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Solar-powered electrocoagulation system for water and wastewater treatment

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ABSTRACT

The objective of this study is to investigate the feasibility of solar powered electrocoagulation (SPEC) for wastewater treatment using aluminium electrodes. Optimisation of various operating parameters such as pH, voltage/current, electrodes gap, pollutant concentration etc. were first performed using direct electrical current. SPEC reactor was designed by connecting with photovoltaic panel (PV) either directly or through a set of batteries and charge control system. SPEC process system was sensitive to variation of solar radiation when connected directly with PV panels. SPEC reactor operated for five different times in a day (4 April 2010) yielded highest organics removal of 85% for UV abs and turbidity removal of 87% at midday (10:00 AM–2:00 PM) under optimum operating conditions. Use of batteries and charge controller with PV panels provided more consistent and efficient performance for the SPEC reactor. The variation in organics and turbidity removal was within the range of 10% for experiments conducted on three different times in a day (9 April 2010) with highest removals at 10:30 AM in the morning. This study indicates that, SPEC is a potential alternative for small scale decentralised water and wastewater purification system.

Keywords: Electrocoagulation, Photovoltaic, Solar energy, Water treatment

1. Introduction

Treatment of water and wastewater by electrochemical methods has attracted great attention. Electrocoagulation (EC) is an electrochemical technology for the treatment of water and wastewater. Removal mechanisms in an electrocoagulation process include coagulation, adsorption, precipitation, and floatation [1]. In its simplest form, EC uses an electrochemical cell with an electrical direct current (DC) voltage applied usually to iron or aluminium electrodes, with water or wastewater as the electrolyte. EC involves the generation of coagulant in-situ by dissolution of metal from the anode with simultaneous formation of hydroxyl ions and hydrogen gas at the cathode. This process produces the corresponding aluminium or iron hydroxides and/or poly hydroxides, with the added benefit of the gas generated assisting in bringing the flocculated particles to the surface while providing them additional buoyancy to float at the water surface. EC presents an alternative method to conventional (chemical) flocculation with several advantages: easy operation, and less space requirement, lower quantities of sludge produced, avoidance of pH adjustment as alkalinity is not consumed and no worries for residual coagulant in the treated water. With its simplicity in operation and design, EC can have a promising potential for decentralized wastewater treatment applications. It has been found effective in treating dye wastewater [2], arsenic containing wastewater [3], phosphate containing wastewater [4],

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electroplating wastewater [5], metal finishing effluents [6] and textile wastewater [7].

Water in many areas of Australia is scarce and of poor quality. In some areas high levels of treatment are required either due to contamination of waters or due to high salinity. In remote communities the operation of such facilities may be limited by the availability of electricity. Solar or photovoltaic (PV) energy is the ideal source of energy in Australia to overcome this problem. There has been several renewable solar energy-powered desalination systems designed to produce 100–3000 l of clean drinking water per day using RO membranes [8, 9]. Studies were done and implemented for PV powered desalination system for remote Australian communities [10] but very few studies have been done on the feasibility of EC using PV solar energy [11,12]. This paper demonstrates the feasibility of the use of EC for wastewater and water treatment powered by a PV panel. It is difficult for national electricity grids to provide resource in many remote communities which makes good quality drinking water a scarce possibility for these communities. Therefore, these communities often drink water of substandard quality, as they do not possess the electrical power or appropriate technology to purify the water. In Australia, nearly 800 remote indigenous communities rely on groundwater as their main water source. Luckily, most areas of Australia possess an excellent solar radiation resource, as depicted in Fig. 1, and more than two-thirds of the country receive an average of at least 6.1 h of full sunshine each day [13,14], albeit the regions with lower population density.

The environmental impact induced by the use of solar energy is minimal and this renders the solar powered EC (SPEC) process environmentally attractive. The application of SPEC system to treat water contaminated with organic pollutants holds promise for regions receiving strong sunlight throughout the year.

