Solar Powered Electrocoagulation: A Review

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***Abstract*— Today's major challenge is to plan for sustainable use of water resource. Bourgeoning population and industrialization, as well as changing life styles call for more and more water. Ironically, rivers, canals and other water-bodies are being constantly polluted due to indiscriminate discharge of industrial effluents as well as other anthropogenic activities and natural processes. So, it is now not only obligatory to control the water pollution through physicochemical treatments but to implement recycling also. Further, in recent years, new processes for efficient and adequate treatment of various wastewaters with relatively low costs are needed due to continually upgrading environmental regulations. In this view, Electrocoagulation (EC) has been proposed by several researchers as an effective method for the treatment of various types of water and wastewater. At this point, the EC process has attracted a great deal of attention in treating various wastewaters because of its versatility and environmental compatibility. The EC process has many advantages such as simple equipment, easy operation, a shortened reactive retention time, no chemical additions, and decreased amount of sludge, which sediments rapidly. Though, EC is dependable technique for treatment the power requirement is a major concern. Solar energy from photovoltaic (PV) panel is the ideal source of energy to overcome this problem. Studies have been done successfully for solar powered EC system to treat the water and wastewater. The environmental impact induced by the use of solar energy is minimal and this renders the solar powered EC process environmentally attractive. This review focuses on various studies those have been dedicated to utilize solar powered electrocoagulation for water and wastewater treatment. This review attempts to highlight the main achievements in the area and outline the advantages of solar powered EC process to broaden its range of application.**

Index Terms*— Electrocoagulation, Solar energy, Water and Wastewater treatment, Photovoltaic panel

I. INTRODUCTION

Water scarcity is one of the greatest current and future challenges that people face, as the world's population and water consumption rates continue to grow. This has led to a renewed interest in developing cost effective, reliable and environmentally friendly water and wastewater treatment technologies that would enable to reuse the huge amounts of wastewater generated.

In India, the living standard is getting upgraded with the development of economy, which consequently increases the generation of wastewater which is harmful to the environment in various aspects. The treatment of wastewater before its final discharge is critical, because wastewater contains a wide variety of pollutants as the organic compounds, phosphates, nitrogen, bacteria and others in significant concentrations.

The water and wastewater can be treated by using different techniques in the conventional systems such as physical, biological, and chemical treatments that are not enough to ensure complete treatment; and so refining technologies should be added to the treatment process such as advanced oxidation process similar to ozonation, ultraviolet radiation (UV), photo-catalysis (UV/TiO2), reverse osmosis which are not economically feasible. Due to high capital and operating costs of these methods there is an urgent need to develop more efficient and cost effective methods which require minimum chemical and energy consumptions [7]. Particularly, in recent years, new processes for efficient and adequate treatment of various water and wastewaters with relatively low costs are needed due to strict environmental regulations.

At this point, the Electrocoagulation (EC) process has attracted a great deal of attention in treating various wastewaters because of its versatility and environmental compatibility. The EC process has many advantages such as simple equipment, easy operation, a shortened reactive retention time, no chemical additions, and decreased amount of sludge which settles rapidly [8]. In recent years, EC has been proposed by several researchers as an effective method for the treatment of various types of wastewater, such as: textile wastewater, urban wastewater, olive oil mill wastewater, restaurant wastewater, saline wastewater, drinking water and seawater for desalination [13]. In a study in Morocco by Elazzouzi et al., 2016, an EC system was combined in conventional treatment chain to study the pollutant removal from urban wastewater. The study showed that by using combination of EC and system flocculation could increase removal efficiency considerably [5].

Nowadays, the social concern about the environment is growing in developed countries, and laws demanding environmental protection are being approved. This fact has led to the research and development of new forms of renewable electric energy. One of the most widespread and studied is the photo-voltaic (PV) generation of electricity. PV panel directly convert sunlight into electricity. The advantages of the use of this type of energy are that it is not polluting, it is also silent, abundant, decentralized, free and long life. The low maintenance cost of these systems is also another positive factor. Solar energy from photovoltaic (PV) cell is the ideal source of energy in India to overcome cost as well as to satisfy the quench of electricity generation. Solar energy could be made financially viable with government tax incentives and rebates. India has an average annual temperature that ranges from 25°C –27.5 °C. According to

National Renewable Energy Laboratory (NREL) report the average solar radiation in India is 5.5-6 kWh / sq. m / day [10].

Studies have been done successfully for PV powered EC system for remote Australian communities to treat the water and wastewater [6] and phosphate removal from landscape water using DC supply directly from PV panel [12]. The environmental impact induced by the use of solar energy is minimal and this renders the solar powered EC process environmentally attractive. PV panels are an excellent choice for remote water treatment applications due to long life, modularity, low maintenance, and low noise [11].

So, in the present review the attempts are made to study several types of solar powered EC for water and wastewater treatment reported earlier. Further, basics of EC are also presented in a few words.

