

# Removal of copper and COD from electroplating effluents by photovoltaic electrocoagulation / electrooxidation process

K. Dermentzis<sup>1,2\*</sup>, D. Stergiopoulos<sup>1,3</sup>, P. Giannakoudakis<sup>3</sup> and A. Moutzakis<sup>4</sup>

<sup>1</sup> *Department of Petroleum & Natural Gas Technology and Mechanical Engineering, Laboratory of Physical Chemistry, Eastern Macedonia and Thrace Institute of Technology, 65404 Agios Loukas, Kavala, Greece*

<sup>2</sup> *Hephaestus Advanced Research Laboratory, Eastern Macedonia and Thrace Institute of Technology, 65404 Agios Loukas, Kavala, Greece*

<sup>3</sup> *Department of Chemistry, Laboratory of Physical Chemistry, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece*

<sup>4</sup> *Department of Environmental Engineering, Laboratory of Environmental and Energy Efficient Design of Buildings and Settlements, Democritus University of Thrace, 67100 Xanthi, Greece*

\* *e-mail: demerz@otenet.gr*

**Abstract:** In this study, a natural wastewater treatment system, the photovoltaic electrocoagulation (PV-EC) process is presented, which combines the autonomous and environmentally friendly photovoltaic solar energy with the capability of electrocoagulation to effectively remove copper and chemical oxygen demand (COD) from industrial copper electroplating effluents. The photovoltaic panel can be connected directly to the electrocoagulation reactor without batteries increasing, in this way, the system sustainability and eliminating the environmental threat of improper battery disposal. 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. All operating parameters affecting the efficiency of the proposed process, such as wastewater conductivity, pH, flow rate, current density, electroprocessing time and solar irradiance were studied and optimal conditions were investigated. The experimental results showed that by applying a current density of 30 mA cm<sup>-2</sup>, the concentration of copper in the treated electroplating wastewater was effectively reduced from its initial value of 65 mg L<sup>-1</sup> to less than the permissible limit (2 mg L<sup>-1</sup>), amounting to a removal percentage of over 99%. The value of COD decreased from 286 to 108 mg L<sup>-1</sup>, i.e., by 62.2 %. Higher COD removal of 93.6% could be achieved by subsequent electrooxidation with boron doped diamond (BDD) electrodes. The proposed process is appropriate for remediating industrial effluents laden with heavy metals and COD, especially for small and decentralized applications in remote and isolated locations without connection to the public electrical system.

**Key words:** Copper; COD; electrocoagulation; electrooxidation; photovoltaic solar energy

## 1. INTRODUCTION

Copper is a persistent, bio-accumulative and toxic heavy metal which does not break down in the environment, is not easily metabolized and can harm human health. Waste streams from copper electroplating industries, textile industries or washing effluents for remediation of soil contaminated with copper may contain up to 500 mg L<sup>-1</sup> copper, which, according to environmental regulations worldwide must be controlled to an acceptable level before being discharged to the environment. Only 30-40% of metals used in plating processes are effectively utilized, i.e., plated on the articles while the remaining contaminate the rinse waters during the plating process when the plated objects are rinsed upon removal from the plating bath.

Several treatment processes have been suggested for the removal of copper from aqueous waste streams, such as adsorption, biosorption, ion exchange, flotation-microfiltration, chemical precipitation and electrochemical methods: electrowinning (Formari and Abruzzese, 1999), electro dialysis/electrodeionization (Caprarescu et al., 2011; Dermentzis et al., 2009; Ren et al., 2013) and electrocoagulation (Adhoum et al., 2004; Verma et al., 2013).

The conventional chemical coagulation relies on the decrease of the net surface charge and the electrical double-layer of colloids by the addition of coagulants, such as Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, FeCl<sub>3</sub>, or organic polyelectrolytes which leads to their coagulation and precipitation.

