters (Nikolaev *et al.,* 1982; Catalino *et al.,* 2002; Holt *et al.,* 2005; Edwards *et al.,* 2006; Chaturvedi, 2013).

METHODOLOGY

In this review, secondary data on electrolytic treatment of water and wastewater were exploited based on literature review of e-journals, seminar proceedings, company literature and published reports and government publications. The literature for the review article has been surveyed using the Departmental Library of the Department of Zoology and Environmental Science, of the Gurukula Kangri University, Haridwar (Uttarakhand), India. The research papers of the relevant literature have been downloaded from different sources like Springer, Elsevier, Taylor and Francis journals, e-books and newsletters in the e-library provided by the University Grants Commission, New Delhi, India to the Gurukula Kangri University, Haridwar (Uttarakhand), India.

Electrocoagulation: Normally, the electrocoagulation is a procedure involving the electrolytic adding of coagulating metal ions directly from sacrificial electrodes. These ions coagulate with turbidity agents in the water, in a related manner to the adding together of coagulating chemicals such as alum and ferric chloride, and allow the easier removal of the pollutants (Rahmani, 2008; Chopra *et al.,* 2011; Cerqueira and Marques, 2012).

Moreover specifically, the electrocoagulation (EC) is a process that involves the generation of coagulants from an electrode by the action of electric current applied to these electrodes. The generation of ions is followed by electrophoretic concentration of particles around the anode. The ions are attracted by the colloidal particles, neutralizing their charge and allowing their coagulation (Figure 2). The hydrogen gas released from the cathode interacts with the particles causing flocculation, allowing the unwanted material to rise and be removed (Cerqueira and Marques, 2012).

Mechanism of electrocoagulation

Reactions at the electrodes in electrocoagulation: The following reactions are taken place on the anode and cathode during the process of electrocoagulation.

Reaction at the anode:

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

$Me^{3+}(aq) + 3H_2O \rightarrow Me(OH)_3 + 3H^+$ (2)

Reaction at the cathode:

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (3)

Electro flotation

Reactions at the electrodes in electro flotation:

Reaction at the anode:

$(4OH^-) - (4e^-) \rightarrow 2H_2O + O_2$ (4)

Reaction at the cathode:

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (5)

Therefore, the descriptive findings of different studies on the electrolytic treatment of water and wastewater along with treatment specifications *viz.,* method of treatment, electrodes used, current density, and time of electrolysis and removal of particular parameters are presented in Table 1 and discussed below:

In an electrolytic study Manvelova *et al.* (2001) observed 80 percent to 90 percent recovery of heavy metals by using the current density of 0.3-1.5A dm^{-2}. They also reported 4-8 kWh kg^{-1} of specific energy consumption during the metal recovery Therefore they suggested that electrolysis is helpful for the removal of heavy metals from the wastewater.

Chaudhary *et al.* (2003) reported that production of the diffusion layer in the dilute solution around the electrode due to a slower reaction rate, other than in absolute

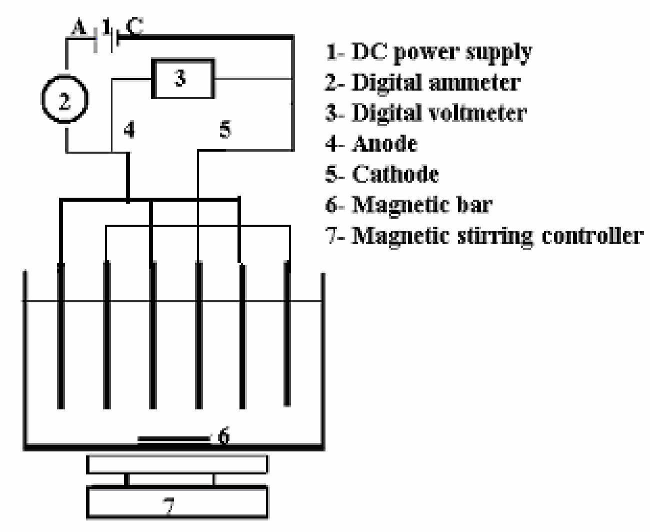

Figure 1. *Preliminary experimental setup for electrocoagulation (Source: Rahmani, 2008).*

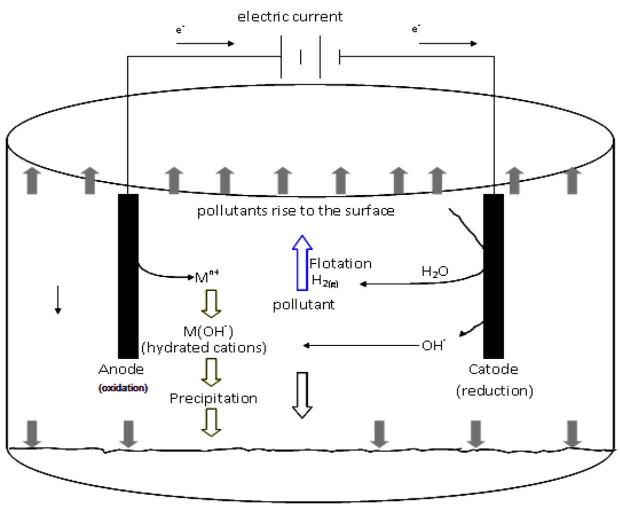

Figure 2. *General mechanism of electro coagulation in an electrocoagulation cell (Source: Mollah et al., 2004; Cerqueira and Marques, 2012).*

Table 1. Feasibility of various electrolytic treatment methods using different types of wastewater.

