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Review Article

Electrocoagulation Followed by Ion Exchange or Membrane Separation Techniques for Recycle of Textile Wastewater

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Abstract

Traditionally, physical, biological, chemical coagulation, adsorption and advanced oxidation processes are used for the treatment of textile wastewater and dye removal. Many of these processes are not cost effective and are responsible for secondary pollution. Electrocoagulation (EC) has recently attracted the attention as a potential technique for treating textile and other industrial effluents due to its versatility, cost effectiveness and environmental compatibility. In this paper an attempt has been made to discuss history, basic principle, mechanism, advantages, and disadvantages, effect of various parameters on the process efficiency and applications of electrocoagulation. The aim of this paper is not to review the electrocoagulation process as several comprehensive reviews have been published covering different aspects of EC applications. Most of the information available in the literature is based on the use of batch flow reactor using Electrocoagulation (EC) process alone to treat the textile wastewater to a level that meets the discharge standards. The focus of the present paper is to throw light on the combined electrocoagulation–ion exchange and combined electrocoagulation-membrane separation processes for the recycling of textile wastewater. Though the combined processes discussed in the present paper are at the conceptual stage, they have the potentials for scaling up to a commercial level.

Keywords: Electrocoagulation; Sacrificial electrode; Ion exchange; Membrane filtration; Solar powered

Introduction

World has entered into a new era where sustainability has become the buzz word due to depletion of natural resources and environmental upsets. Wastewater is not only one of the main causes of irreversible damages to the environmental balances but also contributing to the depletion of fresh water reserves at this planet. Many industrial processes are conducted at the expense of enormous volumes of fresh water generating almost equal volumes of wastewater, which need to be treated suitably to reduce or eliminate the pollutants and achieve the purity level for its reutilization in the industrial process to promote sustainability [1]. In view of this, increasingly stringent environmental policies are adopted by many countries, with greater emphasis on devising economical and environmentally friendly methods for treating wastewater [2].

Textile industry is a major consumers of water with an average water consumption of 160 litres per kg of finished product and consequently causing intense water pollution. Textile industry wastewater comprises different effluent coming from different manufacturing operation such as sizing, desizing, scouring, bleaching, dyeing, printing and finishing [3,4].

Common characteristics of textile waste water are suspended solids, high temperature, unstable pH, high Chemical Oxygen Demand (COD), High Biological Oxygen Demand (BOD) and high colorization. Other pollutants include biocides used for processing of the fibers (e.g., chlorinated aromatics), starches, solvents, fats and greases, heavy metals (e.g., chromium), salts (e.g., carbonate, sulfate, chloride), nutrients (e.g., ammonium salts, urea, phosphate based buffers), oxidizing agents (e.g., hydrogen peroxide, dichromate), reducing agents (e.g., sodium sulphide, sodium hydrosulphite), bleaching agents (e.g., hypochlorite, hydrogen peroxide) and Absorbable Organic Halogens (AOX) etc [5].

This waste water causes extreme water pollution of ground and surface water sources. Discharged textile wastewater containing higher amount organic matter causes depletion of dissolved oxygen, which has an adverse effect on ecology. Nitrogen and phosphorous nutrients content causes an increase of biomass production in aquatic environments, this situation also creates depletion of dissolved oxygen called eutrophication [6]. Due to high colorization caused by dyes and pigments, not only aesthetic pollution occurs (e.g., the eye can detect colour concentrations of 0.005 mg/L of reactive dye in water); color discharged in wastewater strongly inhibits absorption of the sunlight responsible for the photosynthetic activity of aquatic plants and threats to ecosystem. Furthermore, colored effluents may contain considerable amounts of toxic compounds, especially azo dyes, that are known to be highly carcinogenic [7-9].

Traditional methods for dealing with textile wastewater consist of various combinations of biological, physical and chemical treatment methods [10]. Common biological treatment processes

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are often ineffective in removing dyes, which are structured to have low biodegradability [11]. Various physical–chemical techniques are also available for the treatment of aqueous streams to eliminate dyes; chemical coagulation followed by sedimentation [12] and adsorption are the widely used ones [13]. Other advanced techniques are often applied, e.g. UV [14,15], ozonation [16] ultrasonic decomposition, or combined oxidation processes [17-19]. One available treatment technology widely used in recent years is Fenton oxidation. This advanced chemical oxidation technology is based on the production of hydroxyl radicals, $OH^{\bullet}$, which has high oxidation potential [20-25].

These methods are intended to treat the textile wastewater to a level that meets the discharge standards required by the governments. However, high treatment costs of these methods have stimulated, in recent years, the search for more cost effective and environmentally friendly treatment methods to meet reuse/recycle standards. Among the developing technologies, electrocoagulation is the one that received attention from the scientific community during last few years [26].

Electrocoagulation (EC) is an attractive method for the treatment of various kinds of wastewater, by virtue of several benefits including environmental compatibility, versatility, energy efficiency, safety, selectivity, amenability to automation and cost effectiveness [27]. The energy source for the process can be conventional electric source or recently developed renewable solar energy to produce direct electric current [28].

Several comprehensive reviews have been published covering the different aspects of EC applications [29-39]. The readers are advised to refer to these reviews for details. Electrocoagulation methods are indented to treat the textile wastewater to a level that meets the discharge standards required by the governments. However, due to dwindling supply and increasing demand of water in the textile industry, a better alternative is to attempt to further improve the quality of treated wastewater to reuse standard. Meanwhile, high treatment costs of presently available methods have stimulated, in recent years, the search for more cost effective treatment techniques such as electrocoagulation. However, most of the studies on electrocoagulation available in the literature are based on batch flow reactor. Textile industry is water based industry which discharges large quantities of wastewater. Therefore, a batch flow reactor will not offer feasible solution for such large quantity of wastewaters.

In the present paper an attempt has been made to discuss the combined electrocoagulation and ion exchange or membrane separation methods for the treatment and recycling of textile wastewater.