Electrocoagulation is a new alternative way of coagulation, where the coagulants  $\text{Al}(\text{OH})_3$  and  $\text{Fe}(\text{OH})_3$  are not added to the treated solution but are produced in situ by electrodisolution of sacrificial anodes made of aluminum or iron, respectively. During the electrocoagulation process with aluminum electrodes, the following chemical reactions (1) to (3) take place. The electrochemically produced  $\text{Al}^{3+}$  ions combine with  $\text{OH}^-$  ions forming the needed  $\text{Al}(\text{OH})_3$  coagulant according to reaction (3).



Copper, beyond hydroxide precipitation and adsorption on the  $\text{Al}(\text{OH})_3$  flocs, is also partially removed by direct electroreduction at the cathode or by electroless deposition according to the following reaction (4):



The electroless deposition occurs mainly at the anode where, due to electrodisolution, the aluminum surface is more active than that of the cathode (Emamjomeh and Sivakumar, 2009). A dark brown solid deposit of elemental copper is observed mainly in the vicinity of the anode. The generated  $\text{Al}^{3+}$  and  $\text{OH}^-$  ions react to form various monomeric and polymeric species, such as  $\text{Al}(\text{OH})^{2+}$ ,  $\text{Al}(\text{OH})_2^+$ ,  $\text{Al}_2(\text{OH})_2^{4+}$ ,  $\text{Al}(\text{OH})^{4+}$ ,  $\text{Al}_6(\text{OH})_{15}^{3+}$ ,  $\text{Al}_7(\text{OH})_{17}^{4+}$ ,  $\text{Al}_8(\text{OH})_{20}^{7+}$ ,  $\text{Al}_{13}\text{O}_4(\text{OH})_{24}^{7+}$ ,  $\text{Al}_{13}(\text{OH})_{34}^{5+}$ , which finally result in in situ formation of gelatinous  $\text{Al}(\text{OH})_3$  effecting the coagulation and co-precipitation or  $\text{H}_2$  flotation of particulates from the solution by adsorption (Kobyas et al., 2003). The aluminum hydroxide flocs act as absorbents for heavy metal ions. Furthermore, heavy metal ions combine with the electro-generated  $\text{OH}^-$  ions at the cathode and precipitate in form of their insoluble hydroxides. Both phenomena act synergistically leading to a rapid removal of heavy metal pollutants from water.

Bivalent heavy metal ions, such as  $\text{Cu}^{2+}$  are removed by adsorption by the coagulant  $\text{Al}(\text{OH})_3$ . Furthermore, they combine with the electrochemically generated  $\text{OH}^-$  ions and precipitate as insoluble hydroxides according to reaction (5):



Both phenomena act synergistically leading to a rapid removal of  $\text{Cu}^{2+}$  ions from water. The electrochemical coagulation process has the advantage of combined phenomena of oxidation, reduction, flotation, adsorption and coagulation. It is effectively applied to treatment of dye house effluents, oil wastes, paper mill and heavy metal bearing effluents.

Increased environmental pollution and social concern about the environment in the last decades have led to the development of new renewable energy forms. The photovoltaic (PV) solar energy is one of the most popular and well studied renewable energy sources, which, as autonomous and environmentally friendly, is appropriate for small applications and especially in remote and isolated locations with lack of electric grid (Irfan, 1997). Electrochemical processes directly powered by photovoltaic energy have been recently reported in literature (Alvarez-Guerra et al., 2011; Ortiz et al., 2007; Valero et al., 2008; Zhang et al., 2013). As we are aware, none of them deals with heavy metal removal from industrial effluents.

The present paper demonstrates the possibility of remediating copper and COD bearing electroplating effluents using electrocoagulation (EC) with iron electrodes, which is directly powered by a PV array without batteries. The photovoltaic electrocoagulation (PV-EC) system is made versatile according to the instantaneous solar irradiation by adjusting the wastewater flow rate to the current density supplied by the PV array. All operating parameters affecting the PV-EC

process, such as wastewater pH, current density, conductivity, flow rate, contact time and solar irradiation are determined. In addition, a subsequent electrooxidation treatment of the treated wastewater significantly increased the COD removal.

