International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

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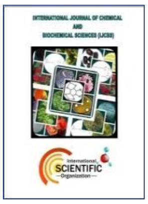

Electrocoagulation and other recent methods for drinking water treatment – A review

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Abstract

Water scarcity is the greatest current and future challenge that is faced by mankind as the world's population is growing at rapid pace and the rate of water consumption is expected to be doubled since 2050. This fact has led to a renewed interest in developing cost efficient, more reliable and highly environmental friendly wastewater treatment technologies that would be able to reuse the huge amounts of wastewater generated by numerous industries constituting organic pollutants and hazardous inorganic substances along with toxic heavy metal ions. Wastewater treatment technologies could be categorized into three major groups: physical methods, chemical processes and biological treatment technologies. In process of electrocoagulation, in-situ energy production is made possible via electro-oxidation of a sacrificial anode that ultimately breaks the emulsions and solid suspended particles in three basic steps by forming the electrical double layer through applying specific amount of electric current in accordance with Faraday's Law. Nevertheless, this process is significantly affected by the nature of electrolyte, initial pH of experimental solution, effect of temperature and effect of inter electrode distance. The theory of stabilization and destabilization of contaminants is also discussed in detail in this review. In short, this review attempts to highlight the main achievements in the area and outlines the major shortcomings with recommendations for promising research options that can enhance the technology and broaden its range of applications at commercial scale.

Key words: Wastewater, Electrocoagulation, Reverse Osmosis, Industrial Effluents, Hazardous Toxicants, Organic Pollutants, Inorganic Impurities

Full length article

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1. Introduction

Water shortage is one of the greatest current and future challenges that are faced by humankind as the world's population and water use rates are continue to grow. This has led to a resume interest in growing cost effective, reliable and environment friendly wastewater treatment technologies that would be able to reuse the huge amounts of wastewater produced from various industries. However some wastewater treatment technologies are available and have been applied for a long period, most of these water treatment technologies consume huge amount of energy from carbon-based energy sources which are non-renewable and contribute to carbon dioxide emissions. Wastewater treatment technologies could be classified into three major groups: physical, chemical or biological processes. A typical wastewater treatment plant consists of a mixture of physical, chemical and biological unit operations to target the removal of different components/pollutants. Physical unit operations depend completely on the physical change in the chemical or biological characteristics of the treated water [1].

Chemical processes are measured as progressive processes as they require the addition of chemicals to react with the desired pollutants to remove it. The nature of additive chemical process makes them unattractive as compared to other processes as they increase the net dissolution of components in wastewater and render it impractical to reuse in other applications. Biological unit processes use microorganisms for the biodegradation of contaminants in wastewater, and the main purpose of these processes is to cut down the organic contents and nutrients in wastewater. Biological units are generally classified into aerobic, anaerobic or facultative depending on the availability of dissolved oxygen in wastewater. Other than the above-mentioned processes, rather more promising and relatively new technologies that use the concepts of electrochemistry are also available such as electrocoagulation, electro oxidation and electro floatation. Although using electricity for water treatment applications goes back to the 19th century, when electrocoagulation was used for the treatment of drinking water in the United States, they were found impractical due to the high capital and electricity cost required. During the last 20 years, electrochemical wastewater treatment technologies started to attain importance as an environmental friendly option that release minimum sludge and requires no chemical additives and minimum footprint without compromising the quality of the treated water.

This article focuses on reviewing recent advances in electrocoagulation with the purpose of identifying the current state of the technology and its potential as an effective water treatment method. Despite the considerable number of publications in electrocoagulation they tend to focus on laboratory scale experiments that prove the effectiveness of the technology in the removal of particular pollutants. Few authors looked into the kinetics, modeling, cell design, cost analysis, integrating electrocoagulation with existing technologies, scale-up and industrial applications, which are key factors that represent major challenges to the success of electrocoagulation. This review attempts to point out specific gaps where more research is needed for the development of electrocoagulation as an authentic and cheaper water treatment technology. Electrocoagulation is an emerging technology in water and wastewater treatment, as it combines the benefits of coagulation, flotation and electrochemistry [2].

The theory behind coagulation/flocculation and electrocoagulation is basically the same. Both methods target the removal of particles from wastewater through destabilizing/neutralizing the repulsive forces that keep the particles suspended in water. When the repulsive forces are neutralized, the suspended particles will form larger particles that can settle down for easier separation from water. The most provoking advantage of the electrocoagulation over chemical coagulation/flocculation is that coagulation/flocculation uses chemical coagulants/flocculants like metal salts or polyelectrolyte while in electrocoagulation the coagulants are generated insitu by the electrolytic oxidation of an appropriate anode material which results in much less mud generation. Another major advantage of electrocoagulation over chemical coagulation/chemical flocculation and other common water treatment methods is the potential of treating oily water, where the presence of electric current can contribute to the electro coalescence of oil droplets. Electro coalescence has been proven successful in dealing with tight emulsions, where droplets are very small, very tight emulsions are often experience in oil and gas industry, either through the presence of fine water droplets in oil or vice versa, as is the case in produced water [1].

Various physical processes such as screening, floatation, filtration and sedimentation and chemical processes like coagulation/flocculation, chlorination, adsorption and ion exchange and biological processes like trickling filters, aerated lagoons and activated sludge are most commonly used. Chemical processes like coagulation is one of the most important physio-chemical operations used in water treatment. This is a process used to cause the destabilization and then collection of smaller particles into larger complexes. Water pollutants such as ions (heavy metals) and colloids (organic and inorganic) are mainly held in solution by electrical charges. Colloidal systems could be destabilized by the addition of ions of the charge opposite to that of the colloid. The destabilized colloids can then mix and afterward be separated from the wastewater. Coagulation can be attained by both the chemical or electrical means. Chemical coagulation has been used for destabilized suspensions and to effect precipitation of soluble species and other pollutants from aqueous streams. Alum, lime and polymers are some of the chemical coagulants used. These processes however tend to generate large volumes of sludge with high bound water contents which can be difficult to separate and dewater.

The processes also run to increase the total dissolved solids content of the waste material, making it unacceptable for reuse within industrial applications. Other aspects of chemical coagulation are also becoming increasingly less acceptable. The disposal cost of large volumes of sludge (generally of fairly high hazardous waste category), the cost of the chemicals required to achieve coagulation and the environmental issues associated with the process are major problems in many industries.

Electrocoagulation, the process of passing the electrical current through water, has proven very effective in removal of contaminants from water. Electrocoagulation systems have been in existence for many years using a variety of anode and cathode geometries, such as plates, balls, fluidized bed spheres, wire mesh, rods and tubes. Although electrocoagulation mechanism resembles the chemical coagulation-the cationic species being responsible for the neutralization of surface charges in many ways however it is very different as well. Electrocoagulation is a process of destabilizing suspended, emulsified or dissolved contaminants in an aqueous medium by introducing electrical current in the medium. The electrical current provides the electromotive force causing the chemical reactions [3].