II. ELEMENTS OF ELECTROCOAGULATION (EC) MECHANISMS

EC is a complicated process involving many chemicals and physical phenomena that use consumable electrodes to supply ions into the wastewater stream. In an EC process the coagulating ions are produced 'in situ' and it involves three successive stages:

(i) Formation of coagulants by electrolytic oxidation of the 'sacrificial electrode',

(ii) Destabilization of the contaminants, particulate suspension, and breaking of emulsions and

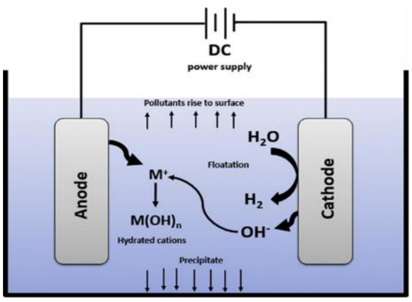
(iii)Aggregation of the destabilized phases to form flocs.

The destabilization mechanisms of the contaminants, particulate suspension, and breaking of emulsions have been described in broad steps and may be summarized as:

(1) Compression of the diffuse double layer around the charged species by the interactions of ions generated by oxidation of the sacrificial anode.

(2) Charge neutralization of the ionic species present in wastewater by counter ions produced by the electrochemical dissolution of the sacrificial anode. 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.

(3) Floc formation; the floc formed as a result of coagulation creates a sludge blanket that entraps and bridges colloidal particles still remaining in the aqueous medium. The solid oxides, hydroxides and oxyhydroxides provide active surfaces for the adsorption of the polluting species. EC has been successfully employed in removing metals, suspended particles, clay minerals, organic dyes, and oil and grease from a variety of industrial effluents.



A schematic representation of basic EC cell

(Source: Moussa et al., (2016))

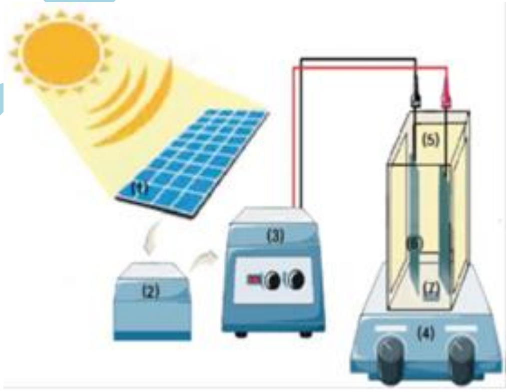
III. SOLAR SETUP FOR EC

A. Photovoltaic cell

Photovoltaic (PV) devices generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid.

Solar cells are typically combined into modules that hold about 40 cells; a number of these modules are mounted in PV arrays that can measure up to several meters on a side. These flat-plate PV arrays can be mounted at a fixed angle facing south, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day. Several connected PV arrays can provide enough power for a household; for large electric utility or industrial applications, hundreds of arrays can be interconnected to form a single, large PV system.

The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. Only sunlight of certain energies will work efficiently to create electricity, and much of it is reflected or absorbed by the material that makes up the cell. Because of this, a typical commercial solar cell has an efficiency of 15%-about one-sixth of the sunlight striking the cell generates electricity. Low efficiencies mean that larger arrays are needed, and that means higher cost. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industries as well as researchers.



Schematic representation of the electrochemical system Source (Pirkarami et al., (2013))

(1: Solar Cell; 2: Charge Controller; 3: DC Power; 4: Stirrer; 5: Reactor; 6: Electrodes; 7: Magnet)

B. MPPT Charge controller

This section covers the theory and operation of "Maximum Power Point Tracking" as used in solar electric charge controllers. It is a circuit (typically a DC to DC converter) employed in the majority of modern photovoltaic inverters. Its function is to maximize the energy available from the connected solar panel at any time during its operation.

A charge controller, charge regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may protect against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk.

C. Battery

The solar power is not available for all the time. So, the batteries are required to store the Direct Current and use it with proper voltage and current for electrocoagulation process.

IV. PREVIOUS WORKS

Garcia et al., (2014) conducted study on "Industrial wastewater treatment by electrocoagulation-electrooxidation process by solar cells". The aim of this study was to evaluate removal efficiency by electrocoagulation (EC)-electrooxidation (EO) using copper electrode for chemical oxygen demand (COD), total organic carbon (TOC), color and turbidity from industrial wastewater from industrial park, powered by solar cells. The solar irradiance was measured by pyranometer and recorded by data logger and total solar powered generated by solar cells was calculated. Effect of operating parameter of EC and EO process such as pH and current intensity was evaluated for optimization of operating condition in batch process. At pH 4 the maximum removal efficiency for COD, TOC, color and turbidity was obtain 89 %, 48 %, 97% and 91 % respectively by EC process. To improve TOC removal EO was carried out in batch process. The maximum removal efficiency for COD, TOC, color and turbidity was obtain was 99.7 %, 70.26 %, 100 % and 95 % respectively by EC + EO process. This study, therefore, indicates that EC + EO process is more efficient than EC process.