History of Electrocoagulation

Electrocoagulation has a long history as a water treatment technology used to remove wide range of pollutants. EC was first proposed in London by Vik et al., in 1889 for the treatment of domestic sewage water by mixing with saline (sea) water. The principle of electrocoagulation was first patented in 1906 by A. E. Dietrich and was used to treat bilge (The lowest inner part of ship's hull, where water accumulates) water from ships. In the United States, J.T. Harries received a patent in 1909 for wastewater treatment by electrolysis using sacrificial aluminium and iron anodes [36]. Extensive EC studies were carried out in the latter half of 20th century in both the United States and the Soviet Union. However, EC remained practically dormant for water and wastewater treatment until the 21st century. This was mainly due to the then-high investment and electricity costs. These economic facts gave other technologies an edge over EC. Presently, the prices of electricity as well as power sources have lowered substantially, making EC again a valuable alternative for water and wastewater treatment. Indeed, the environmental sector has recently shown great interest in EC as a research subject [40-43].

In the last two decades, this technology has been increasingly used in the United States, South America and Europe for treatment of industrial wastewater containing metals. It has also been noted that in North America EC has been used primarily to treat wastewater from pulp and paper industries, mining and metal processing industries. A large one-thousand gallon per minute cooling tower application in El Paso, Texas illustrates growing recognition and acceptance of electrocoagulation in the industrial sector [44].

EC lies at an intersection of three conventional technologies. It combines the functions and advantages of conventional Chemical Coagulation (CC), flotation, and electrochemistry in water and wastewater treatment. All of these are known technologies with decades of extensive research and development. However, the profound mechanism of interaction between these technologies, which is employed in an EC system, is still somewhat shrouded. More research on the core basis of EC is therefore needed to develop a better understanding of the technology as a whole [41].

Electrocoagulation System

At its simplest, an electrocoagulation system consists of an anode and a cathode made of metal plates, both submerged in the aqueous solution being treated. The electrodes are usually made of aluminium, iron or stainless steel, because these metals are cheap, readily available, proven effective and non-toxic [36,38].

Arrangement of Electrodes [32]

The configurations of electrocoagulation system vary. An electrocoagulation system may contain either one or multiple anode-cathode pairs and may be connected either in a monopolar or a bipolar mode. The arrangement of electrodes can be in following three ways:

Monopolar electrodes in parallel connections

Monopolar electrode connected in parallel arrangements is shown in (Figure 1). Monopolar electrodes in parallel connections are the simplest arrangement of an EC cell. It consists of pairs of conductive metal plates positioned in between two parallel electrodes and a DC power supply.

In the experimental set up a resistance box regulates the current density and a multimeter to read the current values. The conductive metal plates are usually known as 'sacrificial electrodes' which may be made up of the same or of dissimilar materials.

Monopolar electrodes in series connections

Monopolar electrode connected in series is shown in (Figure 2). This cell arrangement provides a simple set-up; the sacrificial electrodes are placed between the two parallel electrodes without any electrical connections and only two monopolar electrodes are

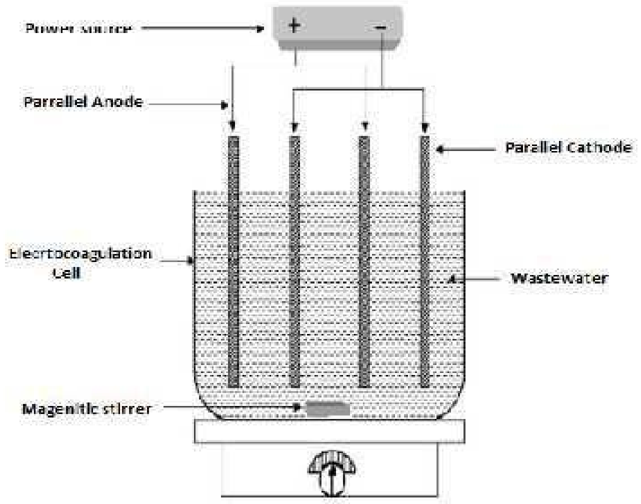

Figure 1: Monopolar electrodes in parallel connections [32].

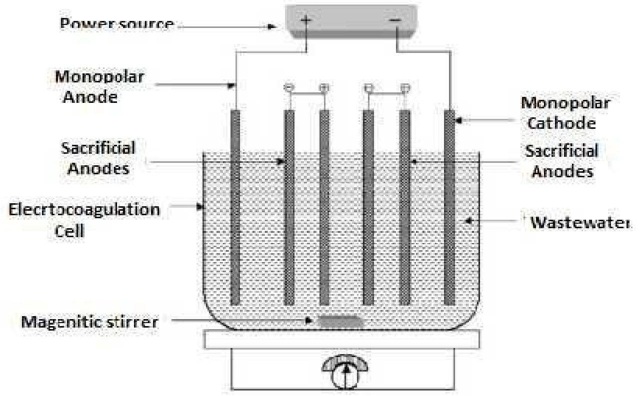

Figure 2: Monopolar Electrode in series [32].

connected to the power supply without any connections between the sacrificial electrodes which helps in easy handling. As current is passed through the pair of electrodes, the neutral sides of the conductive plate will be changed to charged face, which have opposite charge compared to the nearby parallel side. The sacrificial electrodes in this case are also called bipolar electrodes.

Bipolar electrodes in parallel connections

Bipolar electrode connected in parallel arrangements is shown in (Figure 3). This cell arrangement provides a simple set-up, which facilitates easy maintenance. In this arrangement the sacrificial electrodes are positioned between the two parallel electrodes without any electrical connection. Not more than two monopolar electrodes are connected to the electric power supply without any interconnections among the sacrificial electrodes. The neutral sides of the conductive plate will be changed to charged sides when current is passed through the two electrodes. This side has opposite charge contrast to the corresponding side near it. The sacrificial electrodes in this scenario are called as bipolar electrodes.