Wastewater	Experimental specification	Observations	References
Galvanic and printed circuit board shops wastewater	Reverse osmosis, ion exchange, and electrolysis techniques at 0.3-1.5A dm^{-2} current density.	Recovery of 80-85% of metals achieved.	Manvelova *et al.* (2001)
RB4 dye wastewater	Electrochemical reduction and oxidation at reticulated vitreous carbon electrode (RVC) and $Ti/SnO_2/SbOx$ (3% mol)/RuO_2 (30% mol) electrodes.	50% of color removal at 0.6 V and 100% of color removal by 1 hour of electrolysis at 2.4 V.	Patricia *et al.* (2003)
Textile dye house factory wastewater	Electrochemical oxidation and membrane filtrations.	89.8% removal of chemical oxygen demand (COD), 100% reduction in TSS and 98.3% elimination of turbidity.	Xuejun Chen (2003)
Simulated wastewater with aromatic amine nphenyl-n-isopropyl-p-phenylenediamine (Flexzone 3P®)	$Ti/TiRuO_2$ electrodes under 0.025 A/ cm^2 (DC) for different electrolysis durations (5; 15; 30; 45 and 60 minutes).	65.1% reduction the concentration of Flexzone 3P after 60 min of electrolysis.	Thelma Helena Inazaki *et al.* (2004)
Bio refractory organic pollutants	Electrochemical reactor with integrated advanced electrochemical oxidation with activated carbon (AC) fluidization in a single cell.	22%-30% removal of COD with AC fluidization and 97.8% removal with integrated advanced electrochemical oxidation with activated carbon (AC).	Zhou Ming-hua *et al.* (2004)
Domestic sewage from municipal sewers	Electrolytic treatment using Al and Fe electrodes.	38% to 98% reduction in total phosphorus and 10% to 63% removal of COD was obtained	Krzemieniewski Mirosław and Dębowski (2005)
Synthetic wastewater with high Zn content	Electrodialysis with ionic membrane with moderate ion exchange capacities using concentration 1000 ppm, temperature 60 °C, flow rate 0.07 mL/s and voltage 30 V.	97.67% and 98.73% removal of Zn.	Toraj Mohammadia *et al.* (2005)
Industrial wastewater	Glass tank reactor using iron electrodes with DC power supply.	99% cadmium reduction occurring after only 20 minutes at 40 V.	Bazrafshan *et al.* (2006)
Effluents from lagoons	Continuous flow electro-coagulation reactor with three aluminum anodes.	Total suspended solids (TSS) and chlorophyll a removal reached to as high as 99.5% and about 100% by applying a power input of about 550 W.	Azarian *et al.* (2007)
Domestic Wastewater	Flotation techniques with induced air, electro, cavitational and centrifugal flotation systems (CFS).	Over 99% removal of total suspended solids (TSS), 80% of Chemical oxygen demand (COD), and 95% of FOG (over 99.5% of suspended emulsified FOG)	Colic *et al.* (2007)
Paper mill wastewater	Pulsed electrocoagulation treatment with aluminum electrodes	Reduction of EC, SS, COD, and true color were 25.4, 97.1, 76.5, and 70.1%, respectively	Perng *et al.* (2007)
Tannery effluent	Electrocoagulation treatment.	Significantly reduced the TDS, BOD, COD and Cr at the optimum operating conditions $20mA/cm^2$.	Ramesh Babu *et al.* (2007)
Pasta and cookie processing wastewater	Electrolysis in batch reactor using Al electrode for 60 minutes at 3-8 pH range.	80-90% removal in COD and 57% reduction in colour.	Roa-Morles *et al.* (2007)
Poultry Slaughter house wastewater	Batch reactor using Al and Fe electrodes for 60 minutes at pH 6.1-6.5	80-84% reduction in COD, 84-88% BOD, 100% oil and grease and 58-70% TSS	Asselin *et al.* (2008)
Domestic wastewater	Electrocoagulation (EC) process using Fe–Fe electrodes.	The removal efficiency of COD and SS were obtained and shown to be over 60 and 70%, respectively.	Kurt *et al.* (2008)
Paper mill effluents	Electrocoagulation treatment with aluminium and iron electrodes.	80% of lignin, 98% of phenol, 70% of BOD_5 and 75% of COD after 7.5 minutes using aluminum electrodes while the removal capacities were 92%, 93%, 80% and 55%, respectively using iron electrodes at a 77.13 mA current intensity	Ugurlu *et al.* (2008)

