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Review

Electrocoagulation for the treatment of textile industry effluent – A review



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ABSTRACT

Various techniques such as physical, chemical, biological, advanced oxidation and electrochemical are used for the treatment of industrial effluent. The commonly used conventional biological treatment processes are time consuming, need large operational area and are not effective for effluent containing toxic elements. Advanced oxidation techniques result in high treatment cost and are generally used to obtain high purity grade water. The chemical coagulation technique is slow and generates large amount of sludge. Electrocoagulation has recently attracted attention as a potential technique for treating industrial effluent due to its versatility and environmental compatibility. This technique uses direct current source between metal electrodes immersed in the effluent, which causes the dissolution of electrode plates into the effluent. The metal ions, at an appropriate pH, can form wide range of coagulated species and metal hydroxides that destabilize and aggregate particles or precipitate and adsorb the dissolved contaminants. Therefore, the objective of the present manuscript is to review the potential of electrocoagulation for the treatment of industrial effluents, mainly removal of dyes from textile effluent.

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1. Introduction

The textile industry wastewater varies extensively in terms of composition due to the regular impurity in fibers and the chemicals used in different processes. Various types of dyes are produced worldwide and are used in various industries, such as textile, cosmetic, paper, leather, pharmaceutical and food industry. The dyes can be classified as acid, basic, direct, azoic colors, vat, sulphur, reactive and metal complex dyes. There are more than 100,000 commercially available dyes with an estimated annual production of over 7×10^5 tons (Robinson et al., 2001). 10–50% of these dyes are lost in the effluent. In India, there are about 950–1000 number of textile units out of which 50 are in the organized sector while rest are the small scale units. The major pollutants in textile wastewater are especially the organic and inorganic chemicals such as finishing agents, surfactants, inhibitor compounds, active substances, chlorine compounds, salts, dyeing substances, total

phosphate, dissolved solids, suspended solids and total solids. Coloring matter is the major contaminant in the textile effluent and has to be removed before discharging the effluent into the aqueous ecosystem. Without proper treatment, the colored effluent creates an aesthetic problem and its color discourages the downstream use of wastewater. Aesthetic merit, gas solubility and water transparency are affected by the presence of dyes even in small amount or concentrations. The removal of colored material from wastewater has been rated to be relatively more important than the removal of soluble colorless organic substances, which usually contribute the major fraction of biochemical oxygen demand.

Textile industry involves wide range of machineries and processes to produce the required shape and properties of the product. Huge amount of effluent is generated in the various processes such as sizing, scouring, bleaching, mercerizing, dyeing, printing and finishing. This effluent contains mainly byproducts, residual dye, salts, acid/alkali, auxiliary chemicals and cleaning solvents. Salts such as sodium chloride and sodium sulphate are used to assist in exhaustion of anionic dyes and find their way into the effluent as byproducts of neutralization or other reactions in textile wet processing. Typically, for a textile unit processing 400,000 pounds per week of cotton, more than 50,000 pounds of salts are released. The usual salt concentration in effluent is 2000–3000 ppm (Koltuniewicz and Drioli, 2008). The salts in the effluent can lead to the soil infertility and aquatic life damage. The characteristics of the

Abbreviation: AC, alternating current (amp); BOD, biochemical oxygen demand (mg/L); COD, chemical oxygen demand (mg/L); DC, direct current (amp); F, Faraday's constant (96,500 C/mol); ppm, parts per million; SS, suspended solids (mg/L); TDS, total dissolved solids (mg/L); TFS, total fixed solids (mg/L); TOC, total organic carbon (mg/L); TSS, total suspended solids (mg/L); TVS, total volatile solids (mg/L).

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Nomenclature			
<i>a</i>	cost of electricity/kWh	<i>M</i>	relative molar mass of the electrode (g/mol)
<i>b</i>	cost of electrode/kg electrode	MP-P	monopolar electrodes in parallel connections
BP-S	bipolar electrodes in serial connections	MP-S	monopolar electrodes in serial connections
<i>c</i>	cost of chemical/kg of chemical	MS	mild steel
CHC	chemical consumption (kg of chemical/m ³ of effluent)	<i>n</i>	number of electrons in oxidation/reduction reaction
CWAO	catalytic wet air oxidation	SS	stainless steel
EC	electrocoagulation	St	steel
ELC	electrode consumption (kg of electrode/m ³ of effluent)	<i>t</i>	electrolysis time (h)
ENC	energy consumption (kWh/m ³ of effluent)	<i>U</i>	applied voltage (V)
<i>I</i>	applied current (A)	<i>V</i>	volume of treated effluent (m ³)
		WAO	wet air oxidation

effluent generated from different types of the textile industry along with the effluent discharge standards prescribed by the statutory authorities are tabulated in supplemental Table 1. It can be noticed that the textile industry effluent is highly polluted.

A large quantity of the dye is lost during dyeing and finishing processes and is released into wastewater. Accordingly, dye effluent may contain chemicals that are toxic, carcinogenic, mutagenic, or teratogenic to various fish species. Reactive dyes, which have good water solubility and are easily hydrolysed into insoluble forms, are extensively used in dyeing processes, and about 20–40% of these dyes remain in the effluent. During dyeing, dyes are not completely exhausted from dye liquor. The effectiveness of different decoloration techniques for removal of various dyes depends on chromophore as well as auxochromes of the dye. The unsaturated part of the molecule is called the chromophore, which ultimately is responsible for the color. In textile dyes, the chromophore usually consists of aromatic rings (anthraquinone and triphenylmethane) or azo groups (azo benzene). Subsequent groups are known as auxochromes, which shift the wavelengths of the light absorbed into the visible region. Typical auxochromes such as CO, OH and NH₂ tend to absorb light in the blue and violet region and so reflect light in the yellow, orange or red region. The dye is, therefore, colored yellow, orange or red depending on which auxochromes are present. Both anthraquinone and triphenylmethane absorb in the yellow/red region and so appear blue. The color seen is not of absorbed light but of reflected light.

Removal of dyes from wastewater is a major environmental concern as it can lead to severe contamination of surface and ground waters in the vicinity of dyeing industries. Various studies have been reported in the literature (Can et al., 2003, 2006) on color removal techniques which can be classified into physical or physicochemical, chemical, biological and electrochemical. The mechanisms of color removal are physical dye separation, breakdown of the dyes and de-colorization by adsorption/biodegradation. The physical or physicochemical techniques include coagulation/flocculation, adsorption, macrosorb and membrane separation. In

coagulation, the electrostatic attraction between oppositely charged soluble dye and polymer molecule coagulates the effluent. The coagulant dose depends on the type of effluent, concentration of dye and other processing aids used. However, coagulation results in generation of large amounts of sludge and total dissolved solids in the effluent are further increased. Coagulation is effective for sulphur and dispersive dyes. Acid, direct, vat and reactive dyes coagulate but do not settle while the cationic dyes do not coagulate. Adsorption is an effective method for lowering the concentration of dissolved organics in the effluent. But the adsorbent regeneration is expensive and involves the loss of adsorbent. In membrane filtration, the appropriate membrane is capable of removing all types of dyes. The space requirements are less and there is no generation of sludge. There is a reduction in the fresh water usage as the water can be completely recycled and reused. But the high cost of membranes and equipment, the lowered productivity with time due to fouling of the membrane and the disposal of concentrates are the limitations. Many dyes are effectively decolorized using chemical oxidizing agents and seem to hold potential for future use in the textile industry. But it leads to the generation of absorbable organohalides which are toxic in nature.

