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Electrocoagulation Technology in Wastewater Treatment: A Review of Methods and Applications

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Abstract

The purpose of this paper is to review the relevant literature that published from 2010 to 2013 on topics related to electrocoagulation technology within the wastewater. The review describes and discussing issues surrounding electrocoagulation treatment within wastewater, including its concept, the background and various wastewater treatment techniques applications in the industry such as, optimization, modelling, combination composition and ,comparison with other treatment methods.

Keywords: coagulation,electrochemical treatment , electrocoagulation, electrode, wastewater treatment.

1. Introduction

Electrocoagulation (EC) is an electrochemical technique for treating polluted water using electricity instead of expensive chemical reagents. It has been successfully applied for treatment of soluble or colloidal pollutants in various industrial effluents including, effluent issues from food industries, tanneries, mechanical workshop (soluble oil) polymerization manufacture, and wastewater textile industries that containing heavy metals, suspensions solids, emulsified organics and many other contaminants (Erick Butler et al. 2011).

Electrocoagulation has the advantage of removing the smallest colloidal particles compared with traditional flocculation–coagulation,such charged particles have a greater probability of being coagulated and destabilized because of the electric field that sets them in motion. In addition, electrocoagulation-flotation is capable of reducing waste production from wastewater treatment and also reduces the time necessary for treatment (Nazih et al., 2010).

Electrocoagulation has a long history as a water treatment technology having been employed to remove a wide range of pollutants. EC was first proposed in London by Vik et al., in 1889 where a sewage treatment plant built and electrochemical treatment has been used via mixing the domestic wastewater with saline (sea)water (I.Kabdasl et al. 2012).The principle of electrocoagulation was first patented in 1906 by A. E. Dietrich and were used to treat bilge water from ships. In the United States J.T. Harries awarded a patent In 1909 for wastewater treatment by electrolysis using sacrificial aluminium and iron anodes. Thereafter, a wide range of water and wastewater applications followed under a variety of conditions. Coincide with the recent concerns about pollution, industries become under great pressure to find innovative ways to comply with environmental regulations, electrocoagulation has been re-emerged as a viable technology. In this paper, electrocoagulation industrial wastewater process applications were described. A review of the literature published from 2010 to 2013 related to electrocoagulation treatment within wastewater has been presented with special emphasis placed in the several sections. Such as, optimization, modeling, various wastewater treatment techniques, analytical , instrumentation, and comparison with other treatment methods as well as sacrificial electrode materials and electrical energy requirements.

2. Electrocoagulation Process

The (EC) technology includes coagulation and precipitation of contaminants by a direct current electrolytic process followed by the separation of flocculent (settling or flotation) with or without the addition of coagulation-inducing chemicals. The water is pumped through a unit which consists of pairs of metal sheets called electrodes, that are arranged in pairs of two anodes and cathode electrodes made of iron or aluminum are installed. A direct current electric field is applied to the electrodes to induce the electrochemical reactions needed to achieve the coagulation. Treated water is discharged from the system for reuse or disposal. Concentrated contaminants in the form of biosolids are collected for disposal or reclamation. When the cathode electrode

makes contact with the wastewater, the metal is emitted into the apparatus. Coagulation technology induces coagulation and precipitation of contaminants

In an EC process the coagulated ions a produced in "in situ" and it involves three successive stages

1. Information of coagulants by electrolytic oxidation of the sacrificial electrodes.
2. Destabilization of the contaminants, particulates suspension and breaking of emulsions.
3. Aggregation of the destabilized phase to form flocs.

Electrodes which produce coagulants into water are made from either iron or aluminium. Iron and aluminium cations dissolve from the anodes according to Eqs. 1 and 2.

$Fe(s) \rightarrow Fe^{n+}(aq) + ne^{-}$ (1)

$Al(s) \rightarrow Al^{3+}(aq) + 3e^{-}$ (2)

And at cathode according to Eq. 3

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

In solution the positively charged ions are attracted with the negatively charged hydroxides to produce ionic hydroxides that have a strong attraction towards dispersed particles as well as counter ions to cause coagulation (Yadav, 2010).

3. Wastewater Treatment

3.1. Domestic Wastewater Treatment

Several researchers have studied a domestic wastewater Sarala (2012), reported that wastewater usually consists of a number of contaminants, such as TSS,TDS,COD, and colors. a wastewater sample is tested in experimental work, with EC after passing each current(0.12, 0.25 and 0.36) amp for each time period(5, 10, 15 and 20) minutes .The result of the study was shown that the maximum reduction of COD and TDS at 20 minutes for 0.25 amp. While Saleem *et al*. (2011), found that the application of 24.7 mA/cm2 current density with an inter electrode spacing of 5 cm may provide 91.8%, 77.2% and 68.5% removal in turbidity, COD, and TSS within 30 min of EC treatment.

Rodrigo *et al*.(2010), indicated that is a capability of removing ionic phosphorus and COD, when using conductive-diamond electrochemical oxidation and electrocoagulation for persistent organic consumption, specifically regeneration of urban wastewater. The study stated that energy consumption is capable of removing at values lower than 4.5 kWh/m3.