The removal of heavy metals from industrial waste has become one of the most essential applications in wastewater treatment in terms of protection of health as well as the environment. These heavy metals are known to be among the most common pollutants found in industrial wastewaters, pose serious health hazard and are environmentally unfriendly because they are not biodegradable and tend to accumulate in living organisms. Cadmium is a toxic non-essential heavy metal in the environment; it is teratogenic and carcinogenic in nature. Cadmium toxicity causes renal damage pulmonary insufficiency and negative effects on bones, liver and blood. Cadmium poisoning, therefore, creates far greater likelihood of weaker and weaker constitution of such parts of the body obviously performing vital bodily functions. The drinking water guideline value is 0.005 mg. The increased water use and wastewater discharge, particularly industrial wastewater, have added impurities to water which requires cleaning process [4].

It is important to note that the overall treatment cost of metal-contaminated water varies, depending on the process employed and the general conditions. In general technical applicability, simplicity and cost-effectiveness are the key factors in selecting the most suitable treatment of inorganic pollutants. Physical methods such as ion exchange, reverse osmosis and electrodialysis have proved to be either too expensive or costly to remove cadmium from water. Few years ago, electrocoagulation has been suggested as an effective method to treat many types of effluents like wastewater charged with heavy metals, natural water charged with surface water, suspended solids, oils and fats in restaurant wastewater, black liquor from paper industry and cigarette factory wastewater. All these investigations showed that electrocoagulation could achieve a significant reduction of major pollutants and is known to have growing interest on industrial scale.

Electrocoagulation is a simple and efficient process where the production of coagulating agent is managed insitu by means of electro-oxidation of a sacrificial anode. In this case, there is no need for adding chemical coagulants or flocculants to perform the treatment. In process of electrocoagulation, the destabilization mechanism of the contaminants, particles suspension and breaking of emulsions can be summarized as three successive steps such as (a) compression of the diffuse double layer around the charged species by the interactions of ions generated by oxidation of the sacrificial anode (b) charge neutralization of ionic species present in wastewater by counter ions produced by the electrochemical dissolution of sacrificial anode where these counter ions reduce the electrostatic inter-particle repulsion to the extent that the van der waals attraction predominates, thus causing coagulation thereby resulting a zero net charge in process and (c) flocs formation that formed as a result of coagulation thereby creating a sludge blanket that entraps and bridges colloidal particles which are still remaining in the aqueous medium [5].

2. Contaminants in Drinking Water

An equal supply of safe drinking water is one of the major requirements for a healthy life but waterborne disease is still a major cause of death in many parts of the world, particularly in children, and it is also a significant economic constraint in many subsistence economies. Drinking water is derived from two basic sources: surface waters, such as rivers and reservoirs, and groundwater. All water contains natural contaminants, particularly inorganic contaminants that arise from geological strata through which water flows and to varying extent, anthropogenic pollution by both microorganisms and chemicals. In general, groundwater is less vulnerable to pollution than surface waters.

There are a number of possible sources of man-made contaminants, some of which are more important than others. These fall into two categories such as point sources and diffuse sources. Discharges from industrial premises and sewage treatment works are point sources and are readily identifiable and controlled whereas runoff from agricultural land and hard surfaces such as roads are not so obvious or easily controllable. Such sources can give rise to a significant variation in the contaminant load over time. There is also the possibility of overturn of chemicals from industry and agriculture and slurries from intensive farm units that can contain pathogens. In some countries, badly sited latrines and septic tanks are a significant source of contamination, especially of wells. Local industries can also give rise to contamination of water sources, particularly when chemicals are handled and disposed of without proper care. The run-off or leaching of nutrients into slow flowing or still surface waters can result in excessive growth of cyanobacteria or blue-green algae [6].

Many species give rise to avoidance of chemicals that can cause taste and odour and interfere with drinking water treatment. However, they regularly produce toxins, which are of great concern for health, particularly if there is only limited treatment available. If treatment is not optimized, unwanted residues of chemicals used in water treatment can also cause contamination and give rise to sediments in water pipes. Contamination during water distribution may arise from materials such as iron, which can corrode to release iron oxides or from ingress of pollutants inside the distribution system. Diffusion through plastic pipes can occur, for example when oil is spilt on the surrounding soil it gives rise to taste and odour problems. Contamination can also take place in consumers’ premises from materials used in plumbing, such as lead or copper or from back-flow of liquids into the distribution system as a consequence of improper connections. Such contaminants can be either chemical or microbiological.

Drinking water treatment as applied to public water supplies consists of a series of barriers in a treatment train that will vary according to the requirements of supply and the nature and vulnerability of the source. Broadly these comprise systems for coagulation and flocculation, filtration and oxidation. The most common oxidative disinfectant used is chlorine. This provides an effective and robust barrier to pathogens which measured an easily measured residue that can act as a marker to show that disinfection has been carried out, and as a preservative in water distribution. The basis on which drinking water safety is judged is national standards or international guidelines. The most important of these are the WHO Guidelines for Drinking-Water Quality. These are revised on a regular basis and are supported by a range of detailed documents describing many of the aspects of water safety. The guidelines are now based on water safety plans that encompass a much more proactive approach to safety from source-to-tap.

The contamination of drinking water by pathogens causes diarrheal diseases which is the most important aspect of drinking water quality. The problem arises as a consequence of contamination of water by faecal matter, particularly human faecal matter, containing pathogenic organisms. One of the great scourges of cities in Europe and North America in the 19th century was outbreaks of waterborne diseases such as cholera and typhoid. In many parts of the developing world, it remains a major cause of disease. It is therefore essential to break the faecal–oral cycle by preventing faecal matter from entering water sources and/or by treating drinking water to kill the pathogens. However, these approaches need to operate alongside hygiene practices like hand washing, which reduce the level of person-to-person infection [7].

Detection and investigation of pathogens in water are not allowed under most of the circumstances in view of the difficulties and resources required. So, *Escherichia coli* and faecal streptococci are used as indicators of faecal contamination. The assumption is that if indicators are detected, pathogens, including viruses, could also be present and therefore appropriate action is required. However, the time taken to carry out the analysis means that if contamination is detected, the contaminated water will be well on the way to the consumer and credibly drunk by the time the result has been obtained. In addition, the small volume of water sampled (typically 100 ml) means that such check monitoring on its own is not an adequate means of assuring drinking water safety. It is also essential to ensure that the multiple barriers are not only in place but working comfortably at all times, whatever the size of the supply is. Drinking water is not, however, germs and bacteria can be found in the distribution system and even at the tap. Most of these organisms are harmless but some opportunist pathogens like *Pseudomonas aeruginosa* and *Aeromonas* spp. may multiply during distribution under suitable sets of conditions [8].

Currently there is some debate as to whether these organisms are responsible for any waterborne, gastrointestinal disease in the community but *Psedomonas aeruginosa* is known to cause infections in immuno-compromised patients and weakened patients in hospitals. A number of organisms are emerging as potential waterborne pathogens and some are recognized as significant pathogens that give rise to detectable waterborne outbreaks of infection. The most important of these is *Cryptosporidium parvum*, a protozoan, gastrointestinal parasite which gives rise to severe self-limiting diarrhoea and for which there is, currently, no specific treatment. *Cryptosporidium* is excreted as oocysts from infected animals, including humans, which enables the organism to survive in the environment until ingested by a new host. This organism has given rise to a number of waterborne or water associated outbreaks in the UK and an outbreak of cryptosporidiosis in Milwaukee in the USA resulted in many thousands of cases, and probably a number of deaths among the portion of the population which were immuno-compromised.