The biological treatments include anaerobic process, oxidation ponding, trickling filters, activated sludge process, etc. Microbial biomass is also commonly used for the treatment of industrial effluents. The microorganisms such as algae, fungi, bacteria, and yeasts are capable to degrade certain type of dyes. However, their application is limited as biological treatment requires a large land area, has sensitivity toward toxicity of certain chemicals and treatment time is very high. Further, some dyes are generally toxic and are not easily biodegraded by biological process (Hao et al., 2000).

Advanced oxidation processes (AOPs) include wet air oxidation, catalytic wet air oxidation and treatment with oxidizing agents, such as hydrogen peroxide, ozone, UV light or their combinations. Wet air oxidation (WAO) or thermal liquid phase oxidation is useful for treatment of effluents containing high

Table 1
Characteristics of wastewater from textile chemical processing.

Characteristics	Scouring	Bleaching	Mercerising	Dyeing	Composite	Discharge limit into inland water (Bureau of Indian Standards)
pH	10–12	8.5–11	8–10	9–11	8–10	5.6–9.0
TDS (mg/L)	12,000–30,000	2500–11,000	2000–2600	1500–4000	5000–10,000	2100
TSS (mg/L)	1000–2000	200–400	100–400	50–350	100–700	100
BOD (mg/L)	2500–3500	100–500	50–120	100–400	50–550	30
COD (mg/L)	10,000–20,000	1200–1600	250–400	400–1400	250–8000	250
Chlorides (mg/L)	–	–	350–700	–	100–500	1000
Sulphates (mg/L)	–	–	100–350	–	50–300	1000
Color	–	–	Highly colored	Strongly colored	Strongly colored	Colorless

content of organic matter or toxic contaminants. WAO is carried out at elevated temperature and pressure in which there is generation of active oxygen species such as hydroxyl radicals. However, the severe operating conditions result in high installation cost (material of construction of equipment to withstand high temperature and pressure) and operating cost. The introduction of catalyst in WAO, called catalytic wet air oxidation (CWAO) facilitates the oxidation process at considerably low temperature and pressure. CWAO is useful for treatment of effluents where the concentration of organic contaminants is too low for the incineration process to be economical. Further, the CWAO leads to formation of carbon dioxide & water and there is no formation of by-products. Ozone is a more powerful oxidant than chlorine and other compounds (hydrogen peroxide, potassium permanganate, chlorine dioxide and bromine). The oxidation potential of ozone is 2.07 as compared to 1.36 for chlorine and 1.78 for hydrogen peroxide. But ozone is hazardous and it requires an ozone destruction unit to prevent ozone from escaping from the process. Hydrogen peroxide removes the dyes by oxidation resulting in aromatic cleavage of dye molecules. It is an environmental friendly technique but is not effective on all dyes as its oxidation potential is not very high. Further, the process needs to be activated by some other means like UV light, inorganic salts, ozone or ultrasound/sunlight. The advantages and limitations of conventional methods have been summarized by Hao et al. (2000).

2. Electrocoagulation

Electrocoagulation (EC) is a simple and efficient method and has been used for the treatment of many types of wastewaters such as electroplating wastewater (Verma et al., 2013; Adhoun et al., 2004), laundry wastewater (Janpoor et al., 2011), restaurant wastewater (Chen et al., 2000) and poultry slaughterhouse wastewater (Kobya et al., 2006c). Electrocoagulation has been successfully used for the removal of pollutants from different industrial wastewaters and is summarized in supplemental Table 2. Many studies have been reported in the literature (Yuksel et al., 2013; Khandegar and Saroha 2013a, 2013b; Ogutveren et al., 1992) using electrocoagulation for the treatment of dye and textile industry effluent and are shown in supplemental Table 3.

Heavy metals are generally used in tanning, electroplating, leather, textile, metal finishing, magnetic tapes, pigment products, wood preservation and chrome plating industries. Therefore heavy metal in wastewater has become one of the severe environmental concerns. Majority of industrial effluents contain toxic metals such as Cd, Cr, Cu, Ni, Zn, Pb and other compounds which are toxic to living organisms and harmful to the environment when they are directly discharged into the water bodies. They can be easily absorbed by fishes and vegetables due to their high solubility in the aquatic environments and may accumulate in the human body by means of the food chain. It is necessary to treat wastewater containing toxic metals to remove their adverse effects on human and ecology. In recent years, a variety of techniques are used for heavy metal removal from wastewater which include ion-exchange, adsorption, chemical precipitation, membrane filtration, flocculation, coagulation, flotation and electrochemical methods (Fu and Wang, 2011).

Electrocoagulation has been successfully applied to remove soluble ionic species from solutions and heavy metals by various investigators (Verma et al., 2013; Aji et al., 2012; Akbal and Camci, 2011a). Electrocoagulation has also been used for the removal of arsenic (Kumar et al., 2004; Balasubramanian and Madhavan, 2001), phosphate (Bektas et al., 2004a), sulfide, sulfate and sulfite

(Muruganathan et al., 2004), boron (Yilmaz et al., 2005; Bektas et al., 2004b), fluoride (Mameri et al., 1998), nitrate (Kumar and Goel, 2010) and chromate (Gao et al., 2004). Various studies reported in the literature for removal of heavy metals and toxic compounds using electrocoagulation process are summarized in supplemental Table 4.

Combination of various techniques for the treatment of effluent leads to a higher removal efficiency as compared to the use of single treatment method alone. Electrocoagulation in combination with other treatment methods is a safe and effective way for the removal of pollutants. Some studies on the combination of electrocoagulation with other treatment techniques have been reported in the literature and are summarized in supplemental Table 5. Studies have been reported in the literature comparing electrocoagulation with other conventional methods and have been summarized in supplemental Table 6. It can be noticed from supplemental Table 6 that electrocoagulation results in higher removal efficiency compared with other methods for the same concentration of pollutants.

Electrocoagulation is an efficient technique because adsorption of hydroxide on mineral surfaces are 100 times greater on in 'situ' rather than on pre-precipitated hydroxides when metal hydroxides are used as coagulant (Mollah et al., 2004a). Since the flocs formed by EC are relatively large which contain less bound water and are more stable, therefore, they can be easily removed by filtration. It is cost effective, and easily operable. EC needs simple equipments and can be designed for any capacity of effluent treatment plant. Since no chemical addition is required in this process, it reduces the possibility of generation of secondary pollutants. It needs low current, and therefore, can be operated by green processes, such as, solar, windmills and fuel cells (Zaroual et al., 2006). It is an environment-friendly technique since the 'electron' is the main reagent and does not require addition of the reagents/chemicals. This will minimize the sludge generation to a great extent and eventually eliminate some of the harmful chemicals used as coagulants in the conventional effluent treatment methods. Electrocoagulation process can effectively destabilize small colloidal particles and generates lower quantity of sludge compared to other processes.

The advantages of electrocoagulation as compared to chemical coagulation are as follows:

- EC requires no addition of chemicals and provides better removal capabilities for the same species than chemical coagulation
- EC removes many species that chemical coagulation cannot remove
- EC produces less sludge, thus lowering the sludge disposal cost
- EC sludge is more readily filterable and can be utilized as a soil additive.
- EC sludge contains metal oxides that pass the leachability test.
- EC technique needs minimal startup time; the process can be started by turning on the switch

Some of the limitations of the electrochemical coagulation are as follows (Mollah et al., 2001, 2004a):

1. The sacrificial anodes need to be replaced periodically.
2. Electrocoagulation requires a minimum solution conductivity depending on reactor design, limiting its use with effluent containing low dissolved solids.
3. In case of the removal of organic compounds, from effluent containing chlorides there is a possibility of formation of toxic chlorinated organic compounds.

Table 2
Electrocoagulation used for treatment of different types of wastewater.