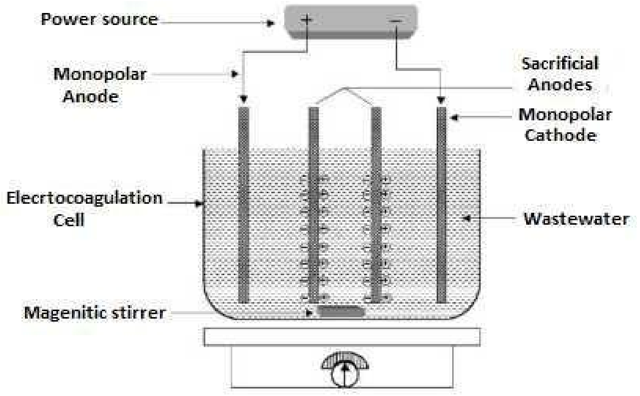

Figure 3: Bipolar electrodes in parallel connections [32].

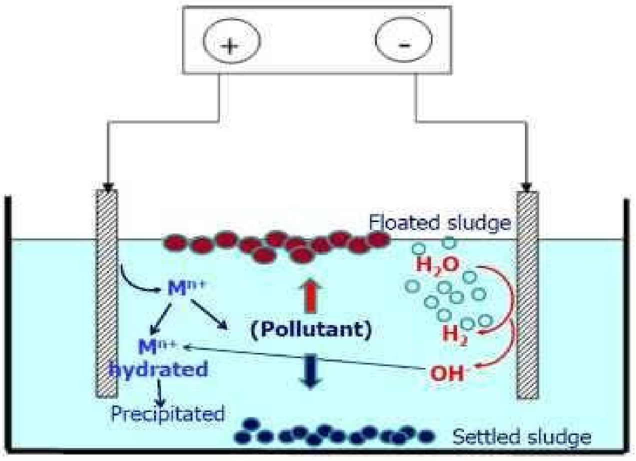

Figure 4: Main reactions during electrocoagulation [32].

Mechanism

Industrial wastewater; depending on the nature of industry contains various impurities including colloidal particles and dissolved organic substances. The finely dispersed colloids or suspended solids are usually repelled by their outer layer of negative electrical charges and maintain the colloidal nature until treated by flocculants/coagulants for their removal. The process of flocculation and coagulation can be defined as “the ionic bridging between the finely divided particles to make flocs followed by their grouping into larger aggregates to be settled under gravity”.

The mechanism involved is the neutralization of the charges on the suspended solids or compression of the double layer of charges on the suspended solids. The electrocoagulation process is based on this principle.

On passage of Direct Current (DC) in the wastewater to be treated causes production of metal ions at the expense of anode as sacrificing electrode and hydroxyl ions at cathode as a result of water splitting. The direct current provides the electromotive force to drive the chemical reactions to produce metal hydroxides. The metal hydroxides produced act as coagulant/flocculent for the suspended solids to convert them into flocs of enough density to sediment under gravity. The reactions taking place during electrocoagulation are shown in (Figure 4). Three main reactions occur serially during Electrocoagulation:

a. Electrolytic reactions at electrode surfaces,

b. In-situ formation of coagulants in aqueous phase,

c. Adsorption of soluble or colloidal pollutants on Coagulants, and removal by sedimentation or floatation [38].

The destabilization mechanisms of the contaminants, particulate suspension, and emulsion breaking have been summarized as follows: [32]

1. The diffuse double layer compression around the charged species by the ions produced by oxidation of the sacrificial anode.

2. Neutralization of charge of the ionic groups in wastewater by counter ions formed by the electrochemical dissolution of the sacrificial electrode. These counter ions decrease the electrostatic inter particle repulsion to such level that the Van der Waals attraction predominates, as a result cause coagulation in the solution. Result of the process is a zero net charge.

3. Formation of floc as a result of coagulation creates a blanket of sludge that entraps and bridges colloidal particles still remaining in the solution. The hydroxides, oxyhydroxides and solid oxides give active surfaces for the adsorption of the polluting species.

The inherent complexities of the above processes, and also the presence of secondary processes, make electrocoagulation quite complex in nature [45].

Reactions at Sacrificial Electrodes

During EC, the following main reactions take place at the Aluminium or Iron electrodes [32,33].

Anodic reactions

Iron Electrode

Anode: $Fe \rightarrow Fe^{2+} + 2e^-$

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Overall: $Fe^{2+} + 2H_2O \rightarrow H_2 + Fe(OH)_2$

OR

Anode: $Fe \rightarrow Fe^{3+} + 3e^-$

Cathode: $3H_2O + 3e^- \rightarrow 1.5H_2 + 3OH^-$

Overall: $Fe^{3+} + 3H_2O \rightarrow 1.5H_2 + Fe(OH)_3$

Aluminium Electrode

Anode: $Al \rightarrow Al^{3+} + 3e^-$

Cathode: $3H_2O + 3e^- \rightarrow 1.5H_2 + 3OH^-$

Overall: $Al3 + 3H_2O \rightarrow AlOH_3 + 1.5H_2$

General equations in electrocoagulation:

Anode: $M \rightarrow Mn^+ + ne^-$

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Overall: $Mn^+ + nH_2O \rightarrow M(OH)n + nH+$

Electrochemically generated metal cations will react spontaneously with OH- ions forming various monomeric and polymeric metal hydroxy species such as

Aluminium metal

Monomeric species

$Al(OH)2^+$, $Al2(OH)_2^{4+}$ and $Al(OH)^4$

Polymeric species

$Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{17}^{4+}$

$Al_8(OH)_{20}^{4+}$, $Al_{13}O_4(OH)_{24}^{4+}$, and $Al_{13}(OH)_{34}^{5+}$

Which finally transform into Al (OH)3 according to complex precipitation kinetics [46]

Iron metal

Ferric ions generated electrochemically may form monomeric ions, ferric hydroxo complexes with OH- ions, and polymeric species. These species/ions are:

Monomeric species

$FeOH^{2+}$, $Fe(OH)^{2-}$, $Fe_2(OH)_2^{4+}$

Polymeric species

$Fe(OH)^{4-}$, $Fe(H2O)_5OH^{2+}$, $Fe(H2O)_4(OH)_2^+$

$Fe(H2O)_8(OH)_2^{4+}$ and $Fe_2(H2O)_6(OH)_4^{2+}$

Which further react to form $Fe(OH)_3$ [45]

The formation of these complexes depends strongly on the pH of the solution. Above pH 9, $Al(OH)^{4-}$ and $Fe(OH)^{4-}$ are the dominant species [47].