The most important barriers to infection are those that remove particles, including coagulation, sedimentation and filtration. However, water is not the only source of infection. It is probable that person-to-person spread following contact with faecal matter from infected animals is more important and there have been outbreaks involving milk and swimming pools. Currently, there is no scientifically based standard for *Cryptosporidium* in drinking water. A similar parasite, *Giardia* has been found responsible for a number of cases of gastrointestinal illness and in the USA; illness was referred to as beaver fever because beavers were shown to be a source in some areas. As with *Cryptosporidium*, water is not the only source but, unlike *Cryptosporidium*, it is reasonably susceptible to chlorine and because of its larger size it can be removed more easily by particle removal processes [9].

Although the common waterborne diseases of the 19th century are now almost unknown in developed countries, it's important that vigilance is maintained at a high level because these diseases are still common in many parts of the world. The seventh cholera pandemic, which started in 1961, arrived in South America in 1991 and caused 4700 deaths in 1 year. According to the Report of WHO in 1998, over 1 billion people do not have an adequate and safe water supply out of which 800 million are in rural areas. WHO also estimate that there are 2.5 million deaths and 4 billion cases due to diarrheal disease, including dysentery, to which waterborne pathogens are a major contributor. There are still an estimated 12.5 million cases of *Salmonella typhi*per per year and waterborne disease is endemic in many developing countries. In this age of rapid global travel, the potential for the reintroduction of waterborne pathogens in developed countries still remains.

In addition, as our knowledge of microbial pathogens improves, we are able to identify many other organisms that cause waterborne disease. The Norwalk-like viruses are named after a major waterborne outbreak in North America, and there is a range of emerging pathogens including *Campylobacter*, a major cause of food poisoning and *Escherichia coli* O157, which has caused deaths in North America where chlorination was not present or failed and all other barriers were found to be inadequate [8]. Microbial contamination of drinking water thus remains a significant threat and constant vigilance is essential, even in the most developed countries.

There are many sources of chemical contaminants in drinking water. However, the most important contaminants from a health standpoint are naturally occurring chemicals that are usually found in groundwater. Waterborne arsenic is a major cause of diseases in many parts of the world including Indian sub-continent, particularly Bangladesh and Bengal, South America, and the Far East. It is the only contaminant that has shown to be the cause of human cancers through exposure via contaminated drinking water. Besides the cancer of skin, lung and bladder and probably liver cancer, arsenic is responsible for a range of adverse effects including hyper-keratosis and peripheral vascular disease [7].

However, epidemiological data also demonstrate that many local factors are important, including nutritional status. There are considerable difficulties in assessing arsenic exposure. In Bangladesh, where millions of tube wells were sunk, the concentration of arsenic can vary significantly between wells only a short distance apart. WHO have set a provisional guideline value of 10 µg/l based on the practical limit of achievability, but there is an ongoing discussion on the scientific basis for this guideline, including whether the available data would allow distinction between a standard of say 5, 10 or 15 µg/l and whether exposure to 50 µg/l, the old guideline, will result in illness.

Waterborne fluoride is another major cause of disease un different parts of the world, including the Indian sub-continent, Africa and the Far East, where concentrations of fluoride can exceed 10 mg/l. High intakes of fluoride can give rise to dental fluorosis, an unsightly brown mottling of teeth, but higher intakes result in skeletal fluorosis, a condition arising from increasing bone density and which can eventually lead to fractures and crippling skeletal deformity. A WHO working group concluded that skeletal fluorosis and an increased risk of bone fractures occur at a total intake of 14 mg fluoride per day, and there is evidence suggesting of an increased risk of bone effects at intakes above about 6 mg fluoride per day [7]. This is a major cause of diseases and can manifest itself at a relatively early age with the result that affected individuals cannot work properly and may be economically as well as physically disadvantageous for life. Many factors appear to influence the risk of such adverse effects, including volume of drinking water, nutritional status and particularly fluoride intake from many other sources.

Selenium and uranium have also both been shown to cause adverse effects on humans through drinking water. Water can contribute to high selenium intakes, which can give rise to loss of hair, weakened nails and skin lesions, and more serious effects include changes in peripheral nerves and decreased prothrombin time [7]. Uranium is found in groundwater associated with granitic rocks and other mineral deposits. It is a kidney toxin and has been associated with an increase in fractional calcium excretion and increased micro-globulin-urea, although within the normal range found in the population. Uranium is a current topic of research with regard to exposure through drinking water [7].

Both iron and manganese can occur at high concentrations in some source waters that are anaerobic in nature [7]. When the water is aerated they are oxidized to oxides that are of low solubility. These will cause significant discoloration and turbidity at concentrations well below those of any concern for health. They may, however, cause consumers to turn to alternative supplies which may be more aesthetically acceptable but are microbiologically unsafe.

Agriculture is another source of chemical contamination. In this case, the most important contaminant is nitrate, which can cause methaemoglobinaemia or blue-baby syndrome in bottle-fed infants under 3 months of age [10]. There remains uncertainty about the precise levels at which clinically apparent effects occur and it also seems that the simultaneous presence of microbial contamination, causing infection, is an important risk factor [11]. The WHO have proposed a guideline value of 50 mg/l nitrate based on studies in which the condition was rarely seen below that concentration, but was increasingly seen above 50–100 mg/l. However, when nitrite is also present, this must also be taken into account, since it is about 10 times as potent as methaemoglobinaemia agent as nitrate. Concern is often expressed about pesticides in drinking water but there is a little evidence that this is a cause of illness, except perhaps following a spill with very high concentrations [12]. In Cambodia, media and public concern regarding pesticides in drinking water resulted in an expensive analytical exercise being carried out that found none of the pesticides of concern. One of the greater concerns is the run-off of nutrients to surface waters, often combined with sewage discharges that lead to significant growths of cyanobacteria. There is a wide range of toxins produced by these organisms and it is probable that not all the toxins have been identified to date.

Urban pollution, industrial wastes and human dwellings are also a source of potential contaminants. The most common are heavy metals and solvents like tri and tetra-chloro-ethene, which are sometimes found in groundwater and hydrocarbons, particularly from petroleum oils. There is little good evidence that these pollutants occur at concentrations in drinking water that are sufficient to cause health effects, but some of the low molecular weight aromatic hydrocarbons can give rise to severe odour problems in drinking water at concentrations less than 30 µg/l.

Drinking water treatment is intended to remove various microorganisms and chemical contaminants. Nevertheless, the process can itself result in the formation of other contaminants such as trihalomethane and halo-acetic acids from the reaction of chemical oxidants with naturally occurring organic matter. This requires a balance to be struck between the benefits of the chemical oxidants in destroying microorganisms and the potential risks from the by-products. Of these by-products, only trihalomethane tend to be routinely monitored in drinking water and the standard for total THMs in the UK is 100 µg/l. However, water treatment can take many forms and can use different chemicals including chlorine, chloramines, chlorine dioxide and ozone. Each treatment methodology has certain advantages and disadvantages, but all of them form by-products of some sort. The type and quantities of by-products formed depend on a number of factors. The formation of by-products during chlorination (one of the most common treatments), for example depends on the amount and content of organic matter, bromine levels, temperature, pH and residence time. Uptake of trihalomethane, generally the most common volatile DBP, can occur not only through ingestion, but also by inhalation and skin absorption during activities such as swimming, showering and bathing. For most other DBPs, ingestion is the main route for uptake [13].