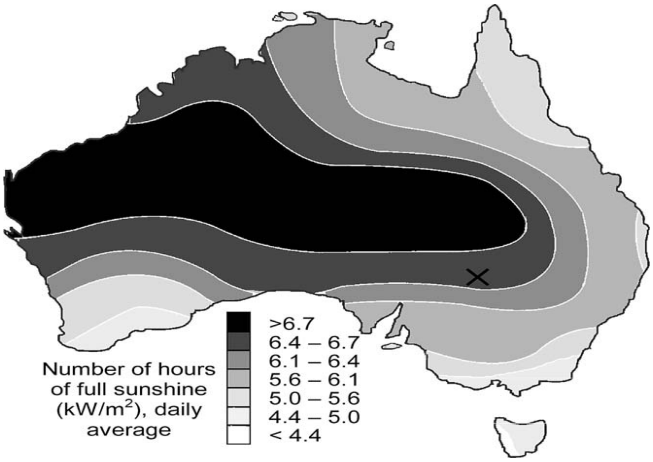


Fig. 1. The solar radiation resource possessed by Australia [13,14].

Solar or PV, panels are an excellent choice for remote water treatment applications due to [14]:

- Long life: solar panels have a warranty of up to 20 years, contain no moving parts, and withstand harsh environments;
- Modularity: More solar panels can be added at a later stage to meet increased demand;
- Low maintenance: solar systems that do not include batteries, an inverter (to convert from DC to AC electricity), the panels follow the path of the sun across the sky, rarely break down and require very little maintenance;
- Low noise level: the only noise would be from the pump. Without batteries, the system would only run in the daytime and would not disturb people at night;
- Well-matched to load: solar panels produce more power in areas that receive more sunshine, where the people are likely to consume more drinking water;
- Storage: it is possible to store energy in batteries.

The SPEC is a promising technology for applications in the remote communities. Decreasing PV panel costs and low maintenance combined with a compact and robust design make this an ideal solution for decentralised and small scale wastewater treatment [14]. The system is modular and easily transported, and no chemicals are required, thus ensuring the safety of community members. This paper demonstrates the feasibility of solar powered EC system powered by a PV. The model electrolyte used in this study was synthetic waste water (SWW). This paper explores immense potential for further research on using solar powered EC treatment for remote Australian communities.

2. Theory of electrocoagulation

EC is a complex and interdependent process. A sacrificial metal anode is used to produce coagulating agent to dose the polluted water and electrolytic gases (mainly hydrogen at the cathode) are generated. Electrochemistry, coagulation and hydrodynamics form the basis of EC [15]. The most widely used electrode materials in EC process are aluminium and iron, sometimes steel. The electrical current causes the dissolution of metal into wastewater. The metal ions, at an appropriate pH value, can form wide ranges of coagulated species and metal hydroxides that destabilize and aggregate the suspended particles or precipitate and adsorb dissolved contaminants. In the case of aluminium, main reactions are as:

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

$$\text{Cathode: } 2\text{H}_2\text{O} + 3e^- \rightarrow 3/2\,\text{H}_2 + 3\text{OH}^- \quad (2)$$

The generated Al^{3+} and OH^- react with each other to form $Al(OH)_3$

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \quad (3)$$

3. Materials and methods

3.1. Synthetic wastewater

Wastewater was prepared in the laboratory using kaolin as model for suspended colloidal particles and humic acid as model for dissolved organic matter (Table 1). Stock solution was prepared using 400 mg humic acid sodium salt and 60 g kaolin which was then diluted up to several times with normal tap water to give a fairly constant turbidity between 15–20 NTU.