Reference	Type of wastewater	Current density or current	Time (min)	pH	Anode–cathode	COD removal efficiency (%)
Mahajan et al. (2013)	Hospital operation theatre	12.2 mA/cm ²	75	6.75	Fe–Fe, Fe–Al, Al–Al	100, 98, 95
Lopez-Vizcaino et al. (2012)	Surfactant-aided soil-remediation processes	7.5 mA/cm ²	–	8.25	Al–Al, Fe–Fe, Fe–Al	100
Kara (2012)	Transport container washing	100 A/m ²	60, 30	6, 9	Al–Al, Fe–Fe	76.3, 79.4
Ahmed et al. (2012)	Lack water	13.33 mA/cm ²	120	8.1	Al–Al	99
Khandegar and Saroha (2012)	Distillery spentwash	0.817 A/cm ²	120	3	Al–Al, Al–Fe, Fe–Fe	81.3, 71.8, 52.4
Akyol (2012)	Paint manufacturing	35 A/m ²	15	6.95	Fe–Fe, Al–Al	93, 94
Gengec et al. (2012)	Baker's yeast	80 A/m ² , 12.5 A/m ²	30	4, 5	Al–Al	48, 49
Orkun and Kuleyin (2012)	Landfill leachate	30 mA/cm ²	180	6.54	Fe–Fe	65.85
Coskun et al. (2012)	Olive mill	1 A	45	4.3	A–Al, Fe–Fe	53.4
Bayar et al. (2011)	Poultry slaughterhouse	1 mA/cm ²	30	3	Al–Al	85
Bouhezila et al. (2011)	Town landfill leachate	500 A/m ²	30	8.2	Al–Al, Fe–Fe	70, 68
Katal and Pahlavanzadeh (2011)	Paper mill	70 mA/cm ²	30	7	Fe–Fe	88.4
Li et al. (2011)	Landfill leachate	4.96 mA/cm ²	90	6.7–7.5	Fe–Fe, Al–Al	49.8, 32.7
Mansouri et al. (2011)	Tannic acid	10 mA/cm ²	120	9	Fe–Fe	100
Top et al. (2011)	Landfill leachate	15.9 mA/cm ²	30	7	Al–Al	45
Saleem et al. (2011)	Raw wastewater	24.7 mA/m ²	30	8.4	Fe–Fe	77.2
Sridhar et al. (2011)	Pulp and paper	15 mA/cm ²	20	7	Al–Al	90
Yavuz et al. (2011)	Dairy	15 mA/cm ²	20	7	Fe–Al	79.2
Janpoor et al. (2011)	Laundry	0–2 A	80	8–9	Al–Al	93.2
Chou et al. (2010)	Chemical mechanical polishing	6.8 mA/cm ²	50	–	Fe–Al, Fe–Fe, Al–Al, Al–Fe	96.3
Hanafi et al. (2010)	Olive mill	250 A/m ²	15	4.2	Al–Al	80
Krishna et al. (2010)	Distillery spentwash	0.03 A/cm ²	120	3	Al–Al	72.3
Chavalparit and Ongwandee (2009)	Biodiesel	–	23.5	6.06	Al–Graphite	55.43
El-Naas et al. (2009)	Petroleum refinery	13 mA/cm ²	60	9.5	Al–Al, SS–Al, SS–Fe	45, 43, 23
Kumar et al. (2009)	Bio-digester	44.65 A/m ²	120	2–8	Fe–Fe	50.5
Linares-Hernandez et al. (2009)	Mixed wastewater	45.45 A/m ²	60	8	Al–Fe	69
Prasad and Srivastava (2009)	Distillery spentwash	14.285 mA/cm ²	180	5	(RuO ₂ –Ti)–SS	37
Thakur et al. (2009)	Distillery spentwash	146.75 A/m ²	130	6.75	SS–SS	63.1
Un et al. (2009)	Vegetable oil refinery	35 mA/cm ²	90	7	Al–Al	93
Zaied and Bellakhal (2009)	Black liquor	14 mA/cm ²	50	7	Al–Al, Fe–Fe	98, 85
Kirzhner et al. (2008)	Winery	2 A	40	–	Al–Al	98.2
Kobyas and Delipinar (2008)	Baker's yeast	70 A/m ²	50	6.5, 7	Al–Al, Fe–Fe	71, 69
Ugurly et al. (2008)	Paper mill	5 mA/cm ²	7.5	7.6	Al–Al, Fe–Fe	75, 55
Asselin et al. (2008)	Oily bilgewater	1.5 A	90	7.09	Fe–Al	78.1
Kurt et al. (2008)	Domestic	0.12 A	5–15	7.4	Fe–Fe	60
Babu et al. (2007)	Tannery	20 mA/cm ²	–	6.8	Fe–Al	52
Feng et al. (2007a)	Tannery	1.0 A	60	9.8, 8.5	MS–MS, Al–Al	68
Murthy et al. (2007)	Restaurant	–	30	7	Al–Al, Fe–Fe	50–72
Drouiche et al. (2007)	Chemical mechanical polishing	125 A/m ²	320	6	Fe–Fe	75
Barrera-Diaz et al. (2006)	Food processing	18.2 A/m ²	30	4	Al–Al	88
Bayramoglu et al. (2006)	Poultry slaughterhouse	150 A/m ²	25	3	Al–Al, Fe–Fe	93, 85
Kobyas et al. (2006b)	Potato chips manufacturing	300 A/m ²	40	4–6	Al–Al	60
Sengil and Ozacar (2006)	Dairy wastewater	0.6 mA/cm ²	1	7	Fe–Fe	98
Zaroual et al. (2006)	Textile	–	3	10.6	Fe–Fe	84
Adhoum and Monser (2004)	Olive mill	75 mA/cm ²	25	4–6	Al–Al	76
Lai and Lin (2004)	Chemical mechanical polishing	–	30	7.3	Al–Fe	85
Muthukumar et al. (2004)	Textile	5 A/dm ²	–	12	(RuO ₂ –Ti)–Ti	85
Bayramoglu et al. (2004)	Textile	200 A/m ²	10	11	Fe–Fe, Al–Al	76, 65
Inan et al. (2004)	Olive mill	20 mA/cm ²	30	6.2	Al–Al, Fe–Fe	52, 42
Manisankar et al. (2004)	Distillery	6 A/dm ²	180	6.9–7.2	Graphite–Graphite	85.2
Calvo et al. (2003)	Soluble oil waste	7 A	–	6.70	Al–Al	91.3
Lai and Lin (2003)	Chemical mechanical polishing	0.06 A	60	8.7	Al–Al	88.5
Bejankiwar (2002)	Cigarette industry	10.9 A/cm ²	300	7.2	Fe–Fe	56
Xu et al. (2002)	Egg processing	–	16, 24	4.5	Al–Al, Fe–Fe, SS–SS	95, 95, 92
Chen et al. (2000)	Restaurant	30–80 A/m ²	90	6–9.5	Al–Al	84.1
Chiang et al. (1995)	Landfills leachate	15 A/dm ²	240	8	(Sn–Pd–Ru)–St	92
Lin and Peng (1994)	Textile	92.5 A/m ²	240	10	Fe–Fe	51

- An impermeable oxide film may be formed on the cathode which may provide resistance to the flow of electric current. However, change of polarity and periodical cleaning of the electrodes may reduce this interference.
- The high cost of electricity can result in an increase in operational cost of EC.

- Anode dissolution,
- Formation of OH[−] ions and H₂ at the cathode
- Electrolytic reactions at electrode surfaces
- Adsorption of coagulant on colloidal pollutants
- Removal of colloids by sedimentation or flotation.

Electrocoagulation involves many chemical and physical phenomena that make use of consumable electrodes to supply ions into the pollutant system. In EC the coagulating ions are produced in situ and it involves the following successive stages:

In an electrocoagulation process, the electrode or electrode assembly is usually connected to an external DC source and the important parameter is the selection of the electrode material and the mode of combination of anode and cathode. The electrode material for treatment of wastewater should be non-toxic to human

Table 3
Electrocoagulation used for removal of various type of dyes.