DBPs have been associated with cancers of bladder, colon and rectum and adverse birth outcomes like spontaneous abortion, (low) birth weight, stillbirth and congenital malformations in epidemiological studies and to a much lesser extent at higher levels in toxicological studies. However, the overall evidence is inconsistent and inconclusive [14]. Endocrine disrupters are chemicals that interfere with endocrine system, for example by mimicking the natural hormones. They may be associated with a range of adverse reproductive health effects; including sperm count decline, hypospadias and cryptorchidism, and cancer of the breast and testes, although the current human evidence is weak [15]. Phthalates, bisphenols, alkyl phenols, alkyl phenol ethoxylates, polyethoxylates, pesticides, human hormones and pharmaceuticals have all been implicated and sewage effluent discharged to surface water has been shown to contain many of these substances [16]. Since many surface waters which receive sewage effluent are subsequently used as drinking water sources (*i.e.* re-use of water), it is important that the water is properly treated, which will remove these substances. Effects on wildlife, such as fish exposed to sewage effluent, have been reported but there is currently little evidence that humans drinking tap water are affected by such types of effluents.

3. Process Description of Electrocoagulation

Electrocoagulation is a simple and efficient process where the production of coagulating agent is managed in coagulants or flocculants to perform the treatment. In the electrocoagulation process, the insitu energy is produced by means of electro-oxidation of a sacrificial anode. In this case, there is no need for adding chemical destabilization mechanism of the contaminants and particles suspension. Breaking of emulsions can be summarized in three successive steps (1) compression of the diffuse double layer around the charged species by the interactions of ions generated by oxidation of sacrificial anode (2) charge neutralization of the ionic species present in wastewater by counter ions produced by the electrochemical dissolution of the sacrificial anode and (3) these counter ions reduce the electrostatic inter-particle repulsion to the extent that the van der Waals attraction predominates, thus causing coagulation. A zero net charge results in the process [5].

A typical system for electrocoagulation includes a feeding tank, reaction chamber with electrodes, a development tank where the reactions initialized within reaction chamber complete; and a sludge separation unit specific to various types of effluent treated [17]. Electrocoagulation is known to have a long history as the first plant was built in London in 1889 for the treatment of sewage. Despite some promising results, the success of this technology has been limited. However, there has been renewed scientific, economic and environmental interest in this technology in recent years due to the demand of alternative water treatment technologies. Electrocoagulation understandably has several similarities with chemical coagulation but also has several significant differences such as number of side reactions, which are discussed in this section. In the electrocoagulation system, there are multiple electrochemical reactions occurring simultaneously at anodes and cathodes. These mechanisms can be divided into main mechanisms that cause destabilization of pollutants and side reactions, such as hydrogen formation [18].

The electrocoagulation unit installed at the BMP premises has a nominal capacity to treat 10 L/hour. As the effluent treated at BMP happens to be highly concentrated, the unit has been operated at only about 50-75% of its nominal flow capacity. The power is supplied to the unit by a primary power source capable of supplying 3 phases at 415 volts and 100 ampere current. The output of the power supply of this unit is 0-750 ampere (tank and all the experiments were based on batch processing).

From the surge tank, effluent is pumped to electrocoagulation chamber. The electrodes in the chambers are positioned vertically; the wastewater is fed into the chamber from the bottom of the chamber and discharged from the top. The residence time within the chamber is typically about 20 seconds. The effluent for the treatment is pumped into the surge-feeding tank having approximate capacity of about 2 L, where acquired concentration or mixture of different streams for the treatment is achieved. At the current stage of operation, the desired dilution of stick water is achieved in the surge (feeding).

From the electrocoagulation chamber, treated wastewater is discharged directly into the first tank of sludge separation while the sludge is scraped from the surface and transferred to the second tank. The treated wastewater is discharged from the lower level of the first separation tank. The sludge in the second tank is processed and handled in the same way as scraped from the surface and transferred to the collection bin from which it is pumped away either to be utilized and mixed with the meat meal material in the drier or disposed of in some alternative way. The processed effluent is ultimately gravity fed to the anaerobiont to be processed together with the rest of abattoir wastewater. From the electrocoagulation chamber, the treated wastewater is discharged directly into the first sludge separation tank. The sludge is scraped from the surface and transferred to the second tank [19].

4. Working of Electrocoagulation Plant

Electrocoagulation is basically an adsorption process that involves many chemical and physical mechanisms for the removal of contaminants [20]. The electrocoagulation process uses electrodes like iron, aluminum and zinc etc., for the in-situ-generation of metallic coagulants. Electrolytic oxidation of anode occurs after the application of direct current. The metallic anodes dissociates into di or tri valent metallic ions and release equivalent number or electrons by the introduction of current. The amount of generation of metallic ions is based on the applied current density (Faraday's law) and dissociation of metallic ions increases with increase in current density [21]. These metallic ions migrate to an oppositely charged ions and aggregation occurs due to charge neutralization. The anode also leads to the water reaction/oxidation releasing hydrogen ion and oxygen to the aqueous system. The chemical reaction of water occurs in the surface of electrode in the cathode regime.

The water molecules dissociate into $\mathrm{H^+}$ ions and $\mathrm{OH^-}$ ions when the electron interaction takes place in the cathode regime. The dissociated $\mathrm{H^+}$ ions again combine with the free $\mathrm{H^+}$ ions and facilitate the generation of H_2 gas. The metallic ions formed at the anode combines with the metallic hydroxide ions generated at the cathode that are very good adsorbents for the pollutants. The generation of amorphous $M(OH)_n$ metallic hydroxide ions having large surface areas with very high adsorption capacity that make bond with the pollutants and forms complexes [22]. The metallic flocs enlarge the size from micro-flocs to macro-flocs attaining the self-settling size. The hydrogen gas generated at cathode and oxygen generated at the anode plays a monomeric or polymeric and soluble or insoluble (amorphous) metallic hydroxides depends on the pH of the aqueous solution [23]. They play vital role in the removal of macroflocs which otherwise never settles down under the effect of gravity. The gas generated takes up the microflocs to the top of the aqueous solution called electro-floatation thereby forming foam like phase which can be removed by skimming. The oxygen generated at anode also plays an important role in formation of hydrogen per-oxide (intermediate), which helps in oxidation of the toxic species to non-toxic species.