Table 1
Properties of SWW

Turbidity, NTU	18
Total organic carbon (TOC), mg/l	5.5
UV Abs (254 nm)	0.150
Conductivity, ms/cm	0.0805

3.2. Electrocoagulation setup

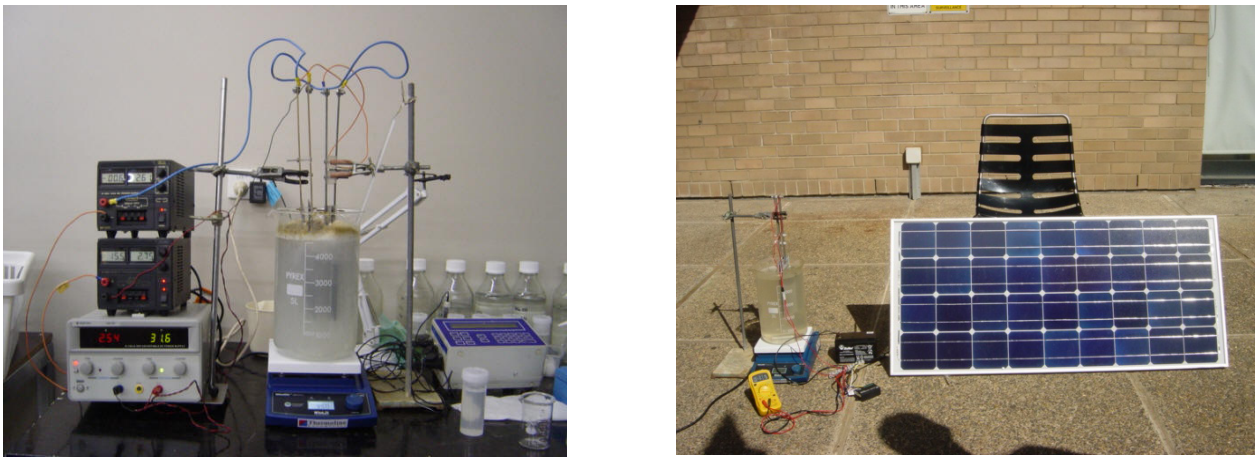
The EC reactor used in this study consisted of a 5 L pyrex glass beaker with two aluminum electrodes (17 cm × 9 cm × 0.2 cm) in a monopolar configuration. The source of power supply included DC power converter (Q1770, Dick Smith Electronics, Australia) or a monocrystalline silicon PV panel (Powertech, Australia) with maximum power of 65 W used with or without charge controller. The dimension of panel was (1210 × 540 × 28) mm and weight 8 kg. Sealed rechargeable batteries were used in conjunction with panel (6 V and 12 V combinations) for power storage system. The basic chemical process occurring for the EC using PV panel is the same as with the electrical DC power supply. Figs. 2a and 2b show the experimental setups. Experiments with the PV panel were carried out at the balcony of the university at latitude of 33° 52′ 58″ and longitude of 151° 12′ 41″. Charge controller with battery system voltage of 12 V was used. Charge controller was installed for the following two reasons:

- To prevent overcharging the battery. It stops the battery from charging when the battery voltage reaches more than 12 V.
- To prevent backward discharge from the battery to the PV panel when the voltage of the battery is higher than the voltage of the PV panel.

Firstly the experiments were performed using DC electrical power supply to optimise the process parameters of EC such as current, pH, pollutant concentration and electrodes gap. The EC performance was monitored in terms of turbidity and dissolved organic removal (UV absorbance). Prior to each test, 5 L of synthetic wastewater was used in the EC cell and EC was carried out by varying the process parameters. The current was adjusted by varying the voltage. EC was later carried out using solar power and compared when powered without and with charge control system. When not in use, the aluminium electrodes were immersed in acid bath (4% HCl) and prior to each experiment, they were carefully cleaned using steel wool to remove any aluminium oxide that may have formed on the surface.

The desired aluminium concentration was achieved by operating the unit under variable generation time (t) mode in accordance with Faraday's law:

$$m_{Al} = \frac{27It}{ZF} \quad (4)$$



(a) (b)

Fig.2. Experimental setup for EC using (a) DC electrical power supply and (b) PV panel.

where m_{Al} is the mass of Al generated (g of Mcm^{-2}), I is the current density (Acm^{-2}), t the time (s), Z the number of electrons transferred per Al atom (3) and F is the Faraday's constant (96,486 C Mol^{-1}).