3.2. Industrial Wastewater Treatment

Several literature has been published on wastewater treatment . El-Ashtoukhy *et al.* (2013) and others have examined the removal of phenolic compounds from oil refinery waste effluent using an electrochemical reactor with a fixed bed anode that has been made of randomly oriented Al. raschig rings packed in a perforated plastic basket located above the horizontal cathode. The phenolic compounds removal,was investigated in terms of various parameters in a batch mode namely: pH, operating time, current density, initial phenol concentration, the addition of NaCl, temperature and the effect of phenol structure (effect of functional groups). The chemical oxygen demand (COD) was measured as well . The study revealed that the optimum conditions for the removal of phenolic compounds were achieved at current density = 8.59 mA/cm2, pH = 7, NaCl concentration = 1 g/L and temperature of 25°C. Remarkable removal of 100% of the phenol compound after 2 hrs can be achieved for 3 mg/L phenol concentration of real refinery wastewater. The new anode design of electrocoagulation cell permits high efficiencies with lower energy consumption in comparison with the other cell design used in previous studies.

Gao *et al*. (2013) argued that an effective electrochemical approach for simultaneous silver recovery and cyanide removal from electroplating wastewater was presented. Accordingly, pulse current (PC) electrolysis with parameters including voltage (4.0 V), frequency (800 Hz), and duty cycle (50%) were settled using static cylinder electrodes. Then the influences of technological conditions on the electroplating wastewater treatment process has been widely investigated, which manifested that the concentration of silver ions in electroplating wastewater could be reduced from 221 to 0.4 mg L−1 and cyanide could be simultaneously removed from 157

to4.9 mg L−1 after 3.0 h of PC electrolysis at pH 9.5 ± 0.5, aeration rate of 100 L h−1, and stirring speed of 1000 rpm with NaCl addition of 0.05 mol L−1 at room temperature. The results of XRD and EDX analysis showed that the silver deposits on the cathode were crystalline in face centered cubic structure and had a high purity.

To determine the effects of the treatment experiment by EC Zongo *et al*. (2012) traces that the effluents allowed to eliminate chromium and to lower COD up to 86% abatement. The process designed for the treatment of liquid waste from tannery works at 10.5 m3 hr-1 for current density of 67.5 A.m-2, 62.5 V, 1.2 kWh m-3 energy consumption, and produces 86,000 m3 of clear water with 200 mg L-1COD, 0 turbidity, 91% color abatement, 0 ppm chromium. The treatment produces nearly 480 m3 yr-1 of sludge after compression using filter-press and 216 T of dry matter contain chromium and iron hydroxides, organic and inorganic pollutants. Mansouri *et al*. (2012) highlighted the Electrocoagulation using aluminum electrodes achieved a high removal efficiency of chemical oxygen demand (≥80%) from aqueous solutions containing 0.51 g·L−1 tannic acid. The primary mechanism implicated in eliminating tannic acid from water by electrocoagulation using Al. electrodes involves the adsorption of tannic acid molecules on the aluminium hydroxide surface. The results of the treatment of real wastewater obtained from the pulp and paper industry with an initial chemical oxygen demand (COD) concentration of 1450 mg·L−1 have shown that more than 60% of COD can be removed by electrocoagulation using Al electrodes under optimized experimental conditions. The specific energy required for the electrochemical process with Al electrodes was estimated to range from 1 to 2 kWh·m−3.Ali and Yaakob (2012) preliminary work on on POME samples were collected from Sri Ulu Langat Palm Oil Mill with COD, turbidity and pH around 50,000 mg/L, 2800 NTU and 4 respectively. Water samples were collected from usual tap water in the laboratory, the pH of tap water was 6 to 8.5. The pH of the water was adjusted to pH 4 by using 1N HCl. The production of hydrogen gas from POME during electrocoagulation was also compared with hydrogen gas production from tap water at pH 4 and tap water without pH adjustment under the same conditions to highlight the advantageous aspects hydrogen production and wastewater treatment simultaneously. Produce hydrogen gas while treating POME with EC to reduce COD and turbidity effectiveness is the main advantage of this study. Electrocoagulation was performed at different voltage (2, 3 and 4 volts). A reactor containing volume 20 liters of POME or water was used to conduct EC experiments. The maximum hydrogen gas produced was about 22.68 liters/hour and an efficient reduction of COD and turbidity of POME by as much as 57% and 62% was achieved respectively.

The way in which the chromate removing strain that isolated from spent chrome effluent and identified as Bacillus circulans strain MN1 was studied extensively by Chaturvedi (2011). The isolated strain was carried out for resistance to Cr (VI) and its ability to remove Cr (VI). The strain was found to tolerate Cr (VI) concentration as high as 4500 mg/L, but the cell growth was heavily influenced when initial Cr (VI) con-centration was increased between 1110 mg/L and 4500 mg/L while Cr (VI) at 500 mg/L to 1110 mg/L did not suppress the cell growth. Series experiments in this study demonstrated that the cells removed toxic Cr (VI) more efficiently at 30°C compared with that at 25°C and 35°C. The optimum initial pH for Cr (VI) removal was 5.6 and final pH values of 5.1-5.6 were observed for initial pH 5.2-5.7. A comparative study done by Dermentzis *et a.l* (2011) found that the removal of hexavalent chromium from synthetic aqueous solutions and actual industrial electroplating wastewater by using iron electrodes. The parameters affecting the electrocoagulation process, such as initial pH, applied current density, initial metal ion concentration, COD and time of electroprocessing were investigated. The optimum pH was found to be in the range 4-8. Initial chromium concentrations of 200 – 800 mg L-1 did not influence its removal rate. Higher concentrations were reduced significantly in relatively less time than lower concentrations. Increased current density accelerated the electrocoagulation process, however, on the cost of higher energy consumption. Results revealed that best removal was achieved at a current density 40 mA cm-2. The electrocoagulation process was successfully applied to the treatment of an electroplating wastewater sample. Its Cr (VI) ion concentration and COD were effectively reduced below the admissible limits in 50 minutes of electroprocessing .