Reference	Dye	Current or current density	Anode–cathode	Removal efficiency (%)
Yuksel et al. (2013)	Reactive orange 84	130 A/m ²	SS–SS, Fe–Fe	66, 76
Khandegar and Saroha (2013a)	Acid red 131, Reactive yellow 86, Indanthrene blue RS, Basic GR 4, Reactive yellow 145	0.0625 A/cm ²	Al–Al	97
Khandegar and Saroha (2013b)	Reactive black B, Orange 3R, Yellow GR	0.0625 A/cm ²	Al–Al	98
Wei et al. (2012)	Azo, Anthraquinone, Xanthene	0.3 A	Fe–Steel wool, Fe–Fe, Fe–SS	98
Pajootan et al. (2012)	Acid black 52, Acid yellow 220	40 A/m ²	Al–Al	92, 95
Akbal and Kuleyin (2011)	Levafix brilliant blue E-B	100 A/cm ²	Al–Al, Fe–Fe	99, 83
Korbahti et al. (2011)	Acid, Reactive	4.0 mA/cm ²	Fe–Carbon	95
Merzouk et al. (2011)	Disperse red	20.8 mA/cm ²	Al–Al	95
Parsa et al. (2011)	Acid brown 14	6.329 A/m ²	Al–SS 304	Bench scale: 91 Pilot scale: 80
Patel et al. (2011)	Reactive black 5	7.5 mA/cm ²	Fe–SS	90
Secula et al. (2011)	Indigo carmine	54.57 A/m ²	MS–SS	100
Aoudj et al. (2010)	Direct red 81	1.875 mA/cm ²	Al–Al	>98
Durango–Usugaa et al. (2010)	Crystal violet	28 A/m ²	Fe–Al, Al–Fe	100
Kobya et al. (2010)	Remazol red 3B	15 mA/cm ²	Fe–Fe	>99
Phalakornkule et al. (2010)	Reactive blue 140, Direct red 1	40 A/m ²	Fe–Fe, Al–Al	>95
Mollah et al. (2010)	Orange II	160 A/m ²	Al–Al	94.5
Sengil and Ozacar (2009)	Reactive black 5	4.575 mA/cm ²	Fe–Fe	98.8
Kabdassii et al. (2009c)	Reactive red, Reactive yellow 145, Reactive blue 221	22 mA/cm ²	SS 304–SS 304, Al–Al	100, 58
Arslan–Alaton et al. (2009)	Reactive	22 mA/cm ²	SS–SS, Al–Al	99, 95
Charoenlarp and Choyphan (2009)	Reactive, Basic	–	Al–Al, Fe–Fe	96, 85.6
Phalakornkule et al. (2009)	Direct red 23	30 A/m ²	Fe–Fe, Al–Al	>95
Aleboye et al. (2008)	Acid Red 14	102 A/m ²	Fe–St 304	>91
Korbahti and Tanyolac (2008)	Levafix blue CA	35.5 mA/cm ²	Fe–Fe	99.5
Yildiz (2008)	Bomplex red CR-L	0.50 mA/cm ²	Al–Al	99.1
Daneshvar et al. (2007)	Acid yellow 23	112.5 A/m ²	Al–St 304	98
Koparal et al. (2007)	Basic red 29	1 mA/cm ²	Boron doped diamond–Boron doped diamond	97.2
Rajkumar et al. (2007)	Reactive blue 19	21.66 mA/cm ²	(Ti–RuO ₂ –IrO ₂)–SS	100
Daneshvar et al. (2006)	Basic red 46, Basic blue 3	80 A/m ²	Fe–St 304	99
Kashefialasl et al. (2006)	Acid yellow 36	127.8 A/m ²	Fe–Fe	83
Kobya et al. (2006a)	Levafix orange	100 A/m ²	Al–Al	95
Sakalis et al. (2006)	Reactive	–	Niobe diamond–Carbon, (Pt/Ti)–Carbon	90
Alinsafi et al. (2005)	Blue reactive	–	Al–Al	95
Yang and McGarrahan (2005)	Reactive blue 19, Acid red 266, Disperse yellow 218	1.6 A	Al–Graphite, Fe–Graphite	98
Golder et al. (2005)	Methylene blue, Eosin yellowish	16.1 mA/cm ²	MS–MS	97, 75
Fernandes et al. (2004)	Acid orange 7	5 mA/cm ²	Boron doped diamond–Copper foil	98
Daneshvar et al. (2004)	Acid red 14	80 A/m ²	Fe–St 304	93
Mollah et al. (2004b)	II Orange	398.7 A/m ²	Carbon steel–Carbon steel	99
Can et al. (2003)	Remazol red RB 133	15 mA/cm ²	Al–Al	92.5
Daneshvar et al. (2003)	II orange	34.62 A/m ²	Fe–Fe	>98
Kim et al. (2002)	Blue P-3R, Suncion yellow H-E4R, Suncron blue RD-400, Suncron yellow 3GE-200, Reactive blue 49, Reactive yellow 84, Disperse blue 106, Disperse yellow 54	1–4.5 A/m ²	Al–Al, Fe–Fe, SS–SS	95–99.6
Vlyssides et al. (2000)	Mixed dyes	–	(Ti/Pt)–SS 304	100
Szpyrkowicz et al. (2000)	Disperse	–	(Ti/Pt–Ir)–SS	90
Vlyssides and Israilides (1998)	Mixed dyes	0.89 A/cm ²	Ti/Pt–SS 304	96.4
Ogutveren et al. (1992)	Acilan Blau	10–17.5 mA	Graphite–Graphite	98–100

health and environment. The electrode materials used commonly as electrodes are aluminum, iron, stainless steel, mild steel and graphite as they are cheap, readily available, nontoxic and very effective (Mollah et al., 2001, 2004a; Emamjomeh and Sivakumar, 2009). The use of different combinations (Al/Al, Al/Fe, Fe/Al, Fe/Fe) of electrode for the treatment of same wastewater has been reported in the literature (Khandegar and Saroha, 2012; Akyol, 2012; Bouhezila et al., 2011; Bayramoglu et al., 2006). When aluminum and iron are used as anode material, metal ions are released from anode and many ionic monomeric hydrolysis species are formed, depending on the pH of the solution. The reactions taking place at electrodes in EC are as follows:

For aluminum electrodes

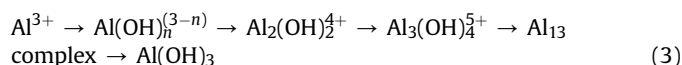
Oxidation reaction takes place at the anode



Reduction reaction takes place at the cathode



Overall reaction during electrolysis



For iron electrodes

Oxidation reaction takes place at the anode

Table 4
Removal of metals and other compounds by electrocoagulation.