Based on the initial pH of the aqueous solution, excess of $\mathrm{OH^-}$ and $\mathrm{H^+}$ generated in the electrocoagulation process helps in buffering the pH of aqueous solution and maintaining a near neutral pH. The slow mixing during the electrocoagulation process increases the oxygen level in the system which helps in oxidation of the pollutants and also allows mixing of pollutants with metallic flocs. The ions or electrolytes like chloride increase the corrosion of metallic species at the anode [24]. At anode, following chemical reactions takes place:

$$\mathbf{M_{(s)} \rightarrow M^{n+}_{(aq)} + ne^-} \ldots\ldots\ldots\ldots (\mathbf{1})$$

$$\mathbf{2H_2O \rightarrow 4H^+_{(aq)} + O_{2(g)} + 4e^-} \ldots\ldots\ldots\ldots (\mathbf{2})$$

At cathode, following chemical reactions takes place:

$$\mathbf{nH_2O + ne^- \rightarrow (\frac{n}{2})H_{2(g)} + nOH^-_{(aq)}} \ldots\ldots\ldots\ldots (\mathbf{3})$$

5. Factors Affecting the Efficiency of Electrocoagulation

The nature of electrolyte, initial pH of solution, effect of temperature and effect of inter electrode distance do have significant effects on the overall efficiency of entire process of electrocoagulation that is discussed in detail below.

5.1 Effect of Electrolyte

The effect of type of electrolyte on the removal efficiencies of 2,4-D and COD for 60 minutes at pH of 10, at initial concentration of 2,4-D of about 200 mg/L, inter-electrode distance of 1 cm, temperature of 30°C and current densities of 62.5, 12.5 and 37.5 mA/cm^2 using Fe, S-S and Al electrodes respectively is highly significant. Electrolytes of 1.5 g/L of the following salts: NaCl, KCl, Na_3PO_4, NaF and Na_2SO_4 were studies by three electrodes. The higher elimination of herbicide and COD in the presence of NaCl was evident due to the formation of hypochlorite (OCl) and hypochlorous acid (HOCl). It is well known that $\mathrm{Cl^-}$ions can destroy the formed passivation layer on electrode thereby enhancing the rate of anodic dissolution of metal which leads to the production of more metal hydroxide ions [25].

5.2 Effect of Initial pH

The pH is an important operating factor or essential parameter that affects the efficiency and performance of electrocoagulation [26]. A series of experiments were carried out to evaluate the effect of initial pH using solutions containing a sample with an initial pH varying in the range (2-10) at initial concentration of 2,4-D 200 mg/L, inter electrode distance of 1 cm, NaCl concentration of 1.5 g/L, temperature of 30°C and current density of 62.5 mA/cm^2, 12.5 mA/cm^2 and 37.5 mA/cm^2 for Fe, S-S and Al electrodes respectively for 60 minutes of time. The removal efficiencies of the 2,4-D and COD were low in acidic medium, meanwhile, in neutral and alkaline medium the removal efficiencies were much higher by using all working electrodes due to the formation of metal hydroxide species which adsorb the herbicide molecules and causes the increase of the removal efficiency The percentage removal increased by increasing the pH. It was observed that below pH 5.8 there was decreasing trend in adsorption, this may be due to:

1. In case of iron anode, oxidation of ferrous iron Fe (II) to ferric iron Fe (III) diminishes, resulting in decreased removal efficiency in acidic pH values. Neutral and slightly alkaline pH, however, tends to favor Fe (II) to Fe (III) oxidation as well as complex polymerization. Finally, hydroxylated colloidal polymers and an insoluble precipitate of hydrated ferric oxide were formed and the removal efficiency was increased. The decrease of removal efficiency was observed when the pH was higher than 10.

Under acidic environment, many investigators evident the amphoteric behavior of $M(OH)_3$ which leads to the soluble metal cations (at acidic pH) and to non-numeric anions (at alkaline pH) [27].

2. In case of aluminum anode, the removal efficiency of the herbicide and COD is high in neutral and moderate alkaline electrolyte. The decrease of removal efficiency at more acidic and alkaline pH was observed by many investigators and was attributed to an amphoteric behavior of $Al(OH)_3$ which leads to soluble Al^{3+} caution (at acidic pH) and to monomaniac anions $Al(OH)^{-4}$ (at alkaline pH). It is well known that these soluble species are not useful for water treatment. When the initial pH was kept in neutral, all the aluminum produced at anode formed polymeric species $Al_3O_4(OH)_7$ and precipitated as $Al(OH)_3$ leading to the higher removal efficiency [28].

5.3 Effect of Temperature

The effect of temperature on the removal of pollutants through EC has been studied in few articles. Effect of temperature from 10 to 50°C has been studied for the removal efficiencies of 2,4-D and COD at time 60 min, initial concentration of 200 mg/L, pH of 10 and NaCl concentration of 1.5 g/L and current densities of 62.5, 12.5 and 37.5 mA/cm^2 using Fe, S-S and Al electrodes respectively. This show that the 2,4-D and COD removal efficiencies decrease with increasing temperatures above 30ºC due to the volume of colloid $M(OH)_3$ that will decrease and pore production on the metal anode will be closed [29]. However, at 30°C the herbicide removal and COD% reached to maximum concentration (g/L).

5.4 Effect of Inter-Electrode Distance

To study the effect of inter-electrode distance on cadmium removal efficiency, several electrocoagulation tests were carried out for different inter-electrode distances of 0.5, 1 and 2 cm. The variation of pH, difference in potential, temperature and treatment cost, and energy consumption versus time for the different values of the S/V ratio was estimated. When the inter-electrode distance increased, the ohmic loss in relation to the anode and cathode over voltages increased and the resistance to mass transfer became larger. The kinetics of both charge transfer and the aluminum oxidation was slowed down. Consequently, there was a smaller amount of Al^{3+} cations at the anode leading to slower formation of coagulants in the middle. The rate of particle aggregation and adsorption of cadmium became lower, which explained the decrease in cadmium removal efficiency.

This resulted in lower removal efficiency at a larger inter-electrode distance. It has been found that the removal percentages of Cd (II) decreased with the increase of inter-electrode distance. The best cadmium removal percentage as well as treatment cost was achieved for the inter-electrode distance value of 0.5 cm. Within 30 min of electrolysis time, decreasing the inter-electrode distance from 2 to 0.5 cm resulted in an increase in cadmium removal efficiency from 82.33% to 91.63% and a reduction in both treatment cost (from 0.270 to 0.210 TND m^{-3}) and energy consumption (from 0.87 to 0.55 KW h m^{-3}) which was evident by the decrease in the temperature of solution from 19.5 to 17.8ºC. This result proved that unlike the case of electrode configuration and S/V ratio, the effect of the inter-electrode distance on energy consumption and treatment cost was insignificant. On the other hand, as the time progressed, it was clear that the formation of a gelatinous aluminum hydroxide film on the anode developed a resistance that increased whenever the inter-electrode distance increased. Hence, it was beneficial to choose an optimum short inter-electrode distance of 0.5 cm to minimize energy consumption and increase the cadmium removal efficiency [5].

6. Colloidal Particles Stability and Destabilization

Colloidal particles exist in many natural and engineered systems. Colloidal particles' stability is often explained by the presence of repulsive electrical charges on the surface of particles and stability can be estimated by considering the interactive forces between particles. When repulsive forces are dominant, the system will remain in a dispersed state. In contrast, when the interactive forces control, the particles will coagulate/flocculate and the suspensions maybe destabilized. Particles with the same charge repel each other, so this repulsion needs to be minimized if destabilization is required. Colloids are microscopic particles that are typically in the range of 1 nm to 2 mm, resulting in a very small ratio of mass to surface area. Given that their total surface area is large as compared to their mass and size; the gravitational forces of colloids are often neglected as compared to the surface phenomena predominating when studying colloidal suspension.