According to Merzouk *et al.*(2011) the efficiency of electrocoagulation (EC) for the abatement of COD, TOC, absorbance (I.e.color) and turbidity from a real textile wastewater, a pure red dye solution (disperse dyes 2-naphthoic acid and 2-naphthol) and a solution combining the two above fluids. The treatment of the dyestuff solution is satisfactory with high levels of color and organic pollution abatement. The treatment of the industrial waste is less efficient. Treatment of the solution combining the two above fluids allows to investigate whether the removal of several polluting matters by electrocoagulation could be considered as the superimposition of the various treatments of single-species effluents, in a sort of additivity principle, as presented in an original model for the treatment of two-pollutant waste. Turbidity and TOC were shown to be additive variables in the treatment of the dye solution and the industrial textile waste: electrocoagulation seems to proceed with no interaction

between the two types of matter to be removed, namely the dyestuff, and the lot of pollutants contained in the industrial waste.

Focus of the study by Mars *et al.* (2010) in which the authors argued that by using an electrocoagulator with sacrificial electrodes, where COD (95%), color (99%), and turbidity (99%) can be reduced when testing fluorescent penetrated liquid for non-destructive testing of parts, where the water was reused 4 times. Aoudj *et al.*(2010) draw attention that decolorization can be achieved at 98% under the optimum condition of a pH of 6, 1.875 A/cm2 current density, inter-electrode distance of 1.5 cm, and NaCl electrolyte when removing Direct Red 8 from synthetic wastewater treatment.Merzouk *et al.*(2010) mentioned that 85.5% SS, 76.2% turbidity, 88.9% BOD, 79.7% COD, and 93% color can removed by the combination of electrocoagulation-electroflotation after ensuring optimum conditions for 300 mg/L silica, current density of 11.55 mA/cm2, pH of 7.6, conductivity of 2.1 mS/cm, treatment time of 10 minutes, and electrode gap of 1 cm. The treatment of textile wastewater having studied the above optimum parameters.

3.3. Heavy Metals

The central focus of a study by Al Aji *et al.* (2012) in which the authors found that the removal of copper (Cu), nickel (Ni), zinc (Zn) and manganese (Mn) from a model wastewater. The influences of current density (from 2 to 25 mA/cm2), initial metal concentration (from 50 to 250 mg/L) and initial pH (3, 5.68, 8.95) on removal efficiency were explored in a batch stirred cell to determine the best experimental conditions.The results indicated that EC was efficient to remove heavy metals from the model wastewater having an initial concentration of 250 mg/L for each metal under the best experimental conditions. According to initial pH results, high pH values are more suitable for metal removal with EC treatment. At the current density of 25 mA/cm2 with a total energy consumption of 49 kWh/m3, more than 96% removal value was achieved for all studied metals except Mn which was 72.6%. Martins *et al.* (2012) stated that the removal of metal ions from synthetic aqueous effluents using a spouted bed electrochemical reactor whose cathode was composed of 1.0mm copper particles. Using a Box–Behnken factorial design, the effects of current (I), electrode thickness (L), draught distance (d) and support electrolyte concentration (Cs*)* on current efficiency (CE), space-time yield (Y) and energy consumption (EC) were analyzed. The results were statistically analysed and the effect of each variable was evaluated using the surface response methodology. The results showed that Cs is the most important variable to consider in the optimization process. A current of 8.0A can be applied in order to obtain high Y and CE with an acceptable EC. Electrode thicknesses greater than 1.3 cm are not recommended because the irregular potential distribution leads to a Y drop owing to the low CE observed for this condition. The draught distance does not have statistical significance; therefore, the particle circulation rate is not important in this kind of electrochemical reactor.

Zhao *et al.* (2010) reported a new and convenient synthetic procedure to obtain the effects of Ca^{2+} andMg^{2+}. The mechanisms and behavior of ECdefluoridation in Ca^{2+}containing systems were different from those in Mg^{2+}containing systems. An increase in Ca^{2+}concentration improved the defluoridation efficiency (ε_F), but it could not change the optimal molar ratio of OH- and $F^-$to Al^{3+} (r_{OH+F}). The highest ε_F can usually be obtained at (r_{OH+F}) = 3 for defluoridation. Only a small portion of Ca^{2+} entered into the flocs, and Ca^{2+} could not influence the mechanism of EC defluoridation. For the Mg^{2+} containing system, the optimal (r_{OH+F}) increased with increasing Mg^{2+}concentration. The optimal (r_{OH+F}) was maintained at 3 after theMg^{2+}concentration was corrected using the obtained correction coefficient of 0.3435. About 50% to 70% of the total Mg^{2+}entered into the flocs. From the XRD analysis, it was found that some Mg-Al-F layered double hydroxides (LDHs) were formed by Mg^{2+}, F^-, and Al^{3+} during electrolysis. It is proposed for the first time that the formation of Mg-Al-F LDH is one of the mechanisms for EC defluoridation in systems containing both F^- and Mg^{2+}. A small-scale study by Petsriprasit *et al.* (2010) reaches different conclusions, finding that Cu, Cr, Pb, and Zn from billet industry wastewater was capable of being removed by 99%, where it was found that density current is 98 A/m2, pH of 5, and 30 minutes electrolysis time. It was noticed that within 120 minutes, pH of 3, and flow rate of 55 mL/min could obtain similar values.