Reference	Metal or other compound	Concentration (mg/L) or other unit	Anode–cathode	Removal efficiency (%)
Vasudevan et al. (2013)	B	3–7	Zn–SS	93.2
Verma et al. (2013)	Cr(III), Cr(VI)	887.29, 1495.27	Fe–Fe	100
Ganesan et al. (2013)	Mn	2	Mg–Fe	97.2
Aji et al. (2012)	Ni, Cu, Zn, Mn	250	Fe–Fe	96, 96, 96, 72.6
Olmez-Hanci et al. (2012)	Naphthalene sulfonates K-acid	600	SS–SS	97
Tran et al. (2012)	P	5–50	MS–MS	97
Henriques et al. (2012)	Nonylphenol polyethoxylate	40	Al–Al	96
Drouiche et al. (2012)	F–	25	Fe–Fe	56
Parga et al. (2012)	Sr	62	Fe–Fe	87.45
Baek et al. (2012)	Se(VI)	1.2 mM	Fe–Fe	45.1
Sinha et al. (2012)	F–	6, 11.6	Al–Al	79, 68
Martinez et al. (2012)	Au, Ag	13.25, 1357	St–St	99.5
Vasudevan and Lakshmi (2012)	B	3–7	MS–SS	93.2
Ghosh et al. (2011)	F–	10	Al–Al	90
Akbal and Camci (2011a)	Ni, Cu, Cr	526, 335, 193	Fe–Al	100
Akbal and Camci (2011b)	Cu, Cr, Ni	45, 44.5, 394	Al–Fe	100
Vasudevan and Lakshmi (2011a)	Cd	20	Zn–Zn	AC: 97.8 DC: 96.9
Vasudevan et al. (2011)	F–	50–20	Al–Al	AC: 93 DC: 91.5
Vasudevan et al. (2011b)	Cd	20	Al–Al	AC: 97.5 DC: 96.2
Behbahani et al. (2011a)	PO ₄ ³⁻	400	Al–Al, Fe–Fe	100, 84.7
Behbahani et al. (2011b)	F–	25	Al–Al	94.5
Lacasa et al. (2011a)	PO ₄ ³⁻ –P	27 mg/dm ³	Al–Al, Fe–Fe	100
Lacasa et al. (2011b)	As	20 mg/dm ³	Fe–Al	99.9
Moussavi et al. (2011a)	Petroleum hydrocarbon	64	St–Fe	Batch process: 95.1 Continuous process: 93.4
Moussavi et al. (2011b)	CN–	300	Fe–Al, Fe–Fe, Al–Al, Al–Fe	93, 87, 35, 32
Dermontzis et al. (2011a)	Cr(VI)	200–800	Fe–Fe	100
Dermontzis et al. (2011b)	Ni(II), Cu(II), Zn(II), Cr(VI)	50	Al–Al	>97, >97, >97, >80
Emamjomeh et al. (2011)	F–	10	Al–Al	92
Hanay and Hasar (2011)	Cu(II), Zn(II), Mn(II)	50–200	Al–Al	99.5
Keshmirizadeh et al. (2011)	Cr(VI)	100	Fe–Al	99
Kobyas et al. (2011)	As	150 µg/L	Al–Al, Fe–Fe	93.5, 94
Murthy and Parmar (2011)	Sr(II)	10	SS–SS, Al–Al	93, 77
Valero et al. (2011)	TOC	2260	Al–Fe	79
Vepsalainen et al. (2011)	Cu	1.25	Fe–Fe	97
Zodi et al. (2011)	As	3.8 µg/L	Al–Al, Fe–Fe	91.5
Ali et al. (2011)	As	123	Al–Fe	>99.6
Malakootian et al. (2011)	NO ₃ ⁻	150	Fe–Fe, Al–Al	90, 89.7
Parga et al. (2010)	Cr	2.31–48.5	Fe–Fe	99
Khatibikamal et al. (2010)	F–	4–6	Al–Al	93
Can and Bayramoglu (2010)	p-Benzoquinone	50	Al–SS	83
Pociecha and Lestan (2010)	Pb, Zn, Cd	170, 50, 1.5	Al–SS	95, 68, 66
Kumar and Goel (2010)	NO ₃ ⁻ , As(V)	300, 1	MS–MS	84, 75
Vasudevan et al. (2010)	B	3–7	Al–Al	86.32
Malakootian and Yousefi (2009)	Total hardness	464	Al–Al	95.6
Nanseu-Njikia et al. (2009)	Hg(II)	2 × 10 ⁻⁵ M	Al–Fe	99.95
Chou et al. (2009)	In(III)	20	Fe–Al, Al–Fe, Fe–Fe, Al–Al	78.3, 70.1, 31.4, 15.8
Vasudevan et al. (2009)	Fe	25	Al–SS	98.8
Kabdasli et al. (2009a)	TOC, Ni, Zn	173, 248, 232	SS 304–SS 304	66, 90, 100
Kabdasli et al. (2009b)	Dimethyl phthalate	100	SS–SS	100
Schulz et al. (2009)	Si, Ca, Mg	40–50, 17–23, 4–6	Fe–Fe, Al–Al	Fe–Fe = 80, 20, 40 Al–Al = 60, 10, 20
Ghernaout et al. (2008)	Bentonite suspension (Turbidity)	20 NTU	Fe–Fe	80
Heidmann and Calmano (2008)	Cr(VI)	10–50	MS–ST 37	100
Modirshahla et al. (2008)	4-nitrophenol	20	St 310–St 304	100
Ghosh et al. (2008)	Fe(II)	25	Al–Al	99.2
Sayiner et al. (2008)	B	1000	Al–Fe	95
Golder et al. (2007a)	Cr(III)	1711, 2235	MS–MS	90.6, 71.4
Golder et al. (2007b)	Cr(VI)	50	Al–Al	42
Golder et al. (2007c)	Cr(III)	1000	Al–Al	99.8
Gomes et al. (2007)	As	1–1230	Al–Fe, Fe–Fe, Al–Al	78.9–99.6
Feng et al. (2007b)	Humic acid	20	Al–Al	97.8
Rodriguez et al. (2007)	Cu	50	Al–Al	99.8
Chen et al. (2007)	NH ₃	40	(RuO ₂ –IrO ₂ –TiO ₂)–Ti	100
Zhu et al. (2007)	F–	5	Al–Al	96
Irdemez et al. (2006)	PO ₄ –P	25	Al–Al	100
Emamjomeh and Sivakumar (2006)	F–	10–25	Al–Al	100
Den and Huang (2005)	Turbidity	70, 400 NTU	Fe–Fe	95
Yilmaz et al. (2005)	B	100	Al–Al	97
Parga et al. (2005b)	As(III), As(V)	2.24	Fe–Fe	>99
Adhoum et al. (2004)	Cu(II), Zn(II), Cr(VI)	50	Al–Al	99, 99, 83

Table 4 (continued)

Reference	Metal or other compound	Concentration (mg/L) or other unit	Anode–cathode	Removal efficiency (%)
Bektas et al. (2004a)	PO ₄ ³⁻	10	Al–Al	100
Bektas et al. (2004b)	B	5	Al–Al	92–96
Murugananthan et al. (2004)	SO ₄ ²⁻	100	Al–Al, Fe–Fe	72, 68
Hu et al. (2003)	F ⁻	25	Al–Al	100
Abuzaid et al. (2002)	Turbidity	76 NTU	SS–SS	95
Ciorba et al. (2002)	Nonylphenol ethoxylates	0.1 g/L	Al–St	30–80
Yang and Dluhy (2002)	F ⁻	16	Al–Al	87.5
Mameri et al. (1998)	F ⁻	2.5	Al–Al	80
Lin and Wu (1996)	NO ₂ –N, NH ₃ –N	5	Fe–Fe	100, 15



Reduction reaction takes place at the cathode



Overall reaction during electrolysis



3. Batch and continuous mode of operation

It can be noticed from the literature that electrocoagulation has been studied for the removal of a wide range of pollutants using batch and continuous mode of operation. A continuous system operates under steady state conditions, specially a fixed pollutant concentration and effluent flow rate. By contrast, a batch reactor's dynamic nature enables to study the range of operating conditions and is more suited for research work. Continuous systems are better suited to industrial processes for large effluent volumes whereas the batch reactors are suited to laboratory and pilot plant scale applications. The continuous mode of operation is preferred due to its better control than the batch mode of operation. The typical batch mode of operation and schematic diagram for continuous mode of operation are shown in Fig. 1.