Table 1. *Contd.*

Textile wastewater	Combinations of coagulation/flocculation and membrane processes	COD removal of 37%, 42% and more than 80% respectively and a color reduction of 65%, 74% and 50%	Farida Harrelkas *et al.* (2009)
Dairy Wastewater	Batch reactor using Fe electrodes and 270 A/m^2 for 50 minutes	70% removal in COD, 100% in colour, 48% in TS and 93% in total nitrogen	Kushwaha *et al.* (2010)
Almond industry wastewater	Batch reactor using Al/Fe electrodes and 45-50 A/m^2 for 15-8.5 minutes	81% reduction in COD, 74-79% in total organic carbon, 99% turbidity, 80% BOD_5, 100% total phosphorus, 99-100% TSS and 75-85% total nitrogen	Valero *et al.* (2011)
Paper mill wastewater	Electrocoagulation at 10 and 15mA/cm^2 using aluminum and iron electrodes.	COD and arsenic removal 47% and 68%, respectively with aluminum electrodes, and 32% and 41%, respectively, with iron electrodes.	Zodi *et al.* (2011)
Textile indigo dye effluent	Electrochemical method in batch type electrolytic cell hang Pt plates, DC power supply (40 V) for 40 minutes	Achieved 46% reduction in COD of textile effluent	Dogan and Turkdemir (2012)
Mixed liquor solution in wastewater	Electrocoagulation was performed using cylindrical perforated iron electrodes.	Electrocoagulation process reached steady state conditions in no more than 60 minutes. At high voltage gradient (6 V/cm), the steady removal efficiencies of COD and nutrients exceeded 89%.	Mohammad Al-Shannag *et al.* (2013)
Wastewater of wastewater treatment plant	Used a submerged membrane electro-bioreactor (SMEBR) is a new hybrid technology for wastewater treatment employing electrical field and microfiltration.	The removal efficiencies of ammonia (as NH_{3+} -N), phosphorus (as PO_4^{3-}-P), and COD were 99%, 99%, and 92%, respectively.	Hasan *et al.* (2014)
Bilge water mixed with seawater	Electrocoagulation/electroflotation process is investigated by using aluminum and iron electrodes in accordance with pH, time, temperature and current density	Chemical oxygen demand and oil–grease removal values obtained as 64.8% and 57% from Al and 36.2% and 12.5% from Fe, respectively.	Ulucan and Kurt (2015)
Pistachio processing wastewaters	Electrocoagulation using aluminum electrode	Maximum COD removal efficiency was 57.4% at 317 A/m^2 current density, pH 6, and 29 min application time	Güçlü (2015)
Livestock wastewater	Electrocoagulation (EC) process using Al electrodes at pH of 8, current density of 30 mA/cm^2, electrolysis time of 30 min.	The removal of colour was 95.2% and COD 93%.	Bong-yul Tak *et al.* (2015)
Tannery wastewater	Electrocoagulation (EC) technique for tannery wastewater treatment using iron and aluminum electrodes	At optimum conditions of COD, total chrome and color removal efficiencies were achieved as 63.3, 99.7, and 82%, respectively.	Deghles and Kurt (2016a)
Tannery effluents	Electrocoagulation process with aluminum either iron electrodes	Removal efficiency of COD, NH_3-N, Cr and color were 92,100,100,100% respectively corresponds to conductivity value of 0.371 mS/cm at 45 minute	Deghles and Kurt (2016b)

solution the diffusion layer has no effect on the rate of diffusion or migration of metal ions to the electrode surface. Fryda *et al.* (2003a) reported in their investigation that the electrodes of metals or diamond are very capable for the effective electrochemical treatment of the industrial wastewater. In another study conducted by Fryda *et al.* (2003b) recommended that the advanced electrochemical oxidation process is highly capable for the removal of pollutants from the wastewater.

Patricia *et al.* (2003) reported 80% removal of TOC and 100% of color from the wastewater in their electrochemical and oxidation experimental studies. As per Xuejun Chen (2003) about 89.8% removal in chemical oxygen demand through electrochemical oxidation 100% reduction in total suspended solids using membrane and 98.3% removal in the turbidity of wastewater of the textile dye house factory but cost of electricity consumption and scarification of electrodes are the major concern throughout the study.

Gheorghe Duca (2004) has studied the removal direct magenta colour and outrageous orange dyes from simulated solutions by means of their adsorption on aluminum hydroxide, obtained during the hydrolysis of the sulfate of aluminum or electrochemical dissolution of the aluminum anodes, depending on the initial concentration, treatment time and effect of pH on the treatment. They have concluded that pH is very important factor for the reduction of colour. Whereas, Krzemieniewski *et al.* (2004) reported that the electromagnetic field (EMF) is impacted on the removal of phosphorus (P) and organic compounds responsible for the chemical oxygen demand (COD) in the household wastewater. Sebahattin Gurmen *et al.* (2004)

investigated the opportunity of using high current densities in the purification of copper in relation to the cell design by means of surface characteristics of cathode material and concluded that no contamination of the cathode surface by the owing of anode slime, which is described as a disadvantage at high current densities.