In another major study Shafaei *et al.*(2010) found that electrocoagulation was capable of removing Mn^{2+} ions with aluminum electrodes under an optimum pH of 7.0. Factors. The authors concluded that the density and electrolysis time, along with initial concentration were capable of determining successful removal rates .

3.4. Organic and Inorganic Pollutants

A recent study by Kitazono *et al.* (2012) have attempted to dispose of a large volume of waste milk with antibiotic residues, which is a great cause of much concern in soil and water environments in the dairy industry. In this study, the electrochemical oxidation of tetracycline antibiotics (TCs) in cow's milk was investigated. Milk contains a high concentration of organic matter, and the concentrations of TCs residues are extremely low. The effects of electrolytes and anode materials on the degradation of oxytetracycline (OTC) were investigated. A higher degradation rate for the OTC was attained using the inactive anode or a NaCl electrolyte. It was found that a physically adsorbed oxidant on the surface of the anode and indirect oxidation using electrogenerated hypochlorite could enhance the degradation of OTC in raw milk. The organic components in milk samples affected the removal rate of the OTC. The removal rate constants for the OTC in raw milk were 2.8-7.7 times higher than the chemical oxygen demand values. It was found that electrochemical oxidation could decompose low concentrations of TCs in high concentrations of organic matter solutions selectively. The results indicate that electrochemical oxidation is an effective method for the treatment of TCs in waste milk.

Studies of the animal husbandry, antibiotics have been done to treat and prevent diseases or to promote growth (Miyata *et al.* 2011). The use of antibiotics for domestic animals enables to promote safety of livestock products and enhance productivity. Tetracycline antibiotics (TCs) are one of the primarily used groups of antibiotics for cattle and swine. However, the unintentional spreading of antibiotics from animal waste to the environment may leave out drug residues, promoting resistant strains of bacteria, and will adversely affect the ecosystem and human health. This study, investigated the electrochemical oxidation of TCs to treat livestock wastewater. The concentrations of TCs in aqueous solutions were reduced from 100 mg/L to less than 0.6 mg/L by 6 h of electrochemical treatment using a Ti/IrO2 anode with Na2SO4 electrolyte. The concentration of Oxytetracycline (OTC) in livestock wastewater was also reduced from 100 mg/L to less than 0.7 mg/L by the same treatment. Thus, the electrochemical oxidation using a Ti/IrO2 anode with Na2SO4 electrolyte was found to be effective for degradation of TCs. The results suggest that the electrochemical oxidation method is a promising treatment for TCs in livestock wastewater.

Bear *et al.* (2011) has studied the effect of current density and stirring speed in the treatment of poultry slaughterhouse wastewater (PSW) using electrocoagulation with aluminium electrodes. In the experiments, initial pH and current density were chosen between 3 and 7, and 0.5 and 2.0 mA/cm2 respectively. The best removal efficiency has been obtained, when initial pH and current density were adjusted to 3.0 and 1.0 mA/cm2, respectively. Increasing current density values decreased COD removal efficiency. The highest removal efficiencies of 85, 85, 81 and 71% were obtained with the current density of 0.5, 1.0, 1.5 and 2.0 mA/cm2, respectively. Initial pH values of these removal efficiencies were 4.0, 3.0, 3.0 and 5.0. When experiments were performed to investigate the turbidity removal efficiency, it was found that current density of 1.0 mA/cm2 provided 98% removal efficiency. Results obtained from the experiments where a stirring speed of 100, 150 and 250 RPM were used, showed the removal efficiency of 85, 90 and 75% respectively with the current density of 1.0 mA/cm2. Results showed that electrocoagulation is a suitable method for treatment of PSW. Electrical conductivity of investigating wastewater was nearly 2860 μS/cm, which caused energy consumption to be relatively lower.

Yuan *et al.* (2010) argued that photocatalytic oxidation mediated by TiO2 is a promisingoxidation process for degradation of organic pollutants, but suffers from the decreased photocatalytic efficiency attributed to the recombination of photogenerated electrons and holes. Thus, a cost-effective supply of external electrons is an effective way to elevate the photocatalytic efficiency. The study reported a novel bioelectrochemical system to effectively reduce *p*-nitrophenol as a model organism pollutant with utilization of the energy derived from a microbial fuel cell. Kinetic analysis shows that the system exhibits a more rapid *p*-nitrophenol degraded at a rate two times the sum of the rates by the individual photocatalytic and electrochemical methods. The system performance is influenced by both external resistors and electrolyte concentration. Either a lower external resistor or a lower electrolyte concentration result in a higher *p*-nitrophenol degradation rate. This system has a potential for the effective degradation of refractory organic pollutants and provides a new way for utilization of the energy generated from conversion of organic wastes by microbial fuel cells.