Table 5

Combination of electrocoagulation with other methods.

Reference	Combination	Effluent	Result (%)
Secula et al. (2012)	EC + Adsorption (granular activated carbon)	Synthetic solution	Indigo carmine dye (99.5)
Asaithambi et al. (2012)	EC + Ozonation	Distillery	COD (83), Color (100)
Modenes et al. (2012)	EC + Photo-fenton	Tannery	COD (99), Turbidity (93), TSS (70), TFS (37), TVS (95), Cr (99)
Filho et al. (2012)	EC + Electroflotation + Fluidized bed anaerobic reactor	Tannery	COD (90)
Orescanin et al. (2012)	Ozonation + EC + Microwaves	Landfill leachate	Color (98.43), Turbidity (99.48), SS (98.96), NH ₃ (98.8), COD (94.17), Fe (98.56)
Bellebia et al. (2012)	EC(Al–Al) + Adsorption (activated carbon), EC(Fe–Fe) + Adsorption (activated carbon)	Cardboard paper mill	COD (98, 93)
Baudequin et al. (2011)	EC + Reverse osmosis	Firefighting water	Fluorinated surfactant (71–77)
Durante et al. (2011)	EC + Electrooxidation	Synthetic solution of Cr–EDTA	Cr (99)
Mahvi et al. (2011)	EC + Electroflotation	Synthetic solution	NH ₃ (98), PO ₄ ³⁻ (98), COD (72)
Yahiaoui et al. (2011)	EC + Ultrafiltration	Olive oil mill	COD (96)
Zhao et al. (2011)	EC + Electrooxidation	Synthetic solution	As (100), F ⁻ (91)
Chang et al. (2010)	EC + Activated carbon–microwave regeneration	Synthetic dye solution	Reactive black 5 (82)
Merzouk et al. (2010)	EC + Electroflotation	Textile	COD (79.7), Turbidity (76.2), SS (85.5), BOD (88.9), Color (93)
Rodriguez et al. (2010)	EC + Phytoremediation	Mixed industrial	COD (91), Turbidity (98), Color (97)
Zodi et al. (2010)	EC + Sedimentation	Textile	COD (70), Turbidity (90)
Aouni et al. (2009)	EC + Nanofiltration	Textile	Color (>99)
Merzouk et al. (2009)	EC + Electroflotation	Textile	COD (68), BOD (83), SS (86.5), Turbidity (81.56), Color (92.5) Metals (95)
Boroski et al. (2009)	EC + Heterogeneous photocatalysis (TiO ₂)	Pharmaceutical and cosmetic	COD (86), Turbidity (91)
Narayanan and Ganesan (2009)	EC + Adsorption (granular activated carbon)	Synthetic solution	Cr(VI) (97)
Wang et al. (2009)	EC + Electroflotation	Laundry	COD (62)
Zhang et al. (2009)	EC + Electrooxidation	Synthetic solution	Acid red 2 (98)
Raju et al. (2008)	EC + Electrooxidation	Synthetic solution	COD (93)
He et al. (2007)	EC + Ozonation	Synthetic solution	Reactive yellow 84 (100), TOC (85)
Niam et al. (2007)	EC + Magnetic field	Synthetic milk powder solution	COD (75.5), SS (30.6)
Linares-Hernandez et al. (2007)	EC + Biosorption	Mixed industrial	COD (84), BOD (78), Color (97), Turbidity (98), Coli form (99)
Parga et al. (2005a)	EC + Air injection	Well water	Cr (99), As (99)
Shen et al. (2003)	EC + Electroflotation	Industrial	F ⁻ (86)
Jiang et al. (2002)	EC + Flotation	Synthetic solution	Dissolved organic carbon (67), Color (89)
Pelegri et al. (1999)	EC + Photochemical	Synthetic solution	Color (98)
Lin and Chen (1997)	EC + H ₂ O ₂ + Ion-exchange	Dyeing and finishing mill	Cl ⁻ (99.8), NO ₃ ⁻ (99.5), SO ₄ ²⁻ (99.9)

Table 6
Comparison of electrocoagulation with other methods.

Reference	Effluent	Removal parameter	Result (%)
Verma et al. (2013)	Electroplating	Cr(III), Cr(VI)	EC: 100 for both Cr(III) and Cr(VI) Coagulation (Ferric chloride): Cr(III) (52.6), Cr(VI) (25.8)
Khandegar and Saroha (2013a)	Textile	Color	EC: 97 Coagulation (Alum): 94
Khandegar and Saroha (2013b)	Textile	Color	EC: 100 Coagulation (Alum): <5
Harif et al. (2012)	Synthetic kaolin solution	–	Electrocoagulation flocs are more porous as compared to flocs formed by alum coagulation
Chen and Deng (2012)	Synthetic solution	Humic acid	EC: 32.9 Ultrafiltration: 26.8
Ouaissa et al. (2012)	Tannery	Turbidity, COD, Cr (VI)	EC: Turbidity (94.2), COD (25), Cr(VI) (24.6) EC + Adsorption: Turbidity (96.1), COD (92), Cr(VI) (75) Adsorption: Turbidity (93.3), COD (50), Cr(VI) (77)
Farhadi et al. (2012)	Pharmaceutical	COD	EC: 34.22 Photoelectrocoagulation (EC + UV): 37.32 Peroxi-electrocoagulation (EC + H ₂ O ₂): 54.32 Peroxi-photoelectrocoagulation (EC + UV + H ₂ O ₂): 50.52
Bani-Melhem and Smith (2012)	Grey water	COD, Color	EC + Submersed membrane bioreactor: COD (88.6), Color (93.7) Submersed membrane bioreactor: COD (86), Color (91.2)
Wang et al. (2012)	Landscape	Algae (Chlorophyll-a)	EC: 79 Coagulation (Aluminum sulfate): 74 Coagulation (Polyaluminum chloride): 71
Zhao et al. (2012)	Plug board	COD	EC: 30 EC + H ₂ O ₂ : 76
Chafi et al. (2011)	Synthetic dye solution	Orange II dye	EC: 98 Coagulation (Aluminum sulfate): 53
Siles et al. (2011)	Biodiesel manufacturing	COD	Acidification + EC + Biomethanization: 99 Acidification + Coagulation–flocculation + Biomethanization: 94
El-Ashtouky and Amin (2010)	Synthetic dye solution	COD	EC: 87 Electrochemical oxidation: 68
Akbal and Camci (2010)	Metal plating	Cu, Cr, Ni	EC: 99.9 in 20 min Coagulation (Aluminum sulfate and ferric chloride): 99.9
Kilic and Hosten (2010)	Aqueous suspension of kaolinite	Turbidity	EC: 96 Coagulation (Aluminum sulfate): 88
Song et al. (2008)	Synthetic dye solution	Reactive blue 19	EC: 44 EC + Ozonation: 96 Ozonation: 10
Song et al. (2007)	Synthetic dye solution	Reactive black 5	EC: 83 EC + Ozonation: 94 Ozonation: 10
Golder et al. (2007b)	Aqueous solution	Cr(VI)	EC: 53.5 Coagulation (Aluminum sulfate): 14.9 Coagulation (Alum): 13.8
Perng et al. (2007)	Paper mill	SS, COD	EC: SS (99.3), COD (75) EC + Coagulation (Polyacrylamide polymer): SS (99.6), COD (92.7)
Roa-Morales et al. (2007)	Pasta and cookie	COD	EC: 80 EC + H ₂ O ₂ : 90
Martins et al. (2006)	Aqueous solution	Nonylphenol polyethoxylate	EC: 95 in 15 min EC + H ₂ O ₂ : 95 in 10 min
Can et al. (2006)	Textile	COD	EC: 23 EC + Alum: 65 EC + Polyaluminum chloride: 80
Kannan et al. (2006)	Distillery	Turbidity	EC: 99 EC + Areca catechu nut carbon: 99
Zhu et al. (2005)	Synthetic solution	MS2 virus	EC: 4-log Coagulation (Iron-coagulant): 2-log Microfiltration: 0.5-log
Kim et al. (2004)	Synthetic dye solution	Disperse, reactive dyes	EC + Fenton oxidation: 99 Fenton oxidation: 85
Dimoglo et al. (2004)	Petrochemical	Turbidity	EC: 88 Electroflotation: 83
Lin et al. (1998)	Saline wastewater	COD	EC: 34 EC + H ₂ O ₂ : 70
Lin and Chen (1997)	Dyeing and finishing mill	COD, color	EC: COD (33), Color (83) EC + H ₂ O ₂ : COD (78), Color (92) EC + H ₂ O ₂ + Polyaluminum chloride: COD (78), Color (90)