## 2. METHODS

The actual wastewater was obtained from an electroplating unit located near Thessaloniki, northern Greece, with the main characteristics listed in Table 1.

Table 1. Main characteristics of treated copper plating wastewater

| Parameter    | Value  |
|--------------|--|
| pH           | 4.1  |
| Conductivity | 4000 $\mu\text{S cm}^{-1}$ (after addition of KCl) |
| Cu (II) mg/L | 65   |
| COD mg/L     | 286  |

The photovoltaic module used was ECO LINE 72/185-200W made of mono-crystalline silicon with a peak power of 200 W. The experiments were conducted in Eastern Macedonia and Thrace Institute of Technology (latitude  $40^{\circ} 55'$ , longitude  $24^{\circ} 22'$  and altitude 138 m above the sea level). DC voltage and current were measured by a multimeter (PHYWE). Conductivity was measured by means of a conductometer (WTW). The pH and the temperature were measured using a Hanna pH-meter. The wastewater was circulated by a peristaltic pump.

Electrolyses were conducted at room temperature in a cylindrical glass cell of 400 mL in which 200 mL of wastewater were placed and slowly stirred with a magnetic bar at 500 rpm. Three commercially obtained aluminum plates of size 10cm x 5cm x 0.2cm immersed to a 6 cm depth with an effective area of 60 cm<sup>2</sup> each, were used as electrodes in the experiments. The inter-electrode distance was 0.5 cm. To remove the oxide and passivation layer from aluminum surface the electrodes were grinded with sandpaper and activated by dipping them in HCl 5N for 1 minute. KCl was added to every treated solution for prevention of passivation on the aluminum electrode surface and decrease of the excessive ohmic drop in the solution. Samples were extracted every 5 minutes, filtered using Whatman filter paper (Grade 40). The residual Cu<sup>2+</sup> ion concentrations were determined by Atomic Absorption Spectroscopy AAS (Perkin Elmer 5100). The chemical oxygen demand (COD) was analyzed using a COD reactor (Thermoreaktor TR 420, MERCK) and a direct reading spectrophotometer (Spectroquant Pharo100, MERCK). The electrodes used for electrooxidation were one central Boron Doped Diamond (BDD) electrode (DiaCCom, Germany), serving as anode, and two outer graphite plate electrodes serving as cathodes. The electrode dimensions and inter-electrode distance were kept the same as by electrocoagulation experiments. Figure 1 shows a flow diagram of the proposed PV-EC process.

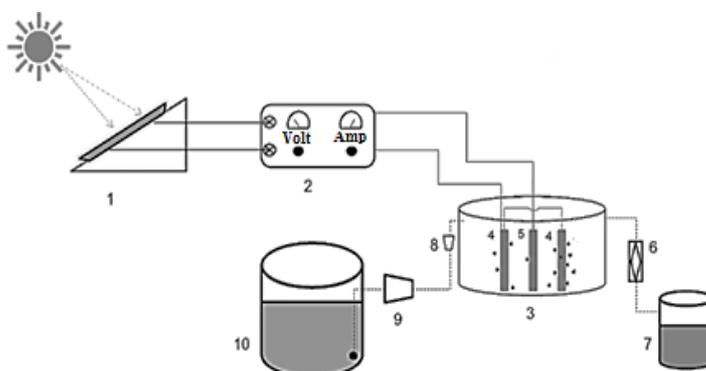


Figure 1. Diagram of the experimental setup: 1. PV Solar module, 2. Regulator, 3. Electrocoagulation reactor, 4. Electrode (a), 5. Electrode (b), 6. Filter, 7. Treated solution, 8. Flow meter, 9. Peristaltic pump, 10. Wastewater deposit.

### 3. RESULTS AND DISCUSSION

#### 3.1 Effect of operating parameters

The PV-EC process is affected by several operating parameters, such as initial pH, current density, conductivity, flow rate, contact time and solar irradiation. In the present study, all these parameters have been explored in order to evaluate a treatment technology for copper and COD removal from actual electroplating wastewater.