3.5 Dye Removal

Un and Aytac (2013) focused on removal of color from real textile wastewater using a packed bed electrochemical reactor in a unique design. The cylindrical iron reactor has been used as a cathode while the packed bed formed from wrapping iron wire netting was used as an anode. Various operating parameters, such as current density, initial pH, wastewater recirculation flow rate and continuous flow regime, were examined for intensifying the performance of the process. The initial COD concentration of 1953 mg/L was reduced to 61 mg/L with a removal efficiency of 96.88%, while the color of the wastewater was almost completely removed. The results of the experimental work , throughout the present study, have indicated that electrocoagulation of textile wastewater using a uniquely designed reactor was very effective and direct discharge able effluent, complying with legal requirements, was obtained. Pajootan *et al.* (2012) published a paper in which they described that the binary system dye removal by electrocoagulation (EC) process using aluminium electrode in a batch electrochemical reactor. Acid Black 52 and Acid Yellow 220 were used as model dyes. However , the wool dyeing process has been performed and the dye removal from real colored wastewater from the electrocoagulation process has been studied. It was found that the increasing of the current density up to 40 A/m2 had increased the dye removal efficiency and the optimum pH for EC process was 5. The increasing of electrolyte concentration from 0 to 8 g/L had a negligible effect on the color removal but it has decreased the electrical energy consumption. Zheng *et al.* (2012) examined the treatment of dye synthetic wastewater containing Rhodamine 6G by electrochemical technology using RuO2-coated the mesh as anode was investigated. It has been demonstrated that the effects of solution pH, temperature, and dye auxiliaries on the performance were investigated. Carbon and nitrogen mass balance analyses, UV- vis spectroscopy, Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), and cyclic Voltammetry (CV) were used to elucidate the working mechanism. It was found that lower solution pH and lower temperature facilitated the declaration of the wastewater. The addition of dye auxiliaries did not significantly affect the decoloration. Under optimal conditions, complete declaration of the synthetic wastewater was obtained within 5 min, and 42.3% of the dye was mineralized. The insoluble substances were floated by the hydrogen bubbles that were generated from the cathode to produce foam products.

The study done by Valero *et al.* (2010) conclusively shown that the feasibility and utility of using an electrooxidation system directly powered by a photovoltaic array for the treatment of a wastewater. The experimental system used was an industrial electrochemical filter press reactor and a 40-module PV array. The influence on the degradation of a dye-containing solution (Remazol RB 133) of different experimental parameters such as the PVarrayandelectrochemical reactor configurations has been studied. It has been demonstrated that the electrical configuration of the PV array has a strong influence on the optimal use of the electric energy generated. The optimum PV array configuration changes with the intensity of the solar irradiation, the conductivity of the solution, and the concentration of pollutant in the wastewater. The results obtained from the preliminary analysis by Phalakorkule *et al.* (2010) for treating Reactive Blue 140 reactive dye and disperse dye II. Results indicated that color was reduced by 95% with an energy consumption of 1 kWh/m3 and a dye concentration of 100 mg/L during synthetic treatment. Mollah *et al. (*2010) removed 94.5% of orange II dye from 10 ppm at density of 160 A/m2, pH of 6.5, conductance of 7.1 mS/cm, flow rate of 350 mL/min, and NaCl concentration of 4.0 g/L. Hanafi *et al.* (2010)compiled a study on olive mill wastewater treatment considering modifying COD, polyphenols, dark color removal, and pH. Through an optimum time of 15 minutes, 2 mg/L of Cl2 concentration, pH of 4.2, and a density of 250 A/m2 , polyphenols were reduced by 70%, electrode composition is 0.085kg Al/kg CODremoved, and energy consumption 2.63 kWh/kg COD removed.

4. Optimization

Several studies have investigated the optimization of the electrochemical wastewater Velazquez-Pena *et al.* (2012) examined the optimization of the electrochemical reduction of hexavalent chromium in electroplating wastewater. pH, electrolyte composition and concentration, and cathode metal were varied and the effect on reduction rate measured. Because the reaction at pH 2 was faster than that at pH 4, acidity is favored. Higher electrolyte concentrations produced faster rates. Copper cathodes were faster than iron ones. Using the optimized conditions of pH 2 and a copper cathode, along with the high electrolyte concentration already present, actual electroplating wastewater was treated. The rate of Cr (VI) reduction was measured as a function of treatment time and was found to be even higher than that of the synthetic solutions. The 180 mg/L of Cr (VI) in the wastewater was completely reduced in about 15 min under optimal conditions.

Parsa *et al.* (2011) investigated the differential impact of removal of Acid Brown 14 (AB14) by a bench scale (BS) and pilot scale (PS). In order to find the best condition of the process, the influence of various parameters such as anode materials, pH, supporting electrolyte, current density and stirring speed were investigated. Energy consumption and optimum conditions were found. The effect of anode surface covering and its position. At the optimum conditions of the BS reactor after 18 min, 91% and 87% of the dye and the COD content of the solution have been removed, respectively. Ultimately the EC process using a pilot scale (PS) reactor was performed. By this apparatus after about 200 min, 80% and 64% of the dye and COD content were removed, respectively.
Tchamango et *al.* (2010) studied the effects of use electrocoagulation for artificial wastewater with milk powder to simulate dairy effluents, COD was reduced by 61%, phosphours by 89%, nitrogen 81%, and 100% turbidity. In addition with low conductivity and neutral pH, treated water would be possible reused, as reagent required was lowered for the aluminum anode for treatment.Zodi *et al.* (2010) derived a statistic analysis using a Box-Behkey design for surface response analysis using electrochemical sedimentation. Having considered current density, pH, and electrolysis design, the authors were capable of studying the effects of COD, turbidity, TS removal, and sludge settling with aluminum electrodes.