The suspension and stability of colloidal particles in water is attributed to the fact that they carry a similar charge, usually negative charge, so they repel each other and remain suspended [5]. In order to neutralize the charge, counter charged particles are used to be attracted to the surface of the colloids thereby forming an electric double layer. The electrical double layer consists of an inner region (stern layer), where oppositely charged ions are tightly bound to the surface of colloidal particles and an outer layer, where the ions move freely due to diffusion (ion diffuse layer or slipping plane). The interface of the inner and outer layers is known as the shear surface which defines the outer limit of the stern layer [30]. The maximum potential occurs at the surface of colloidal particle and is known as the Nernst potential, where it decreases across the stern layer due to the presence of oppositely charged particles resulting in what is defined as the Zeta potential measured at the surface of shear [31]. Zeta potential is the main reason of colloidal system stability, as it represents the electrical charge difference between the first and second layers and gives an indication of the extent of repulsion between colloidal particles carrying the same charge.

The higher the value of Zeta potential, the greater the magnitude of repulsion between particles and consequently the more stable is the colloidal system. In general, colloidal particles in suspensions with zeta potentials more positive than þ30 mV or more negative than -30 mV are normally considered stable [32]. DLVO (Derjaguin-Landua-Verwey-Overbeek) theory is a good starting point to describe the stability of colloidal particles. Simply DLVO theory considers the contributions of the attractive van der Waals potential and the repulsive electrostatic potential. Therefore, according to DLVO theory, the dispersed particles are under the effect of two independent forces (a) attractive van der Waals force and (b) repulsive electrostatic force arising from the presence of electrical double-layer at particles' surfaces. The charges on the particles will be balanced by equal and opposite ions solution. This means that there will be an excess of positive charge accumulated in the interfacial region around a negative ion, and this will govern the electrostatic effects. That is called as electrical-double layer. It follows that the electrostatic double-layer interaction (Vt) between two particles is the outcome of overlapping of two double layers.

Three distinct features of this system are (i) primary minimum (ii) secondary minimum and (iii) maximum. As mentioned earlier, the role of coagulants or flocculants in either chemical coagulation/chemical flocculation or electrocoagulation is to destabilize the colloids by reducing the repulsive forces and forcing the particles to agglomerate for relatively easier separation. Coagulation/flocculation follows four different mechanisms to destabilize colloidal systems depending on several factors like chemical and physical properties of the solution, coagulant/flocculants and pollutant types. These mechanisms are briefly summarized below [1].

6.1 Compression of Electrical Double Layer

The thickness of the electric double layer affects the extent of repulsion between particles and hence their stability. As the thickness of the double layer decreases, the repulsive forces are also reduced and particles can easily come together forming larger particles. In order to compress the electrical double layer, counter charged ions are added to the solution either by metal salts/electrolytes in case of chemical coagulation/chemical flocculation or by oxidation of the anode in case of electrocoagulation. In both cases, these metal ions will diffuse through the double layer causing higher counter ion concentration around the colloidal particle, which in turn reduces the electrical double layer thickness and repulsive forces. When the electrical double layer thickness is compressed, the Zeta potential measured at the shear surface will also be reduced and the optimum destabilization happens if Zeta potential approaches 0 mV. When added to the solution, different metal ions have different destabilization ability. This is best explained by looking at Schultze-Hardly rule, which simply states that as the charge of added counter metal ions increases, its ability to destabilize the colloidal particles also increases. Therefore, it is favorable to use divalent or trivalent metal ions to destabilize counter charged colloids. It is worth mentioning that this mechanism is characterized by large metal ions concentration to achieve destabilization, which makes it impractical for water treatment.

6.2 Adsorption/Charge Neutralization

The concept of this destabilization mechanism is quite simple, where adsorption of counter charged ions on the surface of colloidal particles results in neutralizing their surface charge so that repulsive forces are overcome and van der Waals attractive forces dominate. Eventually colloidal particles approach each other and coagulate.

6.3 Adsorption/Inter-Particle Bridging

When metal coagulants are polymerized, they have the ability to form links/bridges between colloidal particles especially when the polymers have high molecular weight and long chain. This phenomenon is due to the reactive groups that polymers have which can absorb to the colloids' surface in various forms including: charge-charge interactions and hydrogen bonding. The bridging of colloidal particles results in the formation of bigger particles and hence destabilization. This mechanism is quite risky, since colloidal particles can be destabilized in cases where the polymer's chains are attached to all colloidal particles existing, but there are some free extended chains not attached to any particles. In such circumstances, the free chain will reattach to the same particle hence causing destabilization. It is therefore crucial not to use an overdose of polymers. In addition to overdosing of polymer, rapid mixing could also break the bridging between colloids and eventually destabilize them.

6.4 Entrapment of Particles in Precipitate

This mechanism is also called as "sweep coagulation" and it is often encountered when high metal salt concentrations are added. In such cases, the metal salts react with water thereby forming insoluble metal hydrates that precipitate forming a sludge blanket. Formed precipitates eventually entrap colloidal particles during and after precipitation [1].

7. Theory of Stabilization and Destabilization

After understanding the stabilization and destabilization of colloidal systems, it is time to penetrate into the theory of electrocoagulation, which is an advanced technology combining the well-known coagulation, flotation and electrochemistry. Each of the three technologies has been studied extensively in a separate manner; however, there is a limited literature available on integrating these three technologies that are the basis of electrocoagulation where it has been employed to treat the water containing pollutants such as heavy metals, tannery, textile and colored wastewater, pulp and paper industry wastewater, oily wastewater and food industry wastewater [1]. The basic electrocoagulation unit typically consists of an electrolytic cell with an anode and cathode metal electrodes connected externally to a DC power source and immersed in the solution to be treated. Iron and aluminum electrodes are the most extensively used metals for electrocoagulation cells since these metals are available, non-toxic and proven to be reliable. Although electrocoagulation is considered to be quite similar to chemical coagulation/chemical flocculation in terms of the destabilization mechanism, it still differs from chemical coagulation/chemical flocculation in other aspects such as the side reactions occurring simultaneously at both electrodes. The anode serves as the coagulant in an electrocoagulation cell, where it dissociates to give metal cations when DC is passed through the cell. The dissociation of anode follows Faraday's law as given by following equation:

$$\mathbf{M} = \frac{\mathbf{ItMw}}{\mathbf{zF}}$$

where I is the current (A), t is the time of operation (s), Mw is the molecular weight (g/mol), F is Faraday's constant (96,485 C/mol), z is the number of electrons involved in the reaction and m is the mass of anode dissolved (g). The anodic reactions are expressed by both aluminum and iron electrodes.

Depending on the pH of the solution and the potential, iron can form divalent or trivalent cations as illustrated in the E-pH diagram for iron. On the other hand, aluminum only dissolves as trivalent cations. As mentioned previously, several side reactions occur in electrocoagulation cell, which includes evolution of hydrogen bubbles at the cathode along with OH^- ions which lead to an increase in the pH of solution.