Thelma Helena Inazaki *et al.* (2004) investigated the effects of the electrolytic treatment in the simulated wastewater and suggested that during the electrolytic treatment the pH decreased and conductivity increased to some extent. Zhou Ming-hua *et al.* (2004) designed a novel fluidized electrochemical reactor that integrated advanced electrochemical oxidation with activated carbon (AC) fluidization in a single cell was developed to model pollutant *p*-nitrophenol (PNP) abatement. AC fluidization could enhance COD removal by 22%-30%. They have reported 137.8% and 97.8%, reduction in the PNP and COD, respectively.

Ihoş *et al.* (2005) reported 100% colour removal from the textile wastewaters having azo dyes with higher pH=8.3, Cl^- =653 mg/L using electrochemical oxidation at dimensionally stable anodes (DSA) and used two anodic compositions as Ti/RuO.3TiO.7O_2 and Ti/IrO.3TiO.7O_2 but the production of chlorinated organic compounds in the electrochemical treatment of textile wastewaters is major drawback of the treatment. In other study conducted by Karim Beddiar *et al.* (2005) on the electro-osmosis experiments using rigid cylindrical samples containing 0.01M NaCl–water saturated Speswhite kaolinite and found that the treatment efficiency of ingredients was based on pH.

Krzemieniewski Mirosław and Dębowski (2005) reported 38% to 98% reduction in the total phosphorus and 10% to 63% removal in the COD of wastewater using electromagnetic field in 48 hours of the retention period. Li *et al.* (2005) observed that the contents 41–64 mg L^{-1} and 0.27–0.56 mg L^{-1} of $C_6H_{12}O_6$ and Cu^{2+} ions were reduced up to 31–39 mg L^{-1} and 0.14–0.23 mg L^{-1} using electro bioreactor of respectively. Compared with sole electrolysis process or sole biofilm process, it had a much higher Cu^{2+} ion removal rate for combined process.

Toraj Mohammadia *et al.* (2005) carried out a study on zinc elimination from wastewater by electro-dialysis at concentration 1000 ppm, temperature 60 °C, flow rate 0.07 mL/s and voltage 30 V and achieved 97.67% and 98.73%

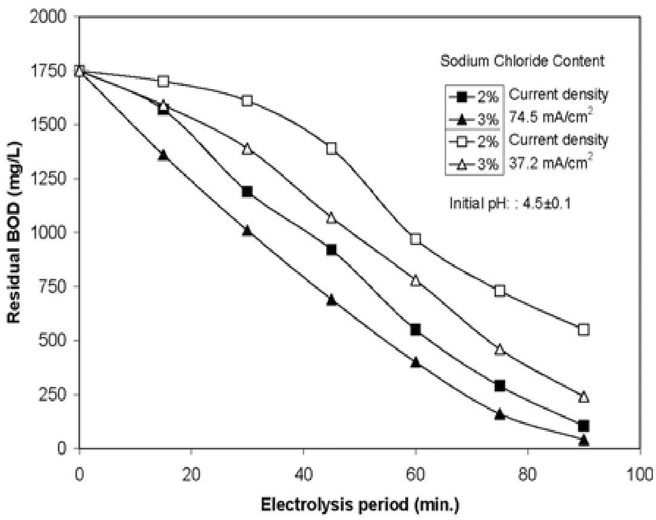

Figure 3. *Change in BOD concentration vs. the electrolysis period (Source: Vijayaraghavan et al., 2008).*

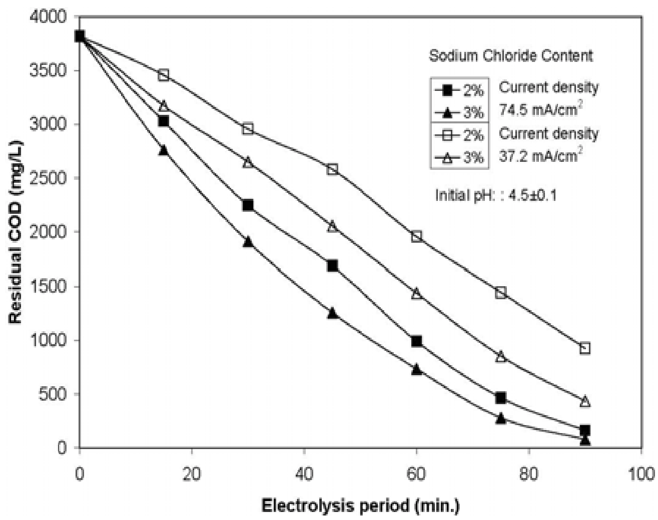

Figure 4. *Change in COD concentration vs. the electrolysis period (Source: Vijayaraghavan et al., 2008).*