5. Modelling

Li *et al.* (2012) proposed a new model that provides insights into why higher pH and lower charge dosage rate (Coulombs/L/min) facilitate As(III) removal by EC and sheds light on the debate in the recent published literature regarding the mechanism of As(III) oxidation during EC. This model also provides practically useful estimates of the minimum amount of iron required to remove 500 μg/L As(III) to <50 μg/L. Parameters measured in this work include the ratio of rate constants for Fe(II) and As(III) reactions with Fe(IV) in synthetic groundwater (k1/k2 = 1.07) and the apparent rate constant of Fe(II) oxidation with dissolved oxygen at pH 7 (kapp = 100.22 $M^{-1}s^{-1}$). Pharmaceutical wastewater has been studied by Abhijit *et al.* (2012) the adsorption capacity of electroflocs using the freundlich isotherm (R^2= 0.8) and the kinetics of adsorption by (Lagergren model) first order(R^2= 0.88) and second-order (R^2= 0.83) kinetic models. For the EO process, the effect of current density (CD) in a range from 40 to 120 A/m^2 and initial pH from 3 to 11 on the treatment efficiency was studied. Under identical operating conditions (CD = 80 A/m^2; pH= 7.2), EC resulted in 24% after 25 min, whereas the EO yielded 35.6% chemical oxygen demand (COD) removal after 90 min of treatment. Response surface methodology (RSM) was found to be an effective optimization tool, which shows the optimum pH/CD/electrolysis time to be 6.56 /76.06 A/m^{-2}/ 86.89 min for achieving 30.89% COD removal by the EO process. Antony and Natesan(2012) proposed the modelling methodology for integrating processes involving electrochemical and biological methods . Optimal combinations of operating variables giving a definite completion of pollutant removal are derived from the empirical models of each process. However, both the electrochemical steps as electrocoagulation and electro-oxidation were observed to perform technically better, and the former was noticeably more attractive based on the overall operating cost. electrocoagulation−biological (EC-Bio) treatment giving 80% COD removal. A 41% reduction in the treatment cost was achieved when the conventional chemical coagulationbiological (CC-Bio) methodology replaced by an EC-Bio system.
Gadd *et al. (*2010) concluded that treatment efficiency was related to the electrode area, along with coagulant and bubbles, functions of electrode area, current density, and efficiency. This operation was completed using a vertical plate electrocoagulation treating molasses process wastewater. Rodrigo *et al.* (2010) developed a model for wastewater pollution considering hydrodynamic conditions using a chemical reaction of reagents and pollutants, where a multivariable modeling of anodes was described. The model combined a macroscopic/maximum gradient approach for all processes with pseudo equilibrium. Zarei *et al. (*2010) considered the treatment of the four dyes within an aqueous solution.I. Basic Blue 3, Malachite green, C.I. Basic red 46, and C.I. Basic Yellow 2 at pH 3 using a carbon nanotube polytetrafluoroethleyene (CNT-PTFE) as the cathode. From the experiment, 90% decolorization was determined within 10 minutes through modeling using the artificial neural network model. From the model, an r2 value of 0.989 was produced for decolorization. Also, TOC for C.I. Basic Yellow was removed at 92% and mixed dyes at 93% within 6 hours. Compared with the real wastewater, 95% removal of Basic Yellow 2 and mixed dyes had a 90% removed within 40 minutes.

6. Combined with Other Treatment

Petrella *et al.* (2013) carried out a number of investigations using laboratory scale unit to perform UV photoinduced catalytic degradation of methyl range.The unit was first characterized from both the hydrodynamics and the hydraulic points of view. Photodegradation kinetics were followed by UV-vis absorption

measurements of the residual methyl orange solution concentration along time, and the synergic effect of the catalyst and the intensity of the UV radiation in promoting degradation of the substrate was demonstrated. The abatement efficiency of the UV/TiO_2 system toward methyl orange was evaluated in the concentration range 0.3−8.5 mg/L. Kinetic patterns were described by first (or pseudofirst) order theoretical models up to the concentration of 0.7 mg/L, whereas at higher concentrations kinetic trends were better described by zero-order models independently of the substrate concentration in the liquid-phase. The performance of Ti/Pt-IrO(2), Ti/SnO(2)-Sb and Si/BDD anodes were evaluated for the electrochemical oxidation of ROC in the presence of chloride, nitrate or sulfate ions (0.05 M sodium salts) was conducted in serial trials by Bagastyo *et al.* (2013. In order to investigate the electro oxidation of ROC with nitrate and sulfate ions as dominant ion mediators, chloride ion concentration was decreased 10 times by electrodialytic pre-treatment. The highest Coulombic efficiency for chemical oxygen demand (COD) removal was observed in the presence of high chloride ions concentration for all anodes tested (8.3-15.9%). Electrooxidation of the electro dialysed concentrate at Ti/SnO(2)-Sb and Ti/Pt-IrO(2) electrodes exhibited low dissolved organic carbon (DOC) (i.e. 23 and 12%, respectively) and COD removal (i.e. 37-43 and 6-22%, respectively), indicating that for these electrodes chlorine-mediated oxidation was the main oxidation mechanism, particularly in the latter case.