Aluminium and iron hydrolysis products then destabilize pollutants present in the solution, allowing agglomeration and further separation by settling or flotation. Destabilization is achieved mainly by means of two distinct mechanisms, i.e.

1. Charge neutralization of negatively charged colloids by cationic hydrolysis products; and

2. "sweep flocculation", where impurities are trapped and removed in the amorphous hydroxide precipitate produced.

Several factors such as pH and coagulant dosage have an impact on charge neutralization and sweep flocculation.

Liberation of O_2 and H_2

Microbubbles (O_2 and H_2) released at the anode and cathode surfaces respectively bring about electroflotation by adhering to agglomerates and carrying them to the water surface due to natural buoyancy [48].

Reactions that take place on the electrode surface for the liberation of O2 and H2 are shown below: [49].

Anode: $2H_2O + O2 \rightarrow 4H^+ + 4e^-$

Cathode: $4H^+ + 4e^- \rightarrow 2H_2$

The gases evolved at the electrodes are helpful to remove the suspended solids in upward direction.

Reactions in presence of salt

Additionally, when the effluent also contains chloride ions which are generally the case in textile effluents, and the anode potential is sufficiently high, the following reactions may take place in the EC cell [50].

$2Cl^- \rightarrow Cl_2 + 2e^-$

The liberated Cl2 will react with water to generate hypochlorite ions

$Cl_2 + H_2O \rightarrow HClO + H^+Cl^-$

$HClO \rightarrow H^+ + OCl^-$

The formation of active chlorine species (Cl^-, HClO, OCl^-) enhances the performance of the EC reactor through oxidation reactions, such as oxidation of organic compounds and dyes present in the effluent.

Mechanism of Dye Removal

Formation rates of the different species play an important role in the decolorization process. Several interaction mechanisms are possible between dye molecules and hydrolysis products and the rates of these depend on pH of the medium and types of ions present.

Two major interaction mechanisms have been considered in recent years: precipitation and adsorption, each one being proposed for a separate pH range. Flocculation in the low pH range is explained as precipitation while it is explained as adsorption in the higher pH range (>6.5) [51].

Precipitation:

DYE + Monomeric Al → [DYE-Monomeric Al] (pH 4.0 – 5.0)

DYE + Polymeric Al → [DYE-Polymeric Al] (pH 5.0 - 6.0)

Adsorption:

DYE-Monomeric Al + $Al(OH)_3$ → [Particle]

DYE-Polymeric Al + $Al(OH)_3$ → [Particle]

Freshly formed amorphous $Al(OH)_3$ "sweep flocs" have large surface areas which are beneficial for a rapid adsorption of soluble organic compounds and trapping of colloidal particles. These flocs polymerize as

$nAl(OH)_3 \rightarrow Aln(OH)_{3n}$ and are removed easily from aqueous medium by sedimentation and H_2 floatation. The same mechanism is also valid for iron [46].

Wilcock and Brewster [52] suggested four mechanisms to describe the process by which dyes are removed from wastewater during electrocoagulation. These consist of surface complexation, electrostatic attraction, chemical medication, and precipitation. The chemistry of surface complexation is not well understood and is specific to each effluent, but is thought to occur in the following manner:

Dye-H + (HO)OFe → Dye-OFe + H_2O

Dye-H + (HO)OAl → Dye-OAl + H_2O

In addition, it may be possible to remove remaining dyestuff by simple electrostatic attraction as various surface complexes contain areas of apparent positive and negative charge. The attraction of opposite charges is sufficient to remove some dissolved species from the effluent stream.

Chemical modification may also occur on passage of effluent through the electrochemical cell as well as during subsequent degassing. The chemistry C= C and N= N (common in dyes) allows "catalytic hydrogenation" or reduction to occur in the presence of hydrogen gas and a catalyst. The presence of metal ions and hydrogen gas in this reaction suggests that the above could occur, but further research is required to confirm the extent of this mechanism and the conditions, which favour it.

Mechanism of COD Removal

Chemical Oxygen Demand (COD) is a measure of the amount of the oxygen used in the chemical oxidation of inorganic and organic matter present in wastewater. Degradation of pollutants in wastewater in its simple form decreases oxygen requirement for chemical oxidation hence decreases COD [53, 54].

A.C versus D.C Electrocoagulation Process [55]

The Direct Current Electrocoagulation (DCE) technology is inherent with the formation of an impermeable oxide layer on the cathode as well as deterioration of the anode due to oxidation. This leads to the loss of efficiency of the EC unit. This limitation of the DCE has been minimized to some extent by the addition of parallel plate sacrificial electrodes in the cell configuration.

However, few researchers have preferred the use of Alternating Current Electrocoagulation (ACE) technology. It is believed that the AC cyclic energization retards the normal mechanisms of electrode attack that are experienced in DCE system, and thus, ensuring reasonable electrode life.

Electrocoagulation Efficiency Parameters

The most important parameters influencing the efficiency of the EC process are the electrode type, shape and size, current density, treatment time, initial pH and the chemical composition of the aqueous solution being treated. Temperature, type of salt used to raise conductivity, presence of chloride, electrode gap, passivation of the anode and water flow rate also have an impact on the pollutant removal efficiency during electrocoagulation and durability of electrodes used [32].

The effect of various parameters is briefly discussed in the present paper. For details the readers are advised to refer the reference [37].

Electrode Types Shapes and Size

The process of electrocoagulation is totally dependent on the electrode types and the shapes and size. Most common electrode types are iron and aluminium while steel and other metals have also been used. The electrodes dissolve at anode and produce metal hydroxides which form large complexes with the pollutants and help in settling the pollutants. Iron and Aluminium ions and hydroxides have different chemistries and applications.

pH

It has been well established that the initial pH is an important factor and has a considerable influence on the performance of electrocoagulation process. pH of the wastewater influences the dissolution of aluminium/iron electrodes and affects the ζ potential of the colloidal particles and also on the speciation (formation of different species) of metal hydroxides in the solution. Different pollutants settle at different pH depending upon their chemical as well as electrical natures. Metals are generally removed at acidic pH while some like Cadmium are removed at alkaline pH. Most of the pollutants are more effectively removed at neutral pH. The effective removal of COD and TSS increased at pH 6-7 and after this the relationship becomes negative in nature [56,57].