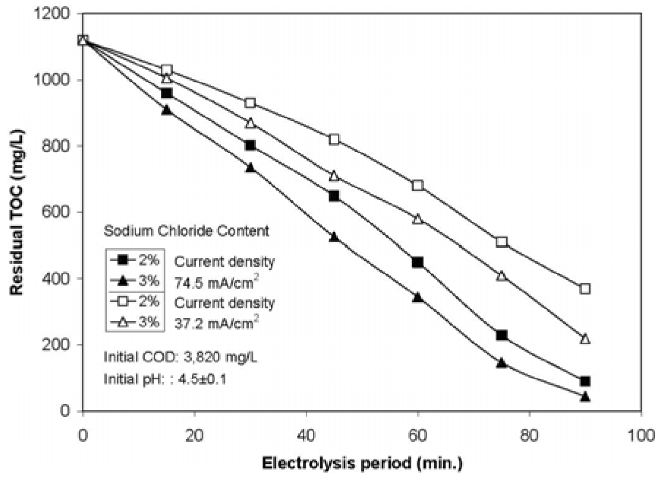

Figure 5. *Change in TOC concentration vs. the electrolysis period (Source: Vijayaraghavan et al., 2008).*

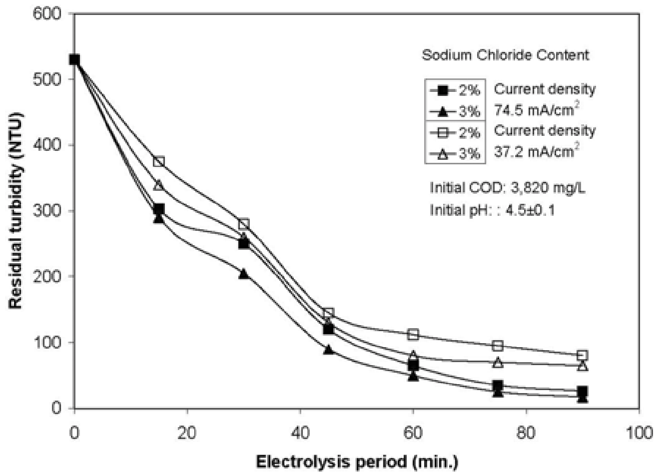

Figure 6. *Change in turbidity vs. the electrolysis period (Source: Vijayaraghavan et al., 2008).*

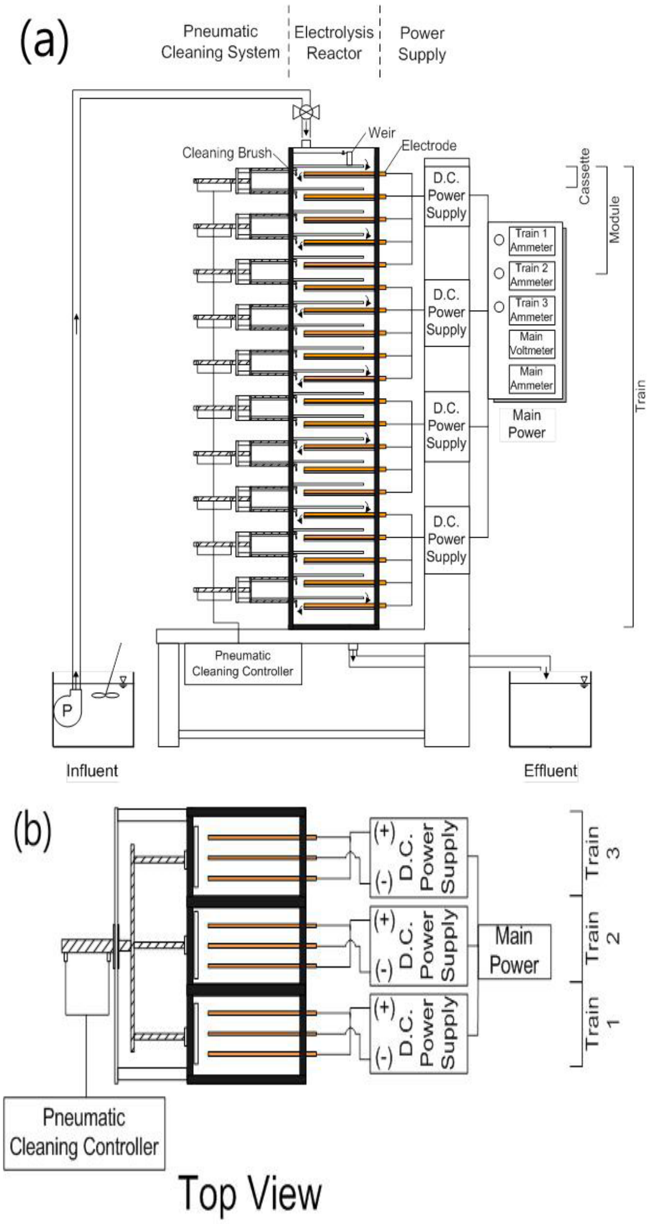

Figure 7. *Schematic diagram of continuous electrolysis system (Source: Dae Gun Kim et al., 2013).*