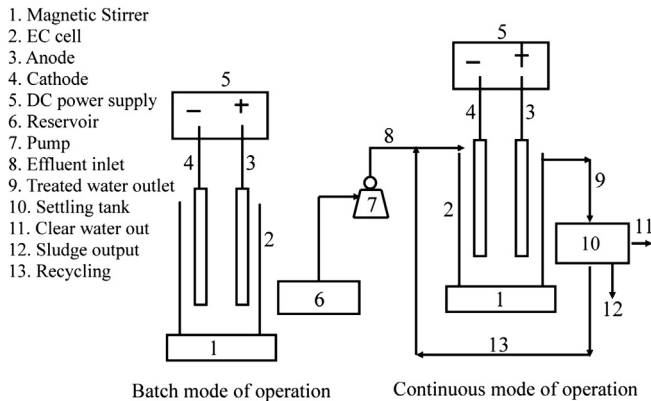


Fig. 1. Schematic diagram of batch and continuous mode of operation.

Batch mode of electrocoagulation reactors exhibits time-dependent behavior as the coagulant is continuously generated in the reactor with the dissolution of anode. The anode material is hydrolysed, and is capable of aggregating the pollutants. As a result, the concentration of the pollutant, coagulant, and pH keeps on changing with respect to time. A batch reactor has neither inflow or outflow of effluent during the electrolysis time.

4. Effect of various operating parameters

The efficiency of the electrocoagulation process depends on many operational parameters such as conductivity of the solution, arrangement of electrode, electrode shape, type of power supply, pH of the solution, current density, distance between the electrodes, agitation speed, electrolysis time, initial pollutant concentration, retention time and passivation of the electrode.

4.1. Solution conductivity

Conductivity of the solution is very important parameter in electrolysis process as the removal efficiency of the pollutant and operating cost are directly related to the solution conductivity.

The solution must have some minimum conductivity for the flow of the electric current. The conductivity of the low-conductivity wastewater is adjusted by adding sufficient amount of salts such as sodium chloride or sodium sulphate. There is an increase in the current density with an increase in the conductivity of the solution at constant cell voltage or reduction in the cell voltage at constant current density (Bayramoglu et al., 2004; Merzouk et al., 2010). The energy consumption is decreased with high conductivity solution.

4.2. Arrangement of electrodes

The electrode material and the connection mode of the electrodes play a significant role in the cost analysis of the electrocoagulation process. Kobya et al. (2011) studied the treatment of textile wastewater and compared the performances of various electrode connection modes as a function of wastewater pH, current density and operating time. They studied three different modes of electrode connection shown in Fig. 2(a)–(c) and are as follows:

Monopolar electrodes in parallel connections (MP-P): The anodes and cathodes are connected in parallel due to which the current is divided between all the electrodes to the resistance of individual cells. The parallel connection needs a lower potential difference compared with serial connections.

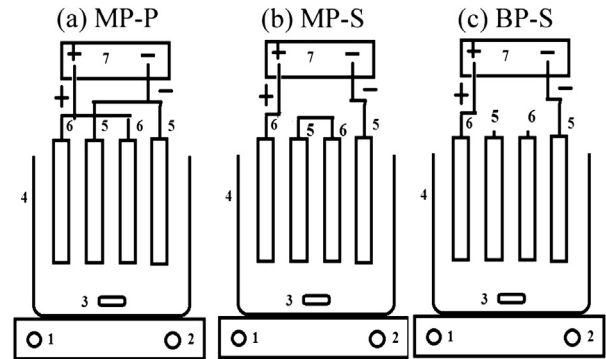


Fig. 2. Different modes of electrode connections.

Monopolar electrodes in serial connections (MP-S): In the monopolar electrodes in serial connection, each pair of sacrificial electrodes is internally connected with each other. The addition of the cell voltages leads to a higher potential difference for a given current.

Bipolar electrode in serial connections (BP-S): In this connection mode, the outer electrodes are connected to the power supply and there is no electrical connection between the inner electrodes.

Kobya et al. (2011) reported that MP-P mode is the most cost effective for both aluminum and iron electrodes.

4.3. Shapes of the electrode

The shape of the electrodes affects the pollutant removal efficiency in the electrocoagulation process. It is expected that the punched holes type electrodes will result in higher removal efficiency compared to the plane electrodes. Very few studies have been reported in the literature (Kuroda et al., 2003; Nielsen and Andersson, 2009) describing the effect of electrode shape on the performance of the electrostatic precipitator. Kuroda et al. (2003) performed experiments using metallic electrodes with/without punched holes as a barrier discharge electrode to study the effect of electrode shape of precharger on the collector efficiency in electrostatic precipitator. They have reported higher discharge current for the electrode with punched holes than for plane electrode resulting in higher collection efficiency with punched electrode compared with plane electrode. The electric field intensity at the edge of punched holes type electrodes is higher (1.2 times) than at plane type electrode resulting in an increase in the discharge current at punched type electrode. More studies are needed to establish the effect of the electrode shape (punched hole diameter and pitch of the holes) on the electrocoagulation process.

4.4. Type of power supply

In the electrocoagulation process, there is an in-situ generation of metal hydroxide ions by electrolytic oxidation of the sacrificial anode. These metal hydroxide ions act as coagulant and remove the pollutants from the solution by sedimentation. Majority of the studies reported in the literature have used direct current (DC) in the electrocoagulation process. The use of DC leads to the corrosion formation on the anode due to oxidation. An oxidation layer also form on the cathode reducing the flow of current between the cathode and the anode and thereby lowering the pollutant removal efficiency.

Vasudevan et al. (2011b) investigated the effect of alternating current (AC) and DC on the removal of cadmium from water using aluminum alloy as anode and cathode. They obtained a removal efficiency of 97.5% and 96.2% with the energy consumption of 0.454 and 1.002 kWh/kL at a current density of 0.2 A/dm² and pH of 7 using AC and DC respectively. The results indicate that the problem of corrosion formation at the electrodes can be reduced by the use of AC in place of DC in the electrocoagulation process.

4.5. pH of the solution

The pH of the solution is an important operational parameter in electrocoagulation. The maximum pollutant removal efficiency is obtained at an optimum solution pH for a particular pollutant. The precipitation of a pollutant begins at a particular pH. The pollutant removal efficiency decreases by either increasing or decreasing the pH of the solution from the optimum pH.

Verma et al. (2013) studied the removal of hexavalent chromium from synthetic solution using electrocoagulation and found that the pH of the solution has a significant effect on the Cr(VI) removal efficiency. They performed the experiments at different pH of the synthetic solution and obtained the maximum chromium removal efficiency at the pH 4. They further reported that the pH of the synthetic solution after the EC process increased with an increase in the electrolysis time due to the generation of OH⁻ in the EC process.