3.3. Analytical measurements

A turbidimeter (HACH 2100P, USA) was used to measure the turbidity for all samples. 25 ml of supernatant was taken for turbidity measurement after 20 min settling period. Measurements for the turbidity were taken three times and the mean value was recorded.

Dissolved organic removal was measured in terms of UV absorbance at 254 nm which was determined with a UV-vis spectrophotometer (Shimadzu, N 595, Kyoto, Japan) in a 1 cm quartz cell. The samples were filtered through a 0.45 μm filter prior to measurement. Current and voltage were measured using multimeter (Jaycar Electronics, N 287).

4. Results and discussion

4.1. Process optimisation

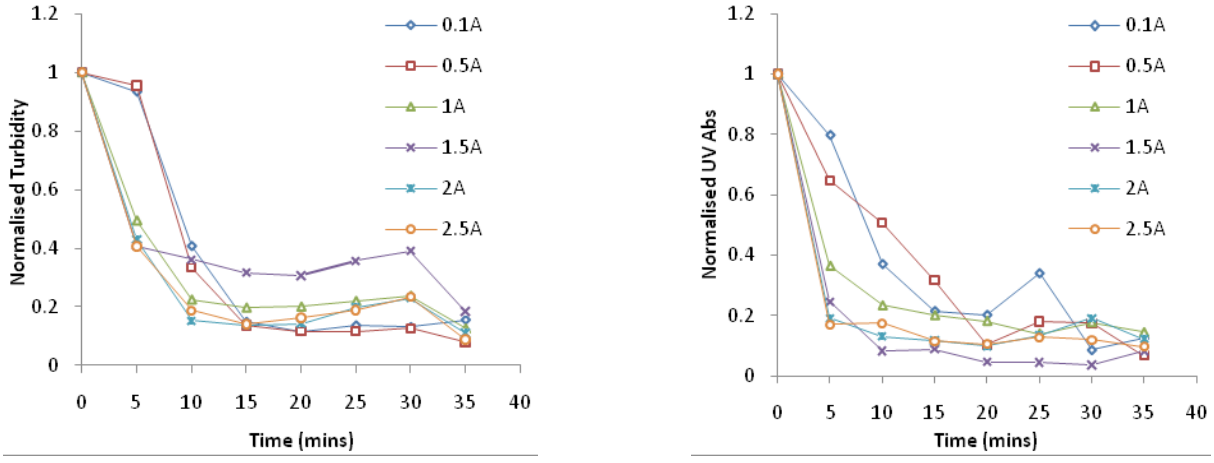
The effects of specific process variables, such as initial pH, mixing, current, initial organic loading, electrode gap were first studied using the DC as a source of power [16]. The optimum values for each variable are determined based on the highest removal of organics (UV254 absorbance) and turbidity.

Figs. 3a. and 3b. show the variation of turbidity and UV absorbance of SWW when EC was carried out at different currents using aluminium plates. Results show that turbidity and organic removal is influenced by the current intensity (or current density) at the initial stage only as the release of aluminium ions is directly dependent on the flow of currents to the electrodes. The highest removal was achieved under a current of 2.5 A (current density of 14.70 mA/cm^2), with 91% for turbidity and 90% for organic removal. However, after 35 min of EC, the removal efficiency remained almost same up to 85–90% for both turbidity and organics irrespective of what current intensity was supplied. This indicates that wastewater treatment can be performed at lower current/voltage (usual characteristics of solar power system) although it may require longer time to treat the same amount of wastewater.