##### 3.1.1 Effect of initial pH

The initial pH value of the treated solution has a considerable effect on the efficiency of the electrocoagulation process. Experiments were conducted in the pH range 2-10 using each time separate wastewater samples. As can be seen in Table 2, after the electrolysis time of 50 minutes at constant current density of  $10 \text{ mA cm}^{-2}$  the percent removal of copper increases considerably with increasing pH in the range 2-10. In acidic environment ( $\text{pH} < 2$ ) the removal is low, whereas it increases considerably at pH 4 and is maintained high in the pH range 4-10. Best removal percentage of COD is observed in the pH range 4-8. The decrease in removal efficiency at strong acidic and alkaline pH was described by other researchers (Adhoum et al., 2004; Vasuderan et al., 2009). It was ascribed to an amphoteric behavior of  $\text{Al}(\text{OH})_3$  which leads to soluble  $\text{Al}^{3+}$  cations (at acidic pH) and to monomeric anions  $\text{Al}(\text{OH})_4^-$  (at alkaline pH). It is well known that these species are not useful for water treatment. For these reasons the electrocoagulation process was conducted in the pH range 4-8.

Table 2. % removal of Cu and COD by electrocoagulation versus initial solution pH

| pH | Cu removal (%) | COD removal (%) |
|----|----------------|-----------------|
| 2  | 23.7           | 11.5            |
| 3  | 79.2           | 23.8            |
| 4  | 95.5           | 61.6            |
| 5  | 97.1           | 62.3            |
| 6  | 98.4           | 62.3            |
| 7  | 99.2           | 62.5            |
| 8  | 99.5           | 62.2            |
| 9  | 99.6           | 55.8            |
| 10 | 99.4           | 43.4            |

##### 3.1.2 Effect of current density

It is well known that the current density determines the coagulant dosage rate, the bubble production rate and size, and the flocs growth resulting in a faster removal of pollutants. Measurements were carried out at different current densities  $10\text{-}30 \text{ mA cm}^{-2}$ , at constant initial copper ion concentrations of  $65 \text{ mg L}^{-1}$  and initial pH 4.5. According to Table 3, the removal rate of copper increased, as expected, with increasing current density. At 40 minutes electrolysis time at the corresponding current densities of 5, 10 and  $15 \text{ mA cm}^{-2}$ , copper ions have been almost quantitatively removed ( $>99\%$ ) and their concentration fell under the admissible limits for effluent discharge to sewage systems ( $2 \text{ mg L}^{-1}$ ). COD was reduced by about 62 %.

##### 3.1.3 Effect of conductivity

The wastewater conductivity affects immediately the applied voltage, and therefore, the electrical energy consumption. The removal percentage of copper and COD is hardly affected and remains constant over 99 % and 62 %, respectively, for the three tested wastewater conductivities of 1500, 3000 and  $4500 \text{ }\mu\text{S cm}^{-1}$  (Table 4).

Table 3. Concentration variation of Cu and COD with time and current density

| Time (min) | Cu removal (%) <sup>*</sup> | COD removal (%) <sup>*</sup> | Cu removal (%) <sup>**</sup> | COD removal (%) <sup>**</sup> | Cu removal (%) <sup>***</sup> | COD removal (%) <sup>***</sup> |
|------------|-----------------------------|------------------------------|------------------------------|-------------------------------|-------------------------------|--------------------------------|
| 0          | 0.0                         | 0.0                          | 0.0                          | 0.0                           | 0.0                           | 0.0                            |
| 10         | 43.3                        | 31.6                         | 64.6                         | 43.4                          | 81.6                          | 52.7                           |
| 20         | 68.4                        | 45.5                         | 87.7                         | 54.3                          | 97.8                          | 61.9                           |
| 30         | 83.6                        | 56.3                         | 98.1                         | 61.6                          | 99.3                          | 62.1                           |
| 40         | 89.3                        | 60.4                         | 99.4                         | 62.2                          | 99.5                          | 62.2                           |
| 50         | 96.2                        | 61.4                         | 99.5                         | 62.2                          |                               |                                |
| 60         | 98.4                        | 62.2                         |                              |                               |                               |                                |
| 70         | 99.4                        | 62.1                         |                              |                               |                               |                                |