Daghrir *et al.* (2012) evaluated the EC-EO process in terms of itscapability to simultaneously produce an oxidant and coagulant agents by using either iron or aluminum electrodes arranged in a bipolar configuration or graphite electrodes arranged in a monopolar configuration in the same electrolytic cell. Relatively high concentrations of active chlorine (9.6 mg/ min) and aluminum (20–40 mg Al／L) or iron (40–60 mg Fe／L) were produced in situ. The best performance for RWWtreatment was obtained by using aluminum and graphite plates alternated in the electrode pack and operated at current of 0.4 A during 90 min of treatment with pH adjusted to approximately 7.0. Under these conditions, more than 98% of oil and greases (O&G) were removed, whereas chemical oxygen demand (COD) and biological oxygen demand (BOD) removal reached 90% and 86%, respectively. Likewise, more than 88% of soluble phosphate was removed, and the process was effective in removing turbidity (98%) and suspended solids (98%). Barrera-Díaz *et al.* (2012) Combine the electrochemical and ozonation processes resulted in a synergythat enhanced the removal of all three contaminants (COD, colour, and turbidity). A COD removal of 79% (170 mg/L) was attained after only 12.5 min and at relatively low current density. Thus, the combination of the electrochemical and ozonation processes is able to noticeably improve wastewater quality. Bagastyo *et al.* (2012)evaluated the electrochemical oxidation of reverse osmosis concentrate (ROC) was evaluated at controlled pH 6-7 and at pH 1-2 (no pH adjustment). A high concentration of chloride ions in the ROC enhanced the oxidation, and 7-11% of Coulombic efficiency for chemical oxygen demand (COD) removal was achieved with 5.2 Ah L(-1) of specific electrical charge. Complete COD removal was observed after 5.2 and 6.6 Ah L(-1), yet the corresponding dissolved organic carbon (DOC) removal was only 48% (at acidic pH) and 59% (at circumneutral pH).

Bagastyo *et al.* (2011) In this study, electrochemical oxidation was investigated for the treatment of ROC generated during the reclamation of municipal wastewater effluent. Using laboratory-scale two-compartment electrochemical systems, five electrode materials (i.e. titanium coated with IrO2-Ta2O5, RuO2-IrO2, Pt-IrO2, PbO2, and SnO2-Sb) were tested as anodes in batch mode experiments, using ROC from an advanced water treatment plant. The best oxidation performance was observed for Ti/Pt-IrO2 anodes, followed by the Ti/SnO2-Sb and Ti/PbO2 anodes. The effectiveness of the treatment appears to correlate with the formation of oxidants such as active chlorine (i.e. Cl2/HClO/ClO-).

Desphande *et al. (*2010) concluded that using a combined electrocoagulation and anaerobic fixed film reactor, COD, BOD, and color could be removed at 24%, 35%, and 70%, respectively, with conditions of pH at 7.2, current density of 80 A/m2, and electrolysis time of 25 minutes for mere electrocoagulation. However, when combined with the anaerobic fixed film reaction, removals increased to 80–90% COD, 86–94% BOD, at 0.6 to 4.0 kg COD/m3s organic loading rate. Phalakornukule *et al.* (2010*)*concluded that treatment of Reactive Blue 140 and Direct Red 23 required electrical energy of 1.42 and 0.69 kWh/m3, respectively, with color (99%), COD (93%), and TS (89%) removal, when using a continuous electrocoagulation. In addition, the authors were able to harvest hydrogen. Moises *et al.* (2010) conducted study to remove color (94%), turbidity (92%), COD (80%) for industrial wastewater at a flow rate of 50 mL/min. Chou *et al.* (2010) used electrocoagulation for removal of COD in oxide CMP wastewater, where it was determined that COD could be reduced by 90%. Also, the authors determined that this process followed pseudo-second order under the Freundlich adsorption isotherm model at various densities and temperatures. Lakshmanan *et al.* (2010) concluded that arsenic was removed by 98% when using NaCl, and was removed by 75% when using sodium sulfate and nitrate during a 5 minute appearance and an initial concentration of wastewater of 10 mg/L within the electrocoagulator. Adsorption was affected by several factors, including magnetic, particle size, and surface properties of the precipitate; solid waste from the

treatment was non-hazardous. Chang *et al.*(2010)combined electrocoagulation-activated carbon adsorption-microwave generation.

Through electrocoagulation, 39% COD removal occurred with a pH of 8, electrolysis time of 8 minutes, and a density of 277 A/m2, and a NaCl contact of 1 g/L. The study produced favorable results with 100 g/L GAC that removed 82% of Reactive Black 5 (RB5) and with 20 g/L GAC that removed the remaining 61% of COD.