Figs. 4a and 4b show the variation of turbidity and UV absorbance of batch reactor when EC was performed at different initial pH. The results indicate that, turbidity and humic acid (HA) removal was significantly influenced by the initial pH of the wastewater. The optimum pH for the EC was pH 8.0 where turbidity and organic removal were 87% and 88% respectively. At pH 3 and 5, the turbidity and UV absorbance increased which may be due to the solubility of Al ions at low pH. This indicates that EC process does not require pH adjustment since raw wastewater usually exists in the pH range.

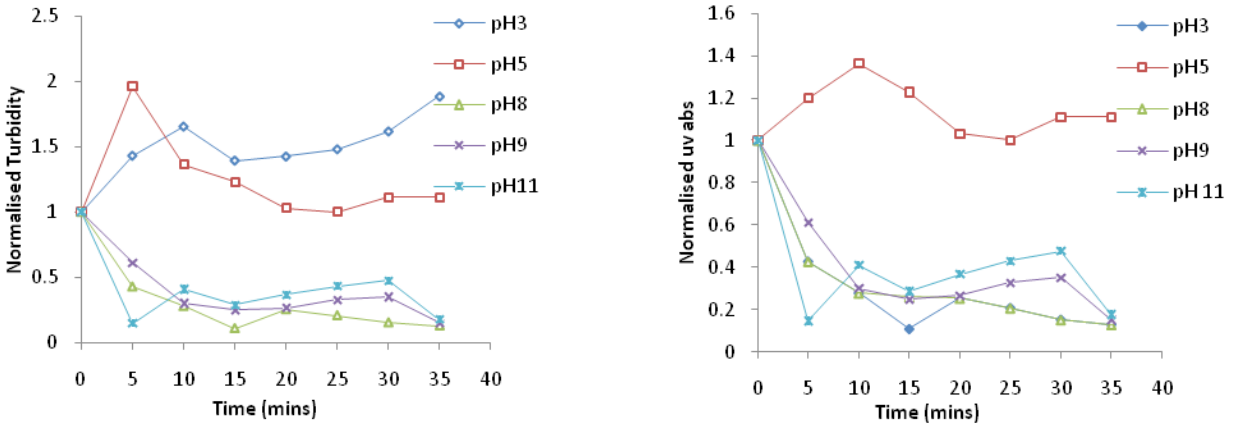
Figs. 5a and 5b show the variation of turbidity and UV absorbance when EC was performed by varying the gaps between the two aluminium electrodes. No noticeable trend was observed both for turbidity and UV absorbance indicating that, EC performance is not affected by the gap between the two electrodes. This is significant from the view of capital cost and other operational convenience with EC process.

Figs. 6a and 6b show the variation of turbidity and UV absorbance at different initial concentrations of HA. The initial HA concentration did not significantly affect the turbidity removal however, the initial removal efficiency (0–10 min) of organics was slightly higher at higher initial



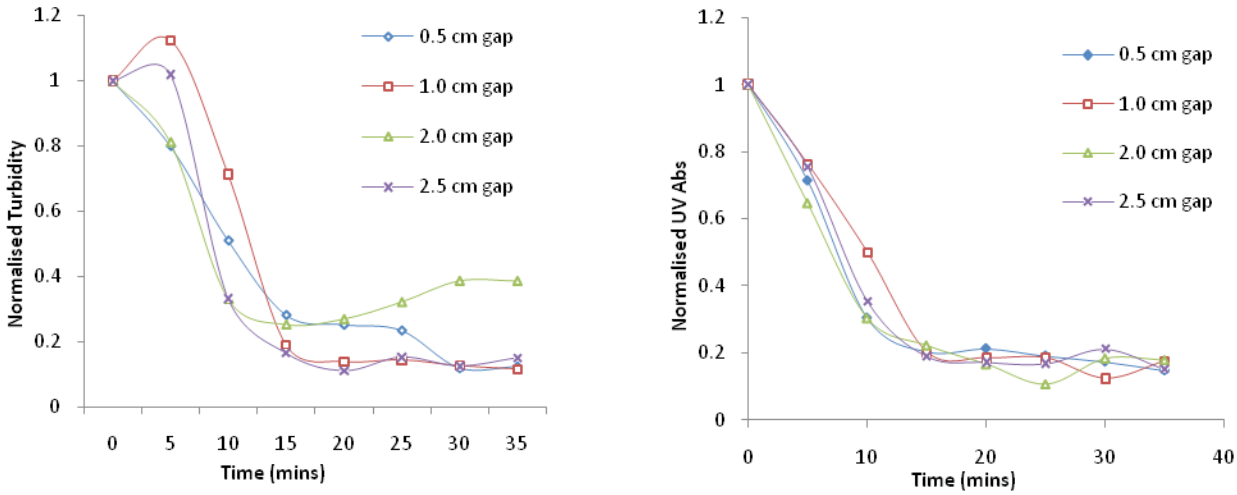
(a) (b)