removal of Zn for these two types of membranes. They concluded that temperature, concentration and voltage are almost the same and are smaller than that of flow rate (69.22%) which means that flow rate is the most influential factor. Bazrafshan *et al.* (2006) studied the elimination of cadmium from industrial wastewater using electro-coagulation process. The experiments were performed in a glass tank having 1.56 L volume with four plate electrode. The iron electrodes were connected with the positive and negative pole of DC power supply. The glass tank was filled with synthetic wastewater that was containing cadmium ion in concentration 5, 50 and 500 mg/L and then electro-coagulation was started up at pH 3, 7 and 10 and in electric potential range of 20, 30 and 40 volts. The results showed that initial contents of cadmium can affect the removal efficiency while for higher contents of cadmium,

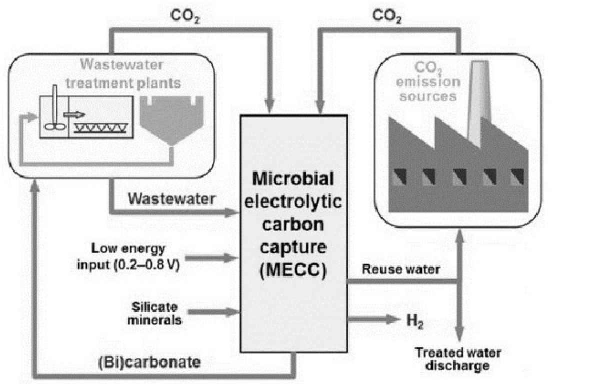

Figure 8. *Microbial electrolytic carbon capture (MECC) approach (Source: Lu et al., 2015).*

higher electrical potential or more reaction time is required. They achieved more than 99 percent removal in cadmium ions at 40Volts only after only 20 minutes.

It has been reported in previous studies that pH has a substantial impact on the effectiveness of the electro-coagulation process (Vik *et al*., 1984; Chen *et al*., 2000). The pH difference of solution after electro-coagulation process in diverse voltages showed that the final pH for all of experiments with iron electrodes is greater than initial pH, (Kobya *et al*., 2003). Through the electro-coagulation the bubbles density enhances and their size reduces with increasing current density resulting in a higher upwards flux and a faster reduction of pollutants and sludge flotation (Khosla *et al*., 1991). It is renowned that electrical current not only decides the coagulant dosage rate but also the bubble generation rate and size and the flocs growth (Letterman *et al*., 1999; Holt *et al*., 2002), which can affect the treatment competence of the electro-coagulation. Kashefialasl *et al.* (2006) studied the influence of electrolyte concentration, initial pH, current density, electrode area; interelectrode distance, dye content, and treatment period on the decolorization effectiveness have been investigated. Iron hydroxypolymeric species formed throughout an earlier stage of the process proficiently eradicate dye molecules by adsorption and precipitation, and in a following step, $Fe(OH)_3$ flocs trap colloidal precipitates and formulate solid liquid separation easier throughout the flotation stage. These stages of electrocoagulation must be optimized to design an inexpensively practicable electrocoagulation method. The augment of current density up to 127.8 A/m^2 increased the color exclusion competence. The results showed that the most favorable electrolysis time was 6 min. The most advantageous pH was determined 8. It was also found that the color elimination percent (R.P.%) with increasing of dye content. The optimum quantity of electrolyte (NaCl) was found to be 8 g/L when the dye content was 50 mg/ L. The results indicated that while the initial content of the dye was 50 ppm, the dye was successfully eliminated (83%) at pH ranging from 7 to 9, time of electrolysis of just about 6 minutes, current density of about 127.8 A/m^2, temperature of roughly 298 K, and interelectrode distance of 2.5 cm. Thus electrocoagulation method in the optimized state causes to near 85% exclusion of color from dye solution.

Toshikazu Takenouchi and Shin-Ichi Wakabayashi (2006) reported the enhancement in the surface sanitation of electroplated nickel by rinsing in alkaline electrolyzed water (AEW) was resolute. When the nickel plated sample was rinsed with the AEW, it was establish that the amount of residual sulfate ion on the surface of a sample reduced just about by half compared to one rinsed only with deionized pure water.

Azarian *et al.* (2007) used the continuous flow electrocoagulation reactor in their studies with three aluminum anodes. This type of metal was selected because it could initiate the flocculation agent into the effluent, thereby algae could be eliminated by both processes of electroflotation and electro-flocculation. The findings of treatment were extraordinarily superior and the effectiveness of total suspended solids (TSS) and chlorophyll a reduction reached to as high as 99.5% and about 100% by using a power input of about 550 W. Colic *et al.* (2007) reported flotation as a wastewater purification technique is designed to eliminate all particles normally encountered as very fine emulsions, suspended solids, and colloids from effluent. They achieved 99% reduction in of total suspended solids (TSS), 80% of chemical oxygen demand (COD).