4.6. Current density

Current density is very important parameter in electrocoagulation as it determines the coagulant dosage rate, bubble production rate, size and growth of the flocs, which can affect the efficiency of the electrocoagulation. With an increase in the current density, the anode dissolution rate increases. This leads to an increase in the number of metal hydroxide flocs resulting in the increase in pollutant removal efficiency. An increase in current density above the optimum current density does not result in an increase in the pollutant removal efficiency as sufficient number of metal hydroxide flocs are available for the sedimentation of the pollutant.

4.7. Distance between the electrodes

The inter-electrode distance plays a significant role in the electrocoagulation as the electrostatic field depends on the distance between the anode and the cathode. The maximum pollutant removal efficiency is obtained by maintaining an optimum distance between the electrodes. At the minimum inter-electrode distance, the pollutant removal efficiency is low. This is due to the fact that the generated metal hydroxides which act as the flocs and remove the pollutant by sedimentation get degraded by collision with each other due to high electrostatic attraction (Daneshvar et al., 2004). The pollutant removal efficiency increases with an increase in the inter-electrode distance from the minimum till the optimum distance between the electrodes. This is due to the fact that by further increasing the distance between the electrodes, there is a decrease in the electrostatic effects resulting in a slower movement of the generated ions. It provides more time for the generated metal hydroxide to agglomerate to form the flocs resulting in an increase in the removal efficiency of the pollutant in the solution. On further increasing the electrode distance more than the optimum electrode distance, there is a reduction in the pollutant removal efficiency. This is due to the fact that the travel time of the ions increases with an increase in the distance between the electrodes. This leads to a decrease in the electrostatic attraction resulting in the less formation of flocs needed to coagulate the pollutant.

4.8. Effect of agitation speed

The agitation helps to maintain uniform conditions and avoids the formation of concentration gradient in the electrolysis cell. Further, the agitation in the electrolysis cell imparts velocity for the movement of the generated ions. With an increase in agitation speed upto the optimum agitation speed, there is an increase in the pollutant removal efficiency. This is due to the fact that with an increase in the mobility of the generated ions, the flocs are formed much earlier resulting in an increase in the pollutant removal efficiency for a particular electrolysis time. But with a further increase in the agitation speed beyond the optimum value, there is a decrease in the pollutant removal efficiency as the flocs get degraded by collision with each other due to high agitation speed (Modirshahla et al., 2008).

4.9. Electrolysis time

The pollutant removal efficiency is also a function of the electrolysis time. The pollutant removal efficiency increases with an increase in the electrolysis time. But beyond the optimum electrolysis time, the pollutant removal efficiency becomes constant and does not increase with an increase in the electrolysis time. The metal hydroxides are formed by the dissolution of the anode. For a fixed current density, the number of generated metal hydroxide increases with an increase in the electrolysis time. For a longer electrolysis time, there is an increase in the generation of flocs resulting in an increase in the pollutant removal efficiency. For an electrolysis time beyond the optimum electrolysis time, the pollutant removal efficiency does not increase as sufficient numbers of flocs are available for the removal of the pollutant.

4.10. Initial concentration of pollutant

The pollutant removal efficiency decreases with an increase in the initial concentration of the pollutant for a constant current density. This is due to the fact that the number of metal hydroxide flocs formed may be insufficient to sediment the greater number of pollutant molecules at higher initial pollutant concentrations (Koby et al., 2006a; Daneshvar et al., 2006).

4.11. Retention time

After the completion of the electrocoagulation process for a particular electrolysis time, the solution is kept for fixed period (retention time) to allow settling of the coagulated species. As the retention time is increased the removal efficiency of pollutant increases. This is due to the fact that with an increase in retention time, all coagulated species settle down easily to give clear supernatant liquid and the sludge. But providing a retention time more than the optimum retention time results in the reduction of pollutant removal efficiency as the adsorbed pollutant desorbs back into the solution (Daneshvar et al., 2003; Khandegar and Saroha (2013b)).

4.12. Electrode passivation

Electrode passivation is the accumulation of an inhibiting layer (usually an oxide) on the electrode's surface. Passivation is undesirable for anode dissolution and electrocoagulation operation. The primary control of passivation is the galvanostatic mode of operation. The current and the potential are dependent on the system's overall resistance. Any resistance from a passivating layer increases the cell potential but does not affect either the coagulant or bubble production rates. The use of deionised water minimizes the presence of contaminants such as carbonates, which can easily

passivate the electrodes. The electrodes should be mechanically cleaned periodically to remove any passivating material. This maintains the integrity of the electrodes and ensures anodic dissolution at a constant rate. Also these impermeable layers prevent the effective current transport between the anode and cathode. Corrosion formation on the electrodes can be removed by using AC in place of DC in the electrocoagulation.

4.13. Cost analysis

Cost analysis plays an important role in industrial wastewater treatment technique as the wastewater treatment technique should be cost attractive. The costs involved in electrocoagulation include, the cost of energy consumption, cost of the dissolved electrode and the cost of addition of any external chemical (for increasing the solution conductivity or varying the pH of the solution). The operating cost using electrocoagulation can be calculated by following equations.

$$\begin{aligned} \text{Electrode consumption(ENC)} & \left(\text{kg/m}^3\right) \\ & = \text{kg of electrode dissolved/m}^3 \text{ of effluent} \\ & = (I \times t \times M) / n \times F \times V \end{aligned} \quad (10)$$

$$\text{Energy consumption(ELC)} \left(\text{kWh/m}^3\right) = (U \times I \times t) / V \quad (11)$$

$$\begin{aligned} \text{Chemical consumption(ChC)} & \left(\text{kg of chemical/m}^3\right) \\ & = \text{Chemicals used/m}^3 \text{ of effluent} \end{aligned} \quad (12)$$

$$\text{Operating cost} \left(\text{cost/m}^3\right) = a\text{ENC} + b\text{ELC} + c\text{ChC} \quad (13)$$

The detailed calculation of operating cost for the treatment of fluoride-containing drinking water using electrocoagulation has been reported by Ghosh et al. (2011).

Espinoza-Quinones et al. (2009), studied the removal of organic and inorganic pollutants from a wastewater of lather finishing industrial process using electrocoagulation. They found the electrocoagulation to be cheaper compared to the conventional method. The operational cost for the electrocoagulation was found to be US \$ 1.7 per m³ of the treated tannery effluent as compared to the cost of US \$ 3.5 per m³ of the treated effluent for conventional methods. Similarly Bayramoglu et al. (2007) have reported that the operating cost of chemical coagulation is 3.2 times as high as that of electrocoagulation for the treatment of textile wastewater.

5. Conclusions

The rapid urbanization and industrialization in the developing countries are creating high levels of water pollution due to harmful industrial effects and sewage discharges. The characteristics of industrial effluents in terms of nature of contaminates, their concentrations, treatment technique and required disposal method vary significantly depending on the type of industry. Further, the choice of an effluent treatment technique is governed by various parameters such as the contaminates, their concentration, volume to be treated and toxicity to microbes. Electrocoagulation is an attractive method for the treatment of various kinds of wastewater, by virtue of various benefits including environmental capability, versatility, energy efficiency, safety, selectivity and cost effectiveness. The process is characterized by simple equipment, easy operation, less operating time and decreased amount of sludge which sediments rapidly and retain less water. However, further

studies needs to be performed to study the effect of shape and geometry of the electrodes (punched hole and pitch of the holes) to possibly improve the pollutant removal efficiency. Efforts should be made to study the phenomena of electrode passivation to reduce the operating cost of the electrocoagulation process. Most of the studies reported in the literature have been carried out at the laboratory scale using synthetic solutions. Efforts should be made to perform electrocoagulation experiments at pilot plant scale using real industrial effluent to explore the possibility of using EC for treatment of real industrial effluent.

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