Fig. 3. Variation of (a) turbidity and (b) UV absorbance of SWW in a batch reactor during EC under different current intensity (Initial turbidity = 18 NTU, initial UV = 0.150, pH = 8.0 and electrodes gap = 1 cm).



(a) (b)

Fig. 4.Variation of (a) turbidity and (b) UV absorbance of SWW in a batch reactor during EC at different initial pH (Current density = 11.5 mA/cm^2, initial turbidity = 18 NTU, initial UV = 0.150 and electrodes gap = 1 cm).



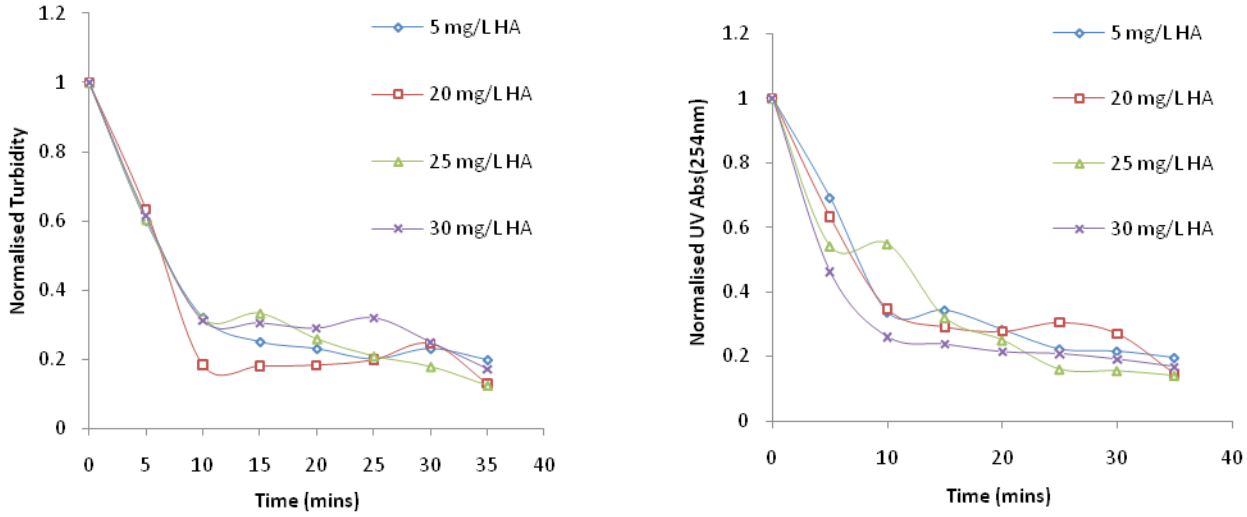
(a) (b)

Fig. 5. Variation of (a) turbidity and (b) UV absorbance of SWW in a batch reactor during EC at different gaps between the two electrodes (Current density = 11.5 mA/cm^2, initial turbidity = 18 NTU, initial UV = 0.150 and pH = 8.0).

HA concentration. This may be due to the generation of aluminium ions for 35 min which was sufficient to coagulate HA easily at this Al release rate. This indicates that EC is suitable for wastewater of any organic concentration.