Perng *et al.* (2007) observed that the electrical conductivity of the waste effluent was decreased with increasing current density and wastewater hydraulic retention time during pulsed electro-coagulation purification. They obtained more than 40% reduction in COD, 85% removal in suspended solids using aluminum electrodes. Ramesh Babu *et al.* (2007) reported that the electrocoagulation can be successfully used for the purification of tannery wastewater. The electro-coagulation of tannery wastewater by generating of polymerized complex molecules and release of oxygen and hydrogen gas at the electrodes significantly diminish the TDS, BOD, COD and Cr at the optimum operating conditions 20mA/cm^{2}. Brillas *et al.* (2008) reported the mineralization of an aromatic pharmaceutical as clofibric acid and the dye indigo carmine in 0.05 M Na_2SO_4 of pH 3.0 by electrochemical advanced oxidation processes. They observed that anodic oxidation also showed immense efficacy to obliterate high indigo carmine contents up to 0.9 g L^{-1}. They concluded that Photoelectro-Fenton is the most competent technique due to the parallel photodecarboxylation of Fe (III)-oxalate complexes with UVA light.

Goncalves *et al.* (2008) reported the electrochemical treatment of oleate using RuO_2 and IrO_2 type dimensionally stable anodes in alkaline medium to build up a viable anaerobic pre-treatment of fatty wastes. The results indicated that the pre-treated wastes over RuO_2 were faster decreased by anaerobic consortium than the raw oleate solutions or the electrolyzed solutions using IrO_2. Klauson *et al.* (2008) conducted experimental research into the aqueous photocatalytic oxidation of organic groundwater pollutants and achived the reduction in methyl-tert-butyl ether (MTBE), tert-butyl alcohol, phenol, humic substances, 2-ethoxy ethanol and ethylene glycol.

Kurt *et al.* (2008) investigated the possible to treat domestic effluent using an electro-coagulation method and obtained considerable 60 and 70% change in COD and SS, respectively with optimum operational conditions as power supply and electrolysis time. Rahmani (2008) observed that the exclusion effectiveness depends on the electrolyze time, types of electrodes and the applied current. Saltykov and Kornienko (2008) studied the effect of the electrode structure on the selectivity of electrosynthesis and noted the effect of that the structure of electrodes also affects the reduction of water impurities.

Ugurlu *et al.* (2008) achieved 80% of lignin, 98% of phenol, 70% of BOD_5 and 75% of COD after 7.5 minutes using aluminum electrodes whereas the reduction effectiveness were 92%, 93%, 80% and 55%, respectively with the use of iron electrodes at a 77.13 mA current intensity. Vijayaraghavan *et al.* (2008) invented a novel technique of latex wastewater purification based on in-situ hypochlorous acid production. And they obtained significant change in the pH, COD, BOD_5, TOC, residual total chlorine and turbidity of wastewater (Figures 3-6).

Cla´udia Telles Benatti *et al.* (2009) conducted the experiments with raw and oxidized wastewater to study the pH effect upon sulfate precipitation on raw wastewaters and achieved 99.8 percent reduction in calcium sulfate and trace metals Fe, Cr, Mn, Co, Ag, Mg, K and Na. Farida Harrelkas *et al.* (2009) describe the purification of textile effluent using combinations of physico-chemical and membrane processes and obtained 37%, 42% and more than 80% reduction in COD and 50%, 65%, 74% change in colour at different current densities. Kuang-Hsuan Yanga *et al.* (2009) used to organize complexes with Au and Cl species on bulk Au substrates electrochemically at diverse temperatures and reported the effect of temperatures (25 and 100 ◦C) on electrocatalytical polymerization of polypyrrole (PPy). Rapee Gosalawit *et al.* (2009) reported that the water uptake, ion exchange capacity and proton conductivity of SPWC membranes enhanced while the content of acid groups was increased. Li *et al.* (2010) reported that the treatment of nitrate contaminated water which is inappropriate for biological purification by an electrochemical technique using Fe as a cathode and Ti/IrO_2–Pt as an anode and concluded that the nitrate reduction rate was more with enhancing current density.

Peng *et al.* (2010) reported 95% reduction in COD, 89% in TOC in pretreated the P-nitro phenol effluent with iron-carbon micro-electrolysis (ME) method. Zayas *et al.* (2011) concluded that electrolysis of wastewater removed 99% of COD and 95% color and polyphenols in 15 minutes of electrolysis using electrochemical oxidation of paper mill effluent. Dae Gun Kim *et al.* (2013) was invented a customized electrolysis method applying an innovative technique with a low current and constant voltage and copper electrode (Figure 7).