8. Advantages and Disadvantages of Electrocoagulation

Electrocoagulation is known to have following advantages (i) since no chemicals are added, there is no chance of secondary pollution due to high concentration of chemicals as in chemical coagulation/chemical flocculation (ii) gas bubbles produced from electrocoagulation facilitates the removal of pollutants by floating them on top of the solution so they can be easily collected (iii) electrocoagulation is easily operated due to the simplicity of its equipment hence; complete automation of the process is possible (iv) wastewater treated by electrocoagulation gives clear, colorless and odorless water (v) flocs formed by electrocoagulation are much larger than chemical coagulation/chemical flocculation and more stable, hence they are easily separated during filtration (vi) electrocoagulation produces much less sludge volume than chemical coagulation/chemical flocculation and the sludge formed is more stable and non-toxic (vii) even the smallest colloidal particles are removed by electrocoagulation since the applied electric current makes collision faster and facilitates coagulation. However, there are some major disadvantages of this method also such as (a) regular replacement of sacrificial anode used in electrocoagulation is necessary since anode dissolves into the solution (b) cathode passivation can occurs which decreases efficiency of the electrocoagulation process (c) in some areas where electricity is not abundant, operating cost of electrocoagulation can be expensive [1].

9. Applications of Electrocoagulation

This section presents an overview of the recent application of electrocoagulation in the treatment of different types of water and wastewater over the past few years. The review was divided into five main categories namely as (i) water containing heavy metals (ii) tannery and textile industry wastewater (iii) food industry wastewater (iv) paper industry wastewater (v) refinery wastewater.

9.1 Water Containing Heavy Metals

Heavy metals are discharged from several industries and wastewater containing heavy metals are challenging to treat as they are non-biodegradable and some metals are toxic. Heavy metals include cadmium, chromium, zinc, lead, mercury and arsenic.

9.2 Tannery and Textile Industry Wastewater

Tannery and textile industry effluent is highly contaminated with organics, chromium and different types of dyes. Chromium on its own is a major concern as it may oxidize to Cr (VI) which is carcinogenic and toxic. The presence of dyes also renders the water quality very poor by preventing the passage of sun light; it is also known to be highly stable, toxic and may resist chemical and biological degradation.

9.3 Food Industry Wastewater

Food industry consumes larger amounts of water for each ton of product compared to other industries. Various contaminants are found in wastewater from food industry depending on the sector but the general characteristics of wastewater are being highly biodegradable and nontoxic with highly suspended solids, COD and BOD. In the case of meat processing industry, color, oil and grease are of significant environmental concerns.

9.4 Paper Industry Wastewater

Paper industry consumes large amounts of water and the effluent is usually blackish in color and highly contaminated with lignin, COD, BOD, organics, suspended solids and arsenic.

9.5 Refinery Wastewater

Refinery wastewater includes wastewater generated from petroleum refineries and petrochemical industries. It usually contains high level of aromatic and aliphatic hydrocarbons, chemicals, dissolved solids, BOD and COD [1].

10. Technology Advancement

Various technological innovations and advanced treatment technologies have been added in this simple process of electrocoagulation that is briefly explained below.

10.1 Advancements in Reactor Design and Electrode Selection

Among all efforts in developing electrocoagulation techniques for oily wastewater treatment, many have been made for the advancement of reactor design and electrode materials. Some recent researchers [33] compared the performances of horizontally and vertically oriented electrodes in electrocoagulation for oil separation. The cell anode was an array of separated horizontal cylinders made of aluminum. It was suggested that horizontal cell design was more efficient than traditional vertical parallel plate cell. The performance of rotating cylinder electrochemical reactor for the emulsification of crude oil emulsions was also investigated [34]. The advantage of this design was demonstrated by the decrease in anode passivation tendency as a result of the improved rate of mass transfer between the anode and solution. In addition, the good mixing conditions in bulk solution arose from the turbulence generated at the rotating cylinder anode. It would speed up the process of electrocoagulation. A high-porosity fixed-bed sacrificial anode was developed for oil separation through electrocoagulation.

It offers many advantages over conventional vertical or horizontal anodes including higher removal rate of emulsions, longer operation time between electrode replacements, and lower space footprint. An aluminum wire gauze anode was also studied in the separation of crude oil from oil-in-water emulsions in a square batch electrocoagulation cell. Use of dimensionally stable anodes represents another electrochemical treatment technique for oily wastewater. The underlying mechanisms involve electrochemical oxidation which does not occur in simple electrocoagulation process. A combined two-step process consisting of electrochemical coagulation with iron anodes and electrochemical oxidation with boron-doped diamond anode was developed for the treatment of a real carwash wastewater [35].

10.2 Advancements in Operation and Control

Another area of technology advancement is the operation and control of parameters taking into considerations of the dynamics of the electrocoagulation process. In the direct current mode, formation of an impermeable oxide layer on the electrode leads to electrode passivation, causing the decline of treatment efficiency. To overcome such impact, the development of pulsed or alternating current applications has been explored in recent years. The effect of pulsed voltage application on energy consumption during electrocoagulation of emulsified oils was investigated by some scientists [35]. It was found that pulsed voltages saved energy during electrocoagulation process. In continuous operation, energy saving was as high as 48%. A sono-electrocoagulation technique was applied to the treatment of oil tanning effluents [35]. It was found that continuous sono-treatment adversely affected the electrocoagulation process. It inhibited the formation of flocs. However, intermittent ultrasonic impingement can be used to overcome passivation. Integration of electrocoagulation and other treatment techniques to better utilize the advantages of different treatment approaches, integrated treatment processes are often employed in engineering application. As a result, considerable efforts have been devoted for using the electrocoagulation combined with other technologies in oil removal. For example, the membrane technology showed potential in oily wastewater treatment. Electrocoagulation can be effectively adopted in combination with membrane filtration to reduce membrane fouling. Some recent researchers [35] examined the feasibility of combined electrocoagulation and kaolin dynamic membrane for improving the performance of oily wastewater treatment.

Electrocoagulation could effectively reduce the reversible resistance, which was primary cause of permeate flux decline. Compared with aluminum anode, iron anode showed better performance in dynamic membrane-electrocoagulation process because aluminum anode seemed more inclined to form a looser layer. The normalized fluxes and oil removal rates increased with the rise of current density and decline of initial pH. The maximal oil removal rates of effluent and permeate at 65 to 98.5% have been observed, respectively. Scientists have investigated the treatment of produced water by electrocoagulation prior to reverse osmotic membrane. An electrocoagulation powered by reverse osmosis process for simultaneous removal of hardness, COD and turbidity was developed.