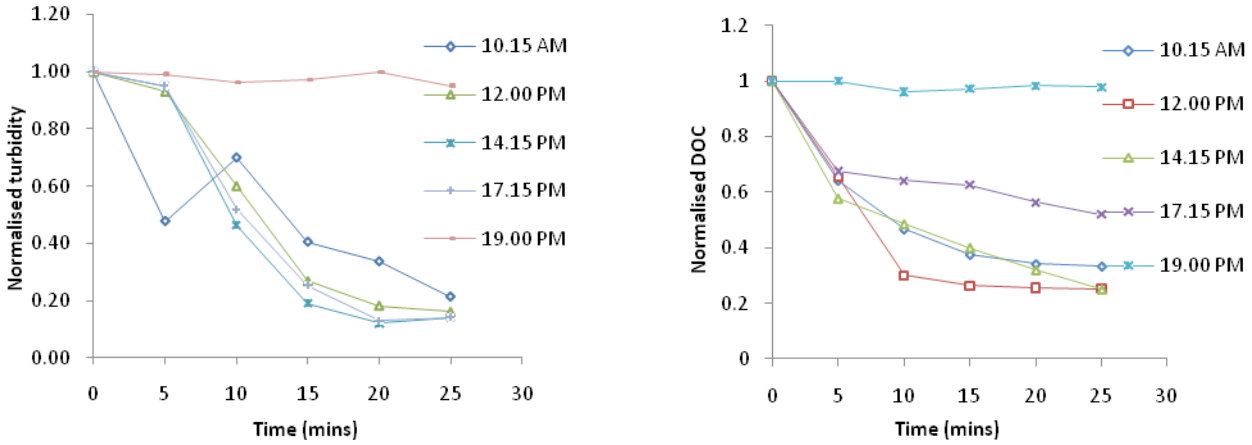
4.2. Electrocoagulation with power directly from a PV panel without charge controller

In this study, water purification system was investigated with EC carried out with power supply coming directly from the PV cells without any charge controller. The current intensity that the panel supplies depends on the solar irradiation and the temperature of the PV module which in turn is affected either in a continuous way or suddenly depending on the weather conditions. Figs. 7a and 7b show the variation of turbidity and UV absorbance for the EC conducted at five different times on 4 April 2010 starting from 10:15 A.M in the morning to 19:00 P.M in the evening. The weather was fine on the day of the experiment. As evident, the results show the variation in turbidity and organic removal is affected by solar irradiation intensity. The maximum turbidity removal (87%) and organic removal (85%) were obtained at around midday (10:00 AM–2:00 PM) when the sunlight intensity was maximum. The variations of removal efficiency were more prominent for UV absorbance than turbidity.



(a) (b)

Fig. 6. Variation of (a) turbidity and (b) UV absorbance of SWW in a batch reactor during EC at different initial concentrations of humic acid (Current density = 11.5 mA/cm^2, initial turbidity = 18 NTU, initial UV = 0.150, electrodes gap = 1 cm and pH = 8.0).