<sup>\*</sup>5mA cm<sup>-2</sup>, <sup>\*\*</sup>10 mA cm<sup>-2</sup>, <sup>\*\*\*</sup>15 mA cm<sup>-2</sup>

Table 4. Electrocoagulation results for various wastewater conductivities

| Conductivity (μS/cm) | Voltage (V) | Energy consumption (kWh m <sup>-3</sup> ) | Cu removal percentage (%) | COD removal percentage (%) |
|----------------------|-------------|---|---------------------------|----------------------------|
| 1500                 | 24.2        | 37.3                                      | 99.4                      | 62.2                       |
| 3000                 | 12.0        | 18.6                                      | 99.6                      | 62.3                       |
| 4500                 | 5.7         | 9.2                                       | 99.2                      | 62.1                       |

### 3.1.4 Effect of flow rate

The current density supplied by the PV array depends on the solar irradiation and the temperature of the PV modules. These parameters cannot be controlled and will change continuously through the hours in a day or suddenly through clouds crossing or changes in wind speed. Ortiz et al. (2007) and Valero et al. (2008) proposed a clever mode of operation in order to make the PV-EC system versatile to instantaneous solar irradiation by keeping constant the ratio current density/flow rate. Thus, when the current density supplied by the PV array changes, also the working flow rate must proportionally change to maintain this ratio constant. This operation way implies that the volume of treated wastewater is directly related to the solar energy incident on the panels. Advantages for not using batteries are the lower installation costs, the higher electrical energy utilization, the avoidance of environmental problems related to improper battery disposal and the increase of the system sustainability. The experiments with constant current density and flow rate were conducted at a sunny midday and in short periods to keep approximately constant values of solar irradiation. As can be obtained from Table 5, by increasing the current density, the cell voltage and flow rate increase proportionally, while the residence time decreases. The removal percentage of copper and COD is hardly affected and remains high over 99 and 62 %, respectively, in all experiments.

Table 5. Electrocoagulation results for different wastewater flow rates.

| Flow rate (L/h) | Current density (mA cm <sup>-2</sup> ) | Voltage (V) | Residence time (min) | Cu removal (%) | COD removal (%) |
|-----------------|--|-------------|----------------------|----------------|-----------------|
| 0.5             | 5                                      | 4.5         | 24                   | 99.6           | 62.3            |
| 1.0             | 10                                     | 8.6         | 12                   | 99.3           | 62.2            |
| 1.5             | 15                                     | 13.2        | 8                    | 99.1           | 62.0            |

### 3.2 Solar irradiation and I-V curve of photovoltaic module

The solar irradiation intensity depends on the occasional meteorological/geographical conditions and influences the photovoltaic output current, and therefore, the performance of the electrocoagulation process. As stated in section 3.1.4, the flow rate of the treated wastewater can be used as the control parameter. The most important characteristics of the current-voltage curve of the

photovoltaic module for a solar irradiation of  $1000 \text{ W m}^{-2}$  and temperature of  $25^\circ \text{ C}$  are given in Figure 2. The short circuit current  $I_{sc}$  is the maximum current supplied by the PV panel at zero voltage between terminals. It depends mainly on solar irradiation and amounts to 5.89 Amperes. The open circuit voltage is the maximum voltage reached in absence of load. It depends mainly on temperature and amounts to 44.27 Volts. The photovoltaic panel produces electrical energy also at periods of low intensity. Table 6 shows the measured solar irradiation and solar electricity generation at both, sunny and cloudy days throughout the months of the year. It is implied that the volume of the treated wastewater depends on solar intensity and the generated electrical energy. The characteristic  $I$ - $V$  curve of the PV module refers to the specific unit used for the experiments.