Sharma et al., (2012) conducted study on "Solar-powered electrocoagulation system for water and wastewater treatment". The purpose of this study was to investigate the feasibility of solar powered electrocoagulation (SPCE) for water and wastewater treatment using two aluminum electrodes for removal of turbidity and organic matter. During the study pH, current density as well as electrode gap was varied in order to investigate their effect on performance of electrocoagulation. In this study the synthetic waste water was used and it was prepared by adding kaolin powder. The study was conducted using three different methods by direct current (DC) supply from electric power, using D.C. generated by Photovoltaic Panel (PV) directly as well as through batteries. Effect of operating parameters for EC process such as pH (3-11) current intensity (0.1-2.5 A), electrode spacing (0.5-2.5 cm), Operating time (0-40 min) were evaluated for optimization of operating condition by using batch process. At pH 8, current intensity 2.5A and operating time 40 min the maximum removal efficiency for turbidity and organic matter was (87-90 %) and (90-95 %) respectively. The effect of the current source (DC and DC generated by PV panel directly as well as through batteries) on the performance of the SPCE was studied and in a day 10% variation in results was noticed. Using batteries with PV panel provided more consistent and efficient performance for SPCE reactor.

Marmanis et al., (2014) conducted study on "Electrochemical treatment of actual dye house effluents using electrocoagulation process directly powered by photovoltaic energy". The purpose of this study was to investigate the feasibility of photovoltaic electrocoagulation (PV-EC) system for dye house effluents using aluminum electrodes for removal of turbidity and COD. During the study pH, conductivity, operating time, flow rate, and as well as solar irradiation was varied in order to investigate their effect on performance of electrocoagulation. In this study the textile dyeing wastewater was obtained from a factory located near Xanthi in northern Greece. The study was conducted using the electrical energy that is obtained from a solar photovoltaic array by directly connecting it to the electrocoagulator without batteries. The removal percentage of turbidity and COD remains high for the three tested wastewater flow rates of 1.0, 2.0, and 3.0 L/h, and the three wastewater conductivities of 800, 1,600, and 3,200 µS/cm.
The maximum removal efficiency for COD and turbidity was obtained was 65 %, and 99% respectively. The (PV-EC) system is made versatile according to the instantaneous solar irradiation by adjusting the wastewater flow rate to the current intensity supplied by the photovoltaic array.

Zhang et al., (2013) conducted study on "Removal of phosphate from landscape water using an electrocoagulation process powered directly by photovoltaic solar modules". The purpose of this study was to investigate the feasibility of removal of phosphate from landscape water using an electrocoagulation process with aluminum electrodes powered directly by photovoltaic solar modules. During the study electrode gap was varied in order to investigate their effect on performance of electrocoagulation. In this study the landscape water was obtained from a ditch for landscape in Zhongshan Park, which was located in Wuhan City, Hubei Province, China. The maximum removal efficiency for total phosphate (TP) was obtained was 95 %.The results showed that total phosphate (TP) residual concentration in landscape water decreases with an increasing electrolysis time. The removal efficiency increases with an increasing number of serial photovoltaic modules during early reaction time.

Pirkarami et al., (2013) conducted study on "Treatment of colored and real industrial effluents through electrocoagulation using solar energy". The purpose of this study was to investigate the feasibility of photovoltaic electrocoagulation system for dye effluents using aluminum and iron electrodes for removal of TOC and COD. In this study the two types of dye procured from a German supplier were used to prepare the synthetic wastewater. The impact of a number of key operating parameters was explored including current density, anode type, temperature, pH, and electrolyte concentration. At current density 45A/m2 and detention time 15 min the maximum removal efficiency for COD and TOC was obtained 95% and 94 respectively. This study was from real effluents through electrocoagulation using solar cells by using charge controller for the purpose of improving economic efficiency of the process.

Deokate A., (2015) conducted study on "Development of Textile Waste Water Treatment Reactor to Obtain Drinking Water by Solar Powered Electro-Coagulation Technique". The purpose of this study was to investigate the feasibility of removal of COD, TSS, TDS and BOD from textile wastewater using an electrocoagulation process with aluminum as well as iron electrodes powered directly by photovoltaic solar modules. During the study current density and detention time was varied in order to investigate their effect on performance of electrocoagulation in batch process. At current 90 V and detention time 90 min the maximum removal efficiency for COD, TSS, TDS and BOD was obtained 92 %, 94 %, 78 and 83.7 respectively.

CONCLUSION

- The conventional wastewater treatment system is deficient in the treatment processes and also costly. Therefore a new cost effective and efficient alternative treatment of water and wastewater treatment is needed.
- At this point, the solar power electrocoagulation (SPEC) process has attracted a great deal of attention in treating due to its versatility and environmental compatibility.
- Research on various application of SPEC has been conducted worldwide to treat water, waste water and the range of feasible application of SPEC is expanding due to its high removal efficiency of various pollutants.
- Most of the authors conducted their SPEC studies using small laboratory scale reactor in batch mode and continuous mode. DC supply is used by directly from PV panel and through batteries. Due to use of solar energy the cost of EC treatment gets reduced and overall treatment becomes energy efficient. The removal efficiency is observed upto 85-95 % for various pollutants
- In the studies discussed above, SPEC has been found to be feasible, economical and energy efficient in treatment of various types of water and wastewater. Due to promising results obtained, the interest in SPEC is getting upgraded.

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