Of electrocoagulation for the pre-treatment of produced water prior to reverse osmosis membranes was highlighted. The optimal operating conditions were determined to be with the initial pH of 7.36, the current density of 5.90 mA/cm^2 and the reaction time of 30.94 min. Approximately 99.9% of oil can be removed after the combined electrocoagulation-reverse osmosis process. For scale-up application developed an integrated mobile system for oil field produced water treatment with the treatment capacity of 15m^3/d. The combination of electrocoagulation and membrane filtration approaches was used with integrated intelligent automation and process optimization in the framework of mobile treatment platform. More than 95% of oil, TOC, COD, TSS and turbidity in produced water could be removed. The system could also effectively remove about 90% of ions, including chloride, sulfate, sodium, calcium and manganese etc. Electrocoagulation has also been used with other physiochemical techniques to achieve high oil removal efficiency. Some recent researchers [35] reported the treatment of olive oil mill wastewater through combined acid cracking and electrocoagulation. Acid cracking was carried out by adjusting the pH to 2 with 0.13 M H_2SO_4 and heating the wastewater samples to 70°C. Electrocoagulation experiments were performed with stainless steel electrodes at pH 2 and current density of 50 mA/cm^2 at 65°C for 120 min. A removal efficiency of 96% could be achieved for oil and grease using this combined acid cracking-electrocoagulation process. These researchers [35] studied the anaerobic co-digestion of wastewater derived from biodiesel manufacturing using electro-coagulation as pretreatment. To reduce the contents of oily organic matter, the wastewater was acidified by adding H_2SO_4 at first. The wastewater was then neutralized by adding NaOH and electrocoagulation reactor with eight aluminum electrodes was further used for pre-treatment. In the electrocoagulation process, the total COD decreased by 6.25% and soluble COD decreased by 13.60% after 30 min. The overall reduction of total COD was found to be 45% with both the acidification-centrifugation and electrocoagulation steps.

The anaerobic co-digestion of glycerol and wastewater was applied after electro-coagulation and biodegradability was found to be around 100%. The application of acidification and electrocoagulation for the remediation of biodiesel wastewater containing vegetable oil was also estimated in some researches. Acid treatment was used before electrocoagulation and 99.36% of oil and grease could be removed by electrocoagulation electro-oxidation process for the treatment of restaurant wastewater with oil, grease and suspended solids. The oxidant and coagulant agents could be produced simultaneously in electrocoagulation electro-oxidation process. More than 98% of oil and greases were removed by using aluminum and graphite plates alternated in the electrode pack and operated at current of 0.4 A during 90 min of treatment with pH adjusted to approximately 7.0. Some recent researchers [35] reported the treatment of olive oil mill processing wastewater by peroxielectrocoagulation/electro-oxidation-electro-floatation process. In the electrochemical unit, aluminum, stainless steel and RuO_2/Ti plates were used.

A removal efficiency of 97.1% for oil and grease could be achieved under optimal conditions of pH 4, current density of 40 mA/m^2, 1000 mg/L H_2O_2, 1 g/L NaCl and 30 min reaction time. This process could also significantly help to improve the biodegradability of olive mill wastewater. Few scientists investigated the feasibility of treating cattle slaughter house wastewater by combined chemical coagulation using PAC and electrocoagulation using aluminum electrodes. Coagulation process alone was not able to meet discharge standards. The removal efficiencies increased by increasing the coagulant dose and electrical potential. At the highest applied voltage, the fastest treatment rate was obtained. More than 99% removal of COD and BOD5 was obtained by adding 100mg/L PAC and applying 40 V voltages. The treatment of poultry slaughter wastewater was made possible through using electrocoagulation-flocculation process. To improve agglomeration of flocs and facilitate sludge sedimentation, the polymer (LPM 9511) was added as flocculants. This combined process can resulted in effective removal of organics (98.5% total oil and grease removal and 81.6% total COD removal), inorganic (with the exception of nitrogen), pathogen destruction and solids and turbidity removal. The presence of H_2O_2 and PAC had significant influence on the treatment of biodiesel wastewater using electrocoagulation. The assistance of oxidation using 2% H_2O_2 could lead to a low final concentration of oil and grease at 18 mg/L; the assistance of coagulation using 0.5 g/L PAC could lead to a final concentration of oil and grease at 387 mg/L. A complete removal of oil and grease could be achieved in the presence of both 2% H_2O_2 and 0.5 g/L PAC. Researchers [35] studied the treatment of olive mill wastewater using electrocoagulation with either iron or aluminum as sacrificial electrode. Differences between treatment efficiencies with and without the aid of H_2O_2 and PAC were found to be significant. The best result for oil and grease removal was obtained in electrocoagulation enhanced with coagulation and oxidation using 2.3% H_2O_2+0.5 g/L reported the use of integrated electro-Fenton, anaerobic digestion and electro-coagulation processes for the treatment of olive mill.

The use of electrocoagulation for the pre-treatment of produced water prior to reverse osmosis membranes was also highlighted by some recent researchers. The optimal operating conditions were determined to be with the initial pH of 7.36, the current density of 5.90 mA/cm^2 and the reaction time of 30.94 minutes. According to an estimate, 99.9% of oil can be removed after the combined electrocoagulation-reverse osmosis process. For scale-up application, developed an integrated mobile system for oilfield produced water treatment with the treatment capacity of $15m^3/d$. The combination of electrocoagulation and membrane filtration approaches was used with integrated intelligent automation and process optimization in the framework of mobile treatment platform. More than 95% of oil, TOC, COD, TSS and turbidity in produced water could be removed. The system could also effectively remove about 90% of ions, including chloride, sulfate, sodium, calcium and manganese etc. Electrocoagulation has also been used with other physiochemical techniques to achieve high oil removal efficiency. Recently, the treatment of olive oil mill wastewater through combined acid cracking and electrocoagulation was reported. Acid cracking was carried out by adjusting the pH to 2 with 0.13 M H_2SO_4 and heating the wastewater samples to 70°C. Electrocoagulation experiments were performed with stainless steel electrodes at pH 2 and current density of 50 mA/cm^2 at 65°C for 120 min [36].

A removal efficiency of 96% could be achieved for oil and grease using this combined acid cracking-electrocoagulation process. The anaerobic co-digestion of wastewater was derived from biodiesel manufacturing using electrocoagulation as pretreatment. To reduce the contents of oily organic matter, the wastewater was acidified by adding H_2SO_4 at first. The wastewater was then neutralized by adding NaOH and electrocoagulation reactor with eight aluminum electrodes was further used for pre-treatment. In the electrocoagulation process, the total COD decreased by 6.25% and soluble COD decreased by 13.60% after 30 min. The overall reduction of total COD was found to be

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In the electrochemical unit, aluminum, stainless steel and RuO_2/Ti plates were used. A removal efficiency of 97.1% for oil and grease could be achieved under optimal conditions of pH 4, current density of 40 mA/m^2, 1000 mg/L H_2O_2, 1 g/L NaCl and 30 min reaction time. This process could also help to significantly improve biodegradability of olive mill wastewater [37].

11. Conclusions

Electrocoagulation is basically a potential electrochemical approach that is extensively used for the treatment of either wastewater or drinking water contaminated with different types of organic or inorganic pollutants and heavy metal ions. Recently this technology has attained considerable attention owing to its cost efficiency and sustainable nature resulting in fruitful applications at commercial scale. It can successfully deal with even minute concentrations of organic or inorganic contaminants with minimum waste generation and negligible hazardous compounds. During past few decades, extensive research has been done on effective utilization of this treatment technology for wastewater, polluted groundwater and industrial effluents with main focus on long lasting and potential future applications. This review summarizes the basic principles of electrocoagulation unit and commercially available setups for electrocoagulation along with factors affecting the process of electrocoagulation such as nature of electrolyte, initial pH of solution, effect of temperature and effect of inter electrode distance that are known to have significant influences on removal of contaminants. Now-a-days, further research is continued on pollutant specific electrocoagulation to be installed at industrial scale as most of the industrial wastewater constitutes specific types of pollutants that need to be treated properly.

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