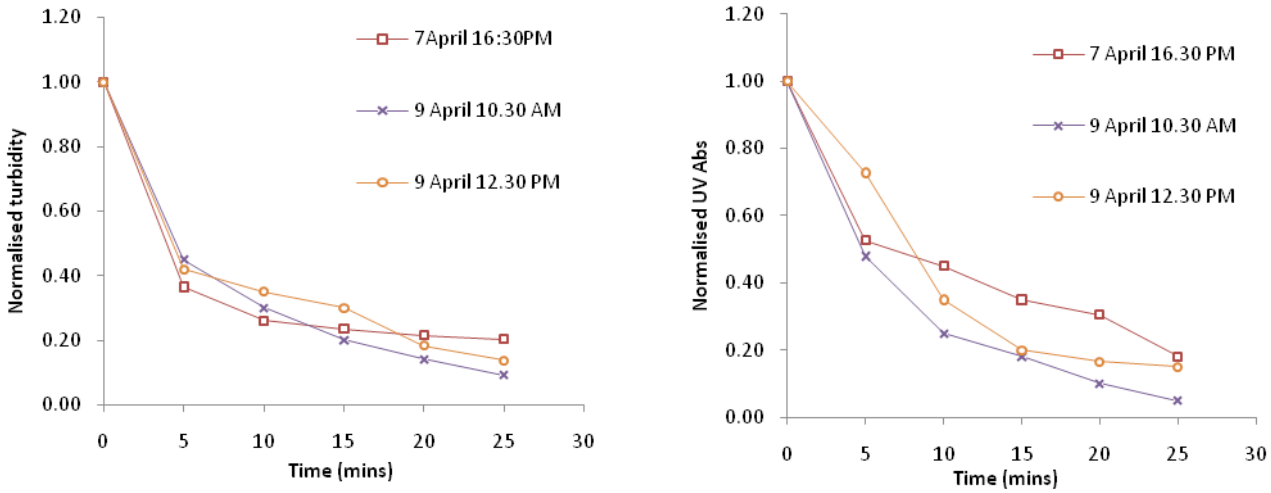
(a) (b)

Fig. 7. Variation of (a) turbidity and (b) UV absorbance of SWW in a batch reactor when EC was performed at five different times of the day (Initial turbidity = 18 NTU, initial UV = 0.150, electrodes gap = 1cm and pH = 8.0. Experiment conducted on 4th April 2010. Weather condition: fine).

4.3. Electrocoagulation with power from PV panel using battery and charge controller

In this part of the study, power supply for EC was controlled by connecting PV panel to a series of batteries connected to a charge controller before supplying to the electrodes. By this configuration, the current through the panel need not have to depend on weather conditions\solar irradiation intensity. The power was stored in a battery and supplied when the solar irradiation was low at a constant voltage of 12 V irrespective of weather conditions or the times of the day.

Figs. 8a and 8b show the variation of turbidity and UV absorbance at different times for two experiment days (7 April 2010 and 9 April 2010) using a charge controller. This configuration resulted in improved and consistent performance of the EC for wastewater treatment. The current intensity didn't fluctuate during the experiments as expected since the power was supplied by the battery during times of low solar intensity. The result showed maximum turbidity removal of 90% at 10:30 A.M in the morning (9 April 2010) and maximum UV removal of 95% at the same time and date.



(a) (b)

Fig. 8. Variation of (a) turbidity and (b) UV absorbance of SWW in a batch reactor when EC was performed at three different times of the day for two different days (Initial turbidity = 18 NTU, initial UV = 0.150, electrodes gap = 1 cm and pH = 8.0, current density = 2.11 mA/cm^2).

5. Conclusions

It is widely recognised that any treatment method powered by renewable energy such as PV panel has significance not only in Australia but all over the world where the solar energy is abundant throughout the year. This investigation was carried out to demonstrate the application of SPEC system for treating water and wastewater which may have potential for future application to remote Australian communities. In this study, the process parameters of the EC system using aluminium electrodes were first optimised using DC power supply. Under optimum conditions the results showed the highest turbidity removal (91%) and organic removal (90%). The EC system was then tested and compared with power supplied by a PV panel with or without the aid of charge control system. When the power was supplied directly from the PV panel without using charge control system, the removal efficiency was influenced by natural conditions such as weather, temperature and other meteorological conditions. The highest turbidity removal (87%) and UV removal (85%) were obtained without a charge control system. However, when the PV panel was used in combination with the batteries and charge control system, the performance of EC improved and was more consistent as there was no fluctuation in the power supply. The maximum removal of turbidity and UV absorbance was 90% and 95% respectively which is comparable to EC system powered by direct current supply. Therefore it is demonstrated here that the SPEC is feasible for water and wastewater treatment which has potential for application in remote communities.

Acknowledgements

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