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Prospective applications of renewable energy based electrochemical systems in wastewater treatment: A review

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ABSTRACT

Recent decades are characterized by incredible rapid technological development resulting in the introducing of various new chemicals, materials and processes with various complexities. This, in turn, is associated with release of increased amounts of pollutants into the environment and for this reason their efficient removal is required. Environmental monitoring results show that many pollutants in ground water are at the excess limit which raises concerns on currently employed wastewater treatments. This review summarizes the electrochemical technology used in wastewater treatment covering its advantages such as high removal efficiency, clean energy conversion, low environmental impact, easy operation and compact design. Significant enhancement of electrochemical methods such as electrocoagulation, electroflotation, electrooxidation, electroreduction and electrodisinfection is discussed and these technologies are combined with an advanced photovoltaic (PV) technology. Important design parameters to obtain the highest efficiency from this combined technology are discussed in details. Moreover, it is shown that the combination systems are capable to produce hydrogen gas at high efficiency which can be used as a supplementary source for green energy thus minimizing the entire process cost.

Contents

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1. Introduction

Groundwater is the most important source of drinking water. According to the United State Environmental Protection Agency, groundwater is seriously polluted by many human activities such as landfills, agricultural byproducts, mining, septic systems, oil, gas and industrial injection wells [1]. The major contaminants discharged by these activities are arsenic (As), mercury (Hg), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), zinc (Zn), selenium (Se), chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-})' phenolic compounds and total dissolved solids (TDS) [2]. Large numbers of environmental pollutants are found at the levels exceeding the permissible concentrations which pose a serious threat on the efficiency of wastewater treatment technologies currently used.

Many research studies are dedicated to investigate various aspects of the wastewater treatment technologies and it is found that waste pollutants can be removed as well as treated by different methods. The conventional methods to remove solid particles from wastewater are sedimentation, flotation, filtration, coagulation and flocculation. For the elimination of organic and inorganic compounds biological treatment, advanced oxidation, adsorption and membrane process are more appropriate [3–6]. The conventional methods of water treatment are effective but they have some drawbacks such as production of large volumes of sludge, requirement of high energy, problems associated with fouling and generation of huge byproducts [7].

In the past two decades, more advanced electrochemical methods have been introduced and widely used in water treatment area. The advantages of the electrochemical treatment include high removal efficiency, clean energy conversion, pollution avoidance due to no emissions generation, easy operation and compact facilities [8,9]. Electrochemical methods include electrocoagulation, electroflotation, electrooxidation, electrodisinfection and electroreduction processes which are discussed further. This review mainly focuses on the application of electrochemical methods in water and wastewater treatment processes powered by solar energy based photovoltaic technology. The discussion provides an opportunity to expand the boundaries of conventional electrochemical system towards higher sustainability and reveals unlimited future prospects for multiple purposes.

2. Electrochemical treatment

2.1. Electrocoagulation

Electrocoagulation process generates coagulants by an in situ process when electric current is passed through aluminum or iron anode which releases metal ions into a solution. The reaction is summarized in Eqs. (1) and (2). The as-synthesized metal ions further react to produce hydroxides, polyhyroxides and polyhydroxy-metallic compounds which have strong affinity towards the oppositely charged ions present in solution to stimulate the coagulation process. Hydrogen is generated at the cathode and it can be recovered for use as an energy source or a reactant for other industrial applications [10]. The formed flocs have large surface area which is capable to adsorb soluble organic compounds and to trap colloidal particles present in the solution. The accumulated flocs are removed by sedimentation or flotation process [11]. Table 1 shows a set of anodic reactions occurring at acidic and alkaline conditions. Some researchers demonstrated that alkaline solution is more suitable for iron anode, whereas neutral or weak acidic solution is effective for aluminum anode in COD (chemical oxygen demand) removal process [12,13]. The benefits of electrocoagulation include generation of reactive coagulant by an in-situ process and having compact equipment setup [14]. However, large-scale installation of electrocoagulation system is rare and can be found only a few numbers worldwide [10]. Table 2 presents the efficiencies of electrocoagulation method in treating different types of wastewater. It is reported that electrocoagulation system has been successfully used in wastewater treatment of tannery, textile, oil, fertilizer, dairy and metal processing industries [12,13,15–19]. Reaction of iron ions and peroxide hydroxide to form Fenton's reagent is discussed in the electrooxidation section.

$$Al \rightarrow Al^{3+} + 3e^- \quad (1)$$

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (2)$$

2.2. Electroflotation

Flotation technique is widely used to recover fine mineral particles, de-inking of recycled paper and to separate oil from water [20]. The recovery of particles (diameter: 1–10 μm) is inversely proportional to the bubble size. In conventional methods to generate bubbles such as agitated and sparged columns is too large [21]. Smaller and homogeneous gas bubbles of hydrogen and oxygen can be produced at the electrodes surface under the applied electric current in electroflotation process. Moreover, the concentration of gas bubbles can be controlled by varying the current density. Increased current density promotes collision among the bubbles, particles and oil drops which in turn affect the concentration of bubbles [22]. Electrode material and pH are the most significant parameters to control the bubble size and their distribution. It is reported that smallest hydrogen bubbles can be obtained at neutral pH; whereas oxygen bubbles size increases with pH [23]. Electroflotation is very efficient for separating oil from water or oil emulsions, textile and heavy metal as it is shown in Table 2.

Some researchers combined both electrocoagulation and electroflotation processes into a single system to treat various types of wastewater. Electrocoagulation occurs at the anodic side, where aluminum or iron anode dissolves to produce coagulant ions of Al^{3+} or Fe^{2+}; while hydrogen evolves at the cathode side thus inducing the flotation process [24]. Current density is the most important parameter in such combined system since the dissolution of anode, generation of bubbles and size of the bubbles increase with increasing the current density [25]. Electrolyte conductivity, electrode arrangement and pH are the other influencing parameters of the combined system. Some experimental results of such combined system for treating textile and heavy metal containing wastewater and river water is tabulated in Table 2.

Table 1
Chemical reactions with different anode materials at acidic and alkaline conditions [9].

Condition	Anode material	Anode reaction	Cathode reaction
Alkaline	Aluminum	$Al^{3+} + 3OH^- \rightarrow Al(OH)_3$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
	Iron	$Fe^{2+} + 3OH^- \rightarrow Fe(OH)_2$	
Acidic	Aluminum	$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$	
	Iron	$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe^{3+} + OH^-$	