7. Comparison

Verma *et al.* (2013) obtained 100% chromium removal efficiency for both trivalent and hexavalent chromium,for an electrolysis time of 45 min at 4 pH. It was found that Cr(VI) is initially reduced to Cr(III) in the acidic medium. An increase in the pH of the effluent was also noticed in the acidic medium due to the generation of hydroxyl ions. Experiments were performed for the removal of chromium using ferric chloride as the coagulant, and it was found that electrocoagulation is more efficient and relatively faster compared to chemical coagulation.
Chafi's *et al.* (2011) comparative study found that the chemical coagulation (CC) using the same amount of metal cations as in EC. Experimental results showed that EC maximized decolorization (up to 98%) in comparison to CC (limited to 53%). For EC, iron electrodes exhibited the highest decolorization yield and minimized simultaneously energy requirements, the amount of floc and operation costs in comparison to aluminium. As voltage vs. current curves did not differ significantly between Al and Fe, higher current was required with Al electrodes to achieve a similar decolorization yield. This was partly explained by differences in the decolorization mechanism, as Al electrodes seemed to promote the electroreduction of the azo bond of Orange II, contrary to Fe electrodes.Merzouk *et al.* (2011) compared the effectiveness of chemical coagulation (CC) with electrocoagulation (EC) with aluminium electrodes forthe decolourization purposee of a synthetic textile wastewater containing a disperse red dye. For CC, ferric chloride $FeCl_3$ and aluminium sulphate $Al_2(SO4)_3$ as the coagulant were compared: the respective effects of initial pH, coagulant dosage, initial dye concentration, ionic strength and mixing conditions were investigated in order to maximize decolourization yield. The comparison between CC and EC is based on recently published data on EC by the same authors. Experimental results showed first that $Al_2(SO4)_3$ was far more effective than $FeCl_3$ for color removal using CC, regardless of operating conditions. A removal yield higher than 90% could be achieved with a 40 mg/L dose of $Al_2(SO4)0_318H_2O$ in a large range of pH from 4 to 8 and for a dye concentration up to 235 mg/L. The removal yield could however be enhanced up to 95% using EC for pH values between 6 and 9 at the expense of higher operating costs. Nevertheless, EC presented the additional advantages to be more robust against pH change and to reduce simultaneously equipment costs in comparison to CC.

8. Equipment and Energy Requirements

Wang *et al.* (2010) concluded that by using DC electrocoagulation, in a treatment time of 25 minutes, decolorization and COD removal was 75.45% and 84.62%, respectively. The authors discovered a relationship between an increase of pH and alkalinity with increase in temperature, and electrolysis time, while the voltage was related to the current. Sasson and Adin (2010) concluded that using electroflotation with a current of 0.4 A, followed by slow-mixing, and filtration to treat pure water with silica-chemical mechanical polishing was able to reduce energy requirements for filtration by 90%. Also, pH must remain above 7 since the permeate change colors due to iron residuals (Fe^{2+} to Fe^{3+}). Sasson and Adin (2010)considered silica-CMP suspensions were pretreated by electrocoagulation at an electric current of 0.4 A, slow mixing, and filtration. Filtration energy was reduced by 90% whenever the pH was between 6 and 6.5, having noticed foul mitigation was on intensity and mechanisms, suspension pH and electroflocculation time. Terrazes *et al.* (2010) determined turbidity removal was 92% with an energy consumption of 0.68 kWh/m3 by using micro-electrolysis and macro-electrolysis electrocoagulation for tissue paper wastewater treatment.

9.Economical Considerations

Operating cost calculations have been made in a few articles. Calculations typicallyinclude the cost of chemicals, electrodes and energy. It should be noted that theprice of materials and energy changes over the course of time and therefore,operating costs are only rough estimates. Cost calculations do not typically includeinvestment costs, which may be significant including, for example power supplies,electrochemical cell vessels and sludge separation systems. Dalvand *et al.* (2011) investigated the operational cost at optimum condition. Electrode

consumption, energy consumption and operating cost were 0.052 kg /m^3, 1.303 kwh /$m^3$and 0.256 US$ /m^3, respectively.Sridhar *et al.* (2011) carried out an economic analysis of the operating cost of EC treatment of pulp and paperindustry bleaching effluents. Operating costs varied from USD 1.52 per m3 to 1.72per m3.
Kobya *et al.(*2010*)*found that the treatment of cadmium and nickel from electroplating rinse water could be achieved at 99.4% for cadmium, 99.1% for nickel, and 99.7% for cyanide. The cost for treatment was $1.05/m3 for cadmium and $2.45/m3 for nickel and cyanide provided that the treatment maintained optimum conditions.Orori *et al.* (2010)took sample a five locations from a Kraft pulp and paper mill effluent primary settling tank, two aerated lagoons, a stabilization, and at the discharge comparing treatment efficiency using graphite electrodes and aluminium electrode with wood ash. Overall treatment with aluminium electrodes was better (60% BOD and 58.8% COD), but was more expensive than graphite ($0.0006 to 0.0008 USD/m3 of wastewater) *versus* ($8.34 to $31.74 USD/m3 of wastewater). Kobya *et al.* (2010)also studied Remazol Red 3B decolorization using iron electrodes and found that 99% decolorization was possible under optimum conditions. The authors found that energy consumption could achieve 3.3 kWh/kg dye at a cost of 0.6 euro/m3. Meas *et al.(*2010)concluded that aluminium electrodes are capable of treating fluorescent penetrant liquid for non-destructing testing part of aircraft industry. Having used electrocoagulation, the treatment present found 95% of chemical oxygen demand (COD), 99% colour, and 99% turbidity. With this high level of treatment, the cost were able to have a return of 17 weeks.

10. Conclusion

This paper has given a review of the successfully electrocoagulation application, for the removal of specific problematic factors (such as color, recalcitrance and toxicity) that cannot be removed effectively via conventional treatment methods. However, this paper has argued that the full potential of the EC technique as a wastewater treatment alternative is yet to be fully realized. However , a number of possible future studies using the same experimental setup are apparent. For optimal performance and future progress in the application of this innovative technology considerably more work will need to be done in better reactor design, understanding and process control has to be provided. This technology will continue to make inroads into the wastewater treatment arena because of the numerous advantages and the nature of the changing strategic wastewater needs in the world.

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