Current Density

The amount of electrochemical reactions taking place on the electrode surface is proportional to Current density. Increase in current density in electrocoagulation causes production of metal hydroxides which shows strong affinity for dispersed and colloidal particles present in wastewater and helps in their coagulation and therefore removing COD and TSS [37].

Other Parameters [32]

Treatment time is relative to the amount of coagulants formed and other reactions taking place in the electrocoagulation system.

Temperature has an effect on formation of floc, conductivity of the solution and reaction rates. Depending on the pollutant, increasing temperature can have either good or bad effect on pollutant removal efficiency.

Electrode potential defines which reactions occur on the electrode surface.

Concentration of the pollutants affects the removal efficiency since coagulation does not follow zero order reaction kinetics but rather pseudo second or first-order kinetics.

Inter-electrode distance has effect on efficiency of the treatment and electricity consumption.

Advantages of electrocoagulation

Electrocoagulation has numerous advantages over other wastewater treatment processes:

- Electrocoagulation is usually recognized by ease of operation due to simple and compact treatment facility resulting in relatively low equipment, operation and maintenance cost. There is also a possibility of complete automation and hybridization with other water purification techniques such as ion exchange or membrane separation.

- Electrocoagulation has the capability to remove a large number of pollutants ranging from dissolved organic matter in the form of chemical and biological oxygen demand, suspended solids, colloidal particles, heavy metals, petroleum products, colour from dye-containing solution, flourine, pathogens etc.

- In most of the cases the process is able to remove color from the effluents up to 95%, BOD 60%. COD 70%. In many laboratory studies the COD removal is as high as 95%. Wastewater treated by EC gives clear, colorless and odorless water [37].

- The gas bubbles produced during electrolysis can conveniently carry the pollutant components to the top of the solution where it can be more easily concentrated, collected and removed by a motorised skimmer.

- The floc formed by EC are similar to chemical floc, except that EC floc tends to be much larger, contains less bound water, is acid-resistant and more stable, and therefore, can be separated faster by filtration.

- Dosing incoming wastewater with sodium hypochlorite assists reduction of Biochemical Oxygen Demand (BOD) and consequent Chemical Oxygen Demand (COD) although this should be avoided for wastewater containing high levels of organic compounds or dissolved ammonia (NH^{4+}) due to formation of Trihalogenated Methanes (THMs) or other chlorinated organic compounds.

- EC systems may also be designed to utilize renewable energy such as wind or solar energy, the price of which is currently significantly declining globally. Due to these facts and the compact size of EC systems, decentralized treatment may be valuable even in rural areas with no access to power grids. Furthermore, since the EC process can be started by turning on the switch, it requires minimal start-up time [30].

Disadvantages

- The sacrificial electrodes are dissolved into wastewater streams as a result of oxidation, and need to be regularly replaced.

- An impermeable oxide film may be formed on the cathode leading to the loss of efficiency of the EC cell.

- Another main disadvantage of EC is the need for adequate water conductivity [26].

- Industrial wastewater often has high enough conductivity due to its high ion concentration. However, e.g. natural water and lightly polluted wastewater lack this feature. Thus, their conductivity must be raised by using a supporting electrolyte. Due to its low price, availability, and non-toxicity, NaCl is the most common supporting electrolyte used [58].

- Toxic chlorinated organic compounds may form from water containing chlorides (e.g., from NaCl) and organic substances [59]

- The hydrogen gas produced could be explosive unless it is collected safely.

- No widely accepted mathematical/kinetic model for EC exists. However, this is more of an academic issue

Applications of Electrocoagulation

Several comprehensive reviews have been published covering the different aspects of EC applications [29-39]. However, as mentioned in the introduction section, the focus of the present paper is on combined EC processes for the recycle of treated water, therefore, only the techniques of electrocoagulation followed by ion exchange and

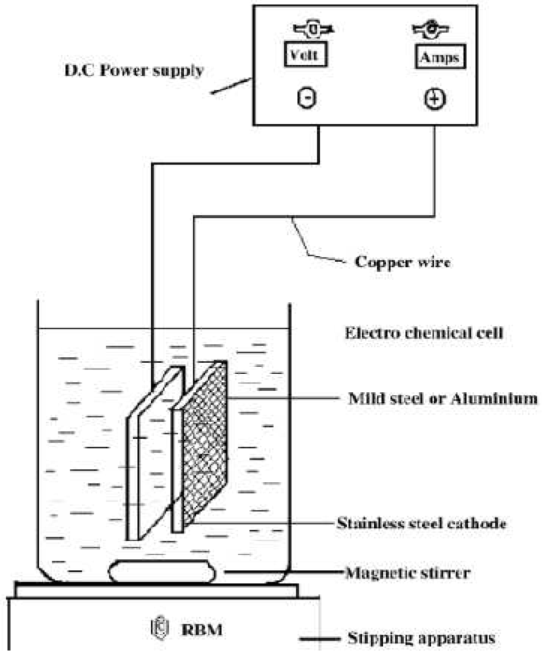

Figure 5: Electrochemical cell [60].

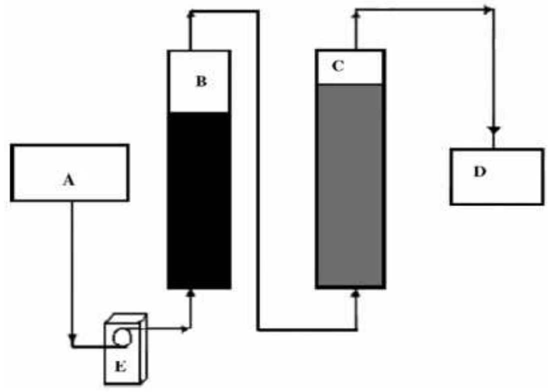

Figure 6: Ion exchange set up [60].
A: EC treated waste water, B: Cation exchange resin column, C: Anion exchange resin column, D: Reusable water, E: Peristatic pump

electrocoagulation followed by membrane separation are discussed. Although the combined processes discussed in the present paper are at the conceptual stage, they have potentials for scaling up to a commercial level for the treatment and recycle of textile wastewater and thus reducing the burden on environment and conserving the valuable resources of fresh water.