Kliaugaite *et al.* (2013) concluded that membrane electrolysis reduced 70% of the colour and chemical oxygen demand from effluent of organic compounds at energy consumption 3 kWh/m^3. Ivanov *et al.* (2013) evaluated the efficiency of microbial electrolysis cells (MEC) purification of various effluents and reported that Coulombic effectiveness can be applied to openly calculate energy utilization relative to effluent purification as COD reduction from the effluent. Mohammad Al-Shannag *et al.* (2013) studied changes of a few properties of the mixed liquor solution in wastewater treatment plants using electro -coagulation. They used cylindrical perforated iron electrodes to obtain a good distribution of the applied direct current in the effluent and achieved 89% reduction in COD within 60 minutes.

Nordin *et al.* (2013) achieved 96% reduction in COD and colour of the effluent of textile industries by electro-coagulation process at 20 mA/cm^2 with stainless steel electrodes. Hasan *et al.* (2014) reported that submerged membrane electro-bioreactor is an innovative new fusion equipment for purification of effluent and can be used for the efficient reduction as 99 percent of ammonia (as NH_{3+} -N) and phosphorus (as PO_4^{3-}-P), and 92 percent of COD. Rahman and Borhan (2014) concluded that the effectiveness of an electrocoagulation method is principally depends on the pH, electrical conductivity of the medium and 100% removal in COD and 85% reduction in TOC can be obtained using suitable conditions. Tyagi *et al.* (2014) studied the impact of current density, detention time and electrolysis time on chemical oxygen demand and colour reduction of textile effluent and obtained 76% change of COD and 95% reduction in colour at pH (9.0), 14-17 mA/cm^2 current densities for 20 minutes. Zhang *et al.* (2014) obtained significant change in fouling property of the effluent using electro-coagulation.

From their study, Bong-yul Tak *et al.* (2015) concluded that the reduction of color and COD of livestock waste effluent was economical at optimum operation conditions (pH, current density and time) in electro-coagulation with Al electrodes. El-Taweel *et al.* (2015) studied the electro-coagulation by iron electrodes for the elimination of chromium hexavalent ions through fixed bed electrochemical batch reactor and obtained significant removal of chromium ions but it was too costly.

Güçlü (2015) reported 57.4% reduction in COD at 317 A/m^2 current density, pH 6, and 29 min using response surface methodology and Box–Behnken experimental design. In another study conducted by Helder Pereira de Carvalho *et al.* (2015) reported that electro-coagulation was 99 percent effective for the removal of Methylene Blue from aqueous form through electro-coagulation and banana peel adsorption coupling process. Moreover, Impa *et al.* (2015) recorded 63.2 percent reduction in COD and 62 percent removal in nitrate at 20V with pH 7-8 through electrolysis. Lu *et al.* (2015) reported a new microbial electrolytic carbon capture technique for the effective purification of wastewater (Figure 8) and achieved 80–93% recovery of CO_2 and 91–95% recovery of H_2 during the operation.

Symonds *et al.* (2015) reported that to protect environmental and human health, improved purification techniques are required to prevent nutrients, microbes, and emerging chemical contaminants from domestic wastewater prior to release into the environment and electro-coagulation treatment is efficient to reduce these pollutants.

According to Ulucan and Kurt (2015) the electrochemical processes: electrocoagulation/electroflotation process are very efflective for the purification of waste effluent using suitable treatment conditions like pH, time, temperature and current density. They obtained 64.8% reduction in chemical oxygen demand and 57% removal in oil–grease removal with Al electrode while and 36.2% reduction in COD and 12.5% removal in oil and grease with Fe electrode.

Deghles and Kurt (2016a) studied the effects of pH, current density and time using electro-coagulation of tannery effluent and obtained significant impact of pH, current density and time on removal of COD during the treatment. In another study carried out by Deghles and Kurt (2016b) they reported that integrated electrodialysis is effectively reduced the COD, NH_3-N, Cr and color in tannery effluent. Moreover, Yu Qing *et al.* (2016) also concluded that the electrochemical treatments as electro-coagulation, and photo-catalysis jointly reduced the BOD_5, COD, TSS and thermo tolerant coliform in different types of wastewater and industrial effluent. Thus, the present review definitely will help the researchers to understand the recent developments in the electrolytic purification of wastewater including the mechanism of electrolytic technology and their affecting parameters (reactor geometry, current density, time and electrode type and arrangement) of the wastewater treatment processes to make the electrolytic treatment more feasible in the future.

Conclusions

The present review concluded that different electrolytic reactors were used for the different types of wastewater including different electrode types, current densities and electrolysis time. The results of these studies are varied in terms of removal of physico-chemical pollutants from the wastewater and no single treatment process was found to be effective for the elimination of all the impurities or pollutants of water and wastewater. Therefore, future research should be focused to quantifying the interactions between electrolytic processes and their feasibility in terms of the development of advanced electrode materials, application of different electrodes types, developing the more refined and optimal design for electrolytic reactors, energy consumption and the economy to make the electrolytic technology more effective, low cost and ecofriendly alternative treatment system for the removal of various physico-chemical pollutants of the water and wastewater.

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