Table 6. Experimental conditions and measured parameters for different meteorological conditions.

| Month       | Unshaded % of the area | Ideal Tilt Azimuth=180 | Actual Unshaded Solar Radiation Sunny day $\text{kWh m}^{-2}$ | Actual Unshaded Solar Radiation Cloudy day $\text{kWh m}^{-2}$ | Actual Unshaded Solar Radiation Sunny day $\text{kW m}^{-2}$ | Actual Unshaded Solar Radiation Cloudy day $\text{kW m}^{-2}$ | Solar electricity generation Sunny day kWh | Solar electricity generation Cloudy day kWh |
|-------------|------------------------|------------------------|---|--|--|---|--|---|
| January     | 100.00%                | 52                     | 3.02  | 2.15   | 0.378  | 0.268   | 1.13                                       | 0.81  |
| February    | 100.00%                | 43                     | 3.63  | 2.6  | 0.404  | 0.289   | 1.33                                       | 0.96  |
| March       | 100.00%                | 31                     | 4.61  | 3.34   | 0.512  | 0.371   | 1.86                                       | 1.37  |
| April       | 100.00%                | 18                     | 5.53  | 4.15   | 0.582  | 0.437   | 2.25                                       | 1.72  |
| May         | 100.00%                | 6                      | 6.27  | 4.83   | 0.66   | 0.508   | 2.78                                       | 2.19  |
| June        | 100.00%                | 0                      | 6.68  | 5.35   | 0.703  | 0.563   | 3.17                                       | 2.59  |
| July        | 100.00%                | 2                      | 6.43  | 5.24   | 0.677  | 0.551   | 2.97                                       | 2.46  |
| August      | 100.00%                | 14                     | 5.84  | 4.79   | 0.615  | 0.504   | 2.44                                       | 2.03  |
| September   | 100.00%                | 30                     | 5.09  | 4.15   | 0.566  | 0.461   | 2.11                                       | 1.74  |
| October     | 100.00%                | 45                     | 4.34  | 3.51   | 0.482  | 0.390   | 1.64                                       | 1.34  |
| November    | 100.00%                | 56                     | 3.64  | 2.8  | 0.455  | 0.350   | 1.38                                       | 1.08  |
| December    | 100.00%                | 57                     | 3.07  | 2.24   | 0.409  | 0.299   | 1.18                                       | 0.87  |
| Yearly avg. |                        |                        |   |  | 0.537  | 0.416   | 2.02                                       | 1.60  |

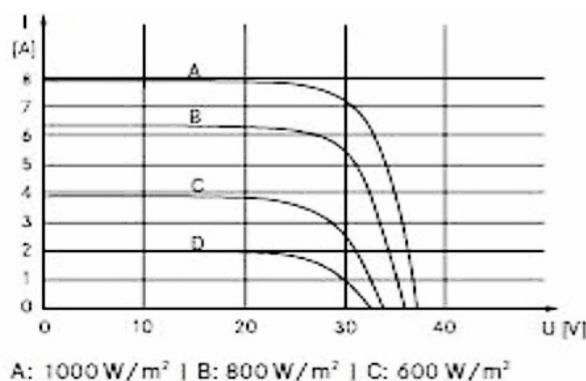


Figure 2.  $I$ - $V$  curve of photovoltaic module

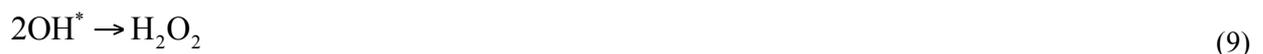
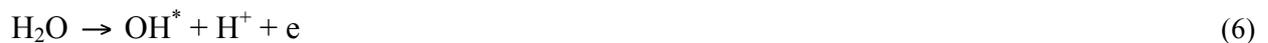
Based on Tables 3 and 6, for a sunny and a cloudy day, e.g., in May, and a wastewater conductivity of  $8000 \mu\text{S cm}^{-1}$