Electrocoagulation Followed by Ion Exchange, For Recycle Of Textile Wastewater

Raghu and Ahmed Basha examined the EC followed by ion exchange process on laboratory scale for the treatment and recycling of the textile dyeing effluent [60].

The experimental set up of electrochemical cell and ion exchange are shown in (Figure 5,6) respectively.

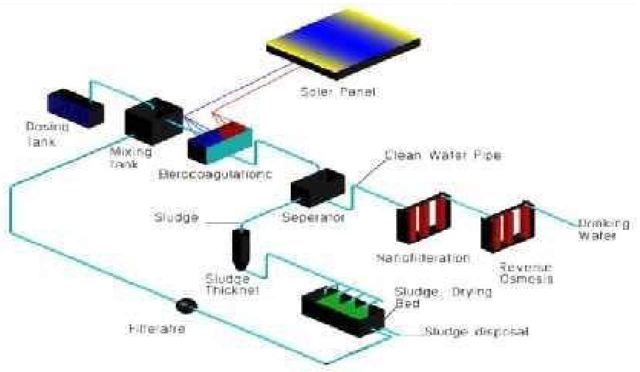

Figure 7: Flow diagram of textile effluent treatment scheme [61].

The textile effluent was subjected to electrocoagulation process using iron/aluminium electrode under various conditions of current densities and pH. Efficiencies of COD reduction, colour removal and power consumption were studied. The electrochemical treatment was indented primarily to remove colour and COD of wastewater while ion exchange was used to further improve the removal efficiency of the colour, COD, Fe concentration, conductivity, alkalinity and Total Dissolved Solids (TDS) to make the treated water suitable for recycling. During electrocoagulation maximum COD removal of about 92.31% (at 0.25 A/dm^2) was achieved with energy consumption of about 19.29 kWh/kg of COD and 80% (1 A/dm^2) COD removal was obtained with energy consumption of about 130.095 kWh/kg of COD at iron and aluminium electrodes, respectively.

Ion exchange

Electrochemically treated wastewater was subjected to ion-exchange process. The conductivity of the wastewater after electrocoagulation treatment was 5200 µmho/cm, against the reuse standard of 100 µmho/cm. Such a high conductivity of wastewater indicated that it still contained a significant amount of inorganic salts and other ions. To remove these ions and other impurities, both cross-linked divinylbenzene-polystyrene based cationic (Amberlite IR 120) and anionic (Amberlite IRA 400) ion-exchange resins were used in the flow cell experiment. As a result, finally ion free water was obtained.

The experimental results indicated that electrocoagulation treatment followed by ion-exchange methods was very effective and was capable of elevating quality of the treated wastewater effluent to the reuse standard for the textile industry.

Electrocoagulation followed by membrane separation (Use of solar energy for EC cell): Amita Deokate investigated the EC of textile waste water using solar energy powered Electrochemical cell [61]. After electrocoagulation the treated water was passed through two membranes, nano-filter and reverse osmosis membranes to make the textile waste water potable/recyclable. The bench model of the effluent treatment plant is schematically shown in (Figure 7) [61].

Typical removal rates after electrocoagulation achieved were as follows:

Colour removal Complete

- TSS 94%

Table 1: Reduction of impurities from textile wastewater after electrocoagulation and membrane treatments [61].

Sr.no	Parameter	Before treatment	Treatment voltage and time during electrocoagulation				After membrane treatment
			30V, 15min	40V, 30min	60V, 60min	90Vmin, 90min	
1	Color	Blackish Brown	-	-	-	-	Colorless
2	pH	9.2	8.5	7.5	6.5	7.5	7.0
3	COD	3162	2500	1500	400	250	Nil
4	TDS	2260	1900	1250	900	500	100
5	TSS	1675	1500	1000	500	100	50
6	BOD	307	290	180	100	50	Il
7	Alkalinity	1300	100	500	10	Nil	Nil
8	Chloride	1200	900	700	500	50	10

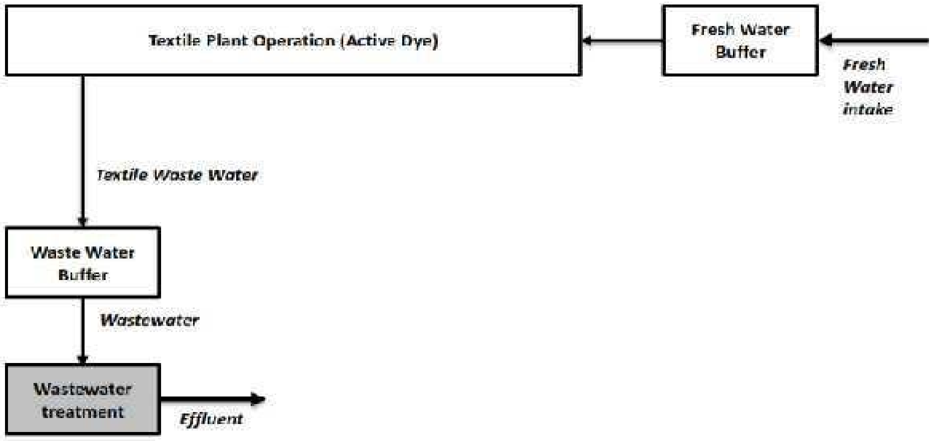

Figure 8: Typical textile mill operations [65].

- TDS77.87 %

- BOD 83.71%

Nano filtration and reverse osmosis: EC treated water was then subjected to nano-filtration (filter pore size 0.001 micron and reverse osmosis (filter pore size around 0.0001 micron). Nanofiltration removed most organic molecules, nearly all viruses, most of the natural organic matter and a range of salts. After water was passed through a reverse osmosis filter, it was essentially pure water. In addition to removing all organic molecules and viruses, reverse osmosis also removed most minerals that were present in the water. Reverse osmosis removed monovalent ions, which means that it desalinated the water making it suitable for recycling.

The reduction of impurities from textile wastewater after electrocoagulation under different voltage and time conditions and after membrane filtration are shown in (Table 1).

Though the investigations were carried out on bench model scale, the research throws light on the possibility of the use of environmentally friendly solar energy as a source of DC electricity and the membrane filters to make textile effluent potable/recyclable.

European consortium to demonstrate EColoRO concept for wastewater reuse in the textile industry [62-64]: On June 1, 2015 the European consortium led by the Dutch company EColoRO BV and the Institute for Sustainable Process Technology (ISPT) in Netherlands announced the commence of a 3.5-year project to demonstrate the new technology on site at full industrial scale, first at a textile mill in Belgium and later at a textile mill in Italy.

The project, which is part of Europe’s Horizon 2020 research program, has a budget of €4.8 million, of which €3.7 million will be provided by the European Union. The other consortium members are Belgian textile mill, Belgium’s VITO institute for technology research, Czech company INOTEX Ltd, Dutch company Morselt Borne BV, and EURATEX – the European Apparel and Textile Confederation. EColoRO will provide operational management and ISPT is responsible for overall project coordination. The consortium consists of a focused and well-balanced team with key know how on wastewater purification (VITO, EColoRO), textile technology and production (Inotex, Utexbel), electrocoagulation and engineering (Morselt), process technology, innovation and project support (ISPT) and EU wide market access in the textile sector (Euratex).

An advisory board with stakeholders from textile, process industry and waste water sectors will provide guidance, critical feedback and dissemination support.

The EColoRO technology consists of electrocoagulation followed by membrane filtration. The electrocoagulation enables the removal of 93 to 96 per cent of the dyes and pigments in the textile wastewater. The waste water will then be purified using membranes in ultra-filtration and reverse osmosis steps.

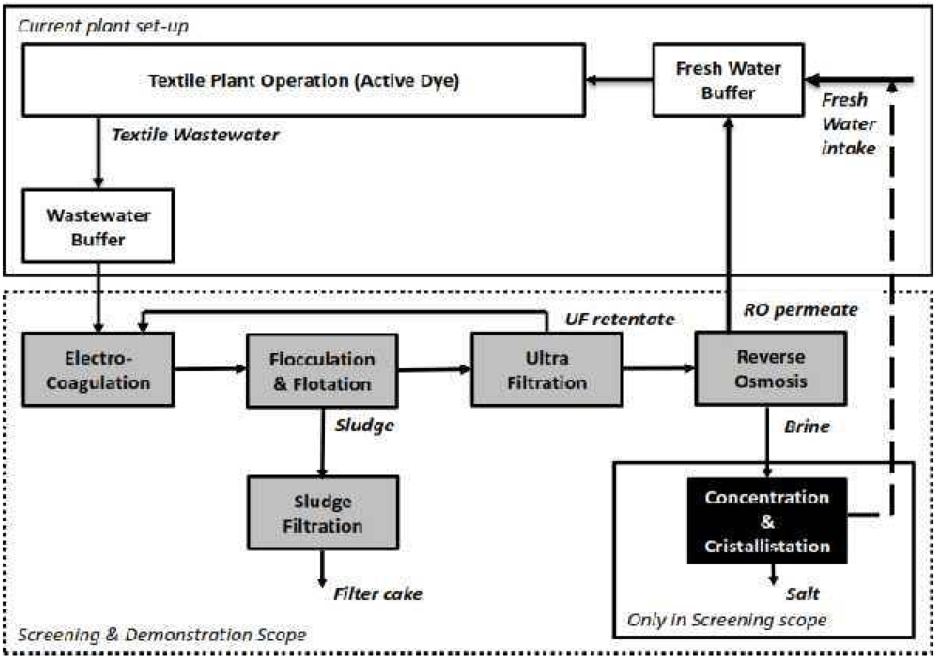

Figure 9: EcoloRO concept [65].

The aim of ECWRTI project is to demonstrate this innovative EColoRO technological concept for treatment of wastewater from textile industry at full industrial scale in textile mills in Belgium and Italy. Together with the demonstration of industrial application of the EColoRO concept, the project will also investigate optimal reuse of treated wastewater in textile manufacturing process aiming to close the water loop. It is estimated that using this technological concept, companies can reduce their water consumption by up to 90%. Also the reuse of the pigments/dyes and iron-rich slurry generated during the treatment process will be investigated within the project.

This technological solution contributes to the qualitative and quantitative protection of the water resource and reflects the zero-waste approach as one of the principles of circular economy strategy supported by European authorities as a concept of the way to a resource-efficient processing.

Technology [65]

The technology is at the development stage, therefore, full technical details are not yet disclosed. The present status of the technology is the development of demonstration plant. It is envisaged to implement the technology on commercial scale in two textile mills, first in Belgium and then in Italy. Therefore, presently only the technology concepts are available in the form of schematic diagrams as shown in (Figure 8-10) [65].

The EcoloRO concept

In EcoloRO concept the textile effluent is treated in two steps:

Step 1: Subjecting the textile waste water to electrocoagulation

At this stage chemical impurities such as COD, BOD, Suspended and colloidal particles are removed to an extent of 93-96% and color removal is almost 100% except salts and other dissolved solids.

Step 2: Ultra filtration followed by Reverse Osmosis

At this stage all the residual impurities including total dissolved solids in the form of common salt and other electrolytes are removed making water recyclable.

The close loop cycle of EcoloRO concept is shown in (Figure 9) [65]. The entire process flow diagram is shown in (Figure 10) [65]. Strict control analysis at each step is used to confirm the efficiency of the different processes. It is estimated that using this technological concept, companies can reduce their water consumption by up to 90%.

Researchers now plan to upscale the existing test unit to a bigger one to be used at the factory, with an eye to creating a closed loop where water is constantly recycled and reused [66].

The EColoRO concept is an excellent alternative to existing energy-intensive wastewater treatment techniques. The new technology is also very useful for textile mills in water-deficient areas in Europe and other developing countries like India where the provision of drinking water is a growing problem. It also aligns with the industry's desire to increase the use of energy from renewable resources, in this case the use of renewable electricity e.g. solar energy can be used to treat and reuse large quantities of process wastewater [63].

Scientists at the consortium hope this technology could also improve the competitiveness of the textile and clothes manufacturing sector in the European Union, that employs some 1.6 million people [66].

This technological solution contributes to the qualitative and quantitative conservation of the water resource and reflects the zero-waste approach as one of the principles of circular economy strategy supported by European authorities as a concept of the way to a resource-efficient processing. [62].

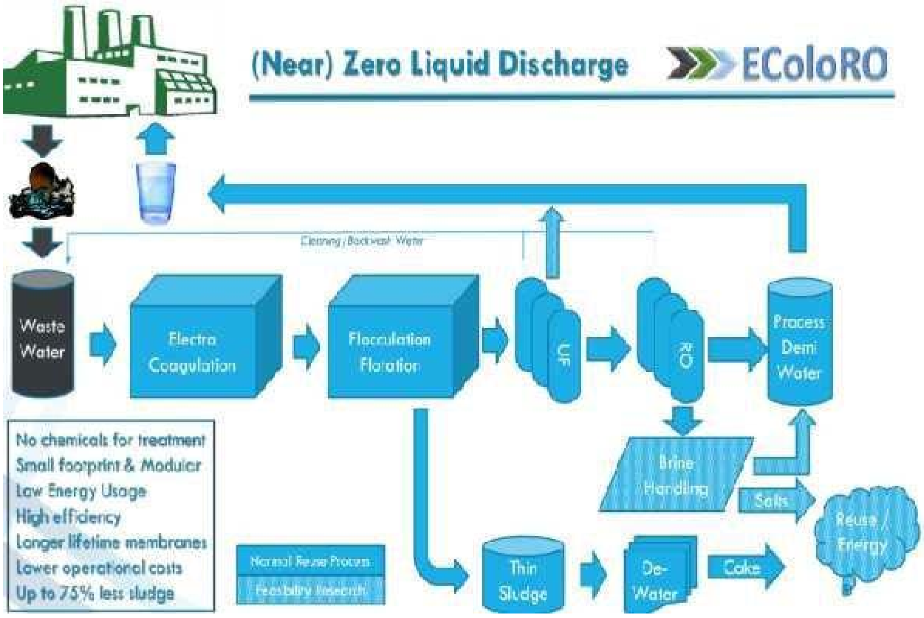

Figure 10: EcoloRO process flow diagram [65].

Advantages [64]

The key advantages of EcoloRO concept are:

- 90% reuse of waste-water in textile industry reducing fresh-water intake by at least 75%.
- Low-cost and economically highly attractive.
- Very flexible, containerized for easy transport and modular, easy scalable, low footprint, suitable for retro-fit, brown field or green field applications.
- Low energy use, no use of chemicals or flocculants.
- Enabler for optimizing use of water, allowing for renewable energy and resource efficiency in the textile manufacturing processes

EColoRO's innovative approach integrates electrocoagulation with systems that are already being used in industrial applications, accelerating the step to commercial market implementation when the project completes [63].

Cost comparison

Technical advantages of electrocoagulation over conventional waste water treatment processes have been pointed out by several researchers; limited information is available on the cost benefits of electroagulation compared to traditional methods of waste water treatment. Ahmed Samir Nanje et al., has compared the cost analysis of electrocoagulaion with chemical coagulation process. The impact of several operating parameters such as bipolar electrode element (Fe or Al), electrolysis time (RT), current Intensity (I), pH, chemical support, Interelectrode Distance (IED), and stirring speed(Mrpm) were examined. Additionally, the consumption of electrodes and electrical energy, sludge compaction, operating costs comparison with the traditional chemical coagulation method has been investigated. The most suitable EC performance was achieved by using monopolar and bipolar aluminium-type plates. Under optimal operating conditions of I=0.6 A, pH=6, NaCl=0.1 kg/m^3, IED=0.5 cm, and Mrpm=500, high removal efficiency of COD (92.6%), TSS (96.4%), color (96.5%), BOD5 (88%), TDS (87%), turbidity (96%), phenols (over 99%), and phosphate (95%) was achieved. The overall operating cost for the EC operation was 1.76US$/m^3. This value was calculated based on the electrode and energy consumption, chemicals, and sludge disposal. In comparison, under optimum conditions the operating cost of chemical coagulation using Aluminium sulphate as coagulant was US$2.86/m^3. This indicated the superiority of electrocoagulation over chemical coagulation both in terms of better quality of treated water at low cost [67]. Due to excellent removal of suspended solids and the simplicity of the EC operation, tests conducted for the U.S.Office of Naval Research concluded that the most promising application of EC was found to be as pre-treatment to a multi-membrane system of Ultrafiltration/Reverse Osmosis (UF/RO) or Microfiltration/Reverse Osmosis (MF/RO). In this function the EC provides protection of the low-pressure membrane that is more general than that provided by chemical coagulation. EC is also very effective at removing a number of membrane fouling species (such as silica, alkaline earth metal hydroxides and transition group metals) as well as removing many species that chemical coagulation alone cannot remove [44]. In this way the life of RO membrane is increased, indirectly giving the cost advantage compared to chemical coagulation followed by RO process.

Conclusion

Water is becoming scarce commodity, therefore, there is need to conserve water to the extent possible. In view of this, serious attempts are being made to recycle wastewater not only in textile industry but in all industrial sectors. The present paper establishes the fact that combined electrocoagulation-ion exchange or combined electrocoagulation-membrane separation processes have great future to treat textile wastewater to make it suitable for recycling. Though such combined processes presently are at the conceptual stage, it is apparent that these technologies will continue to make inroads into the wastewater treatment arena because of their numerous advantages and changing strategic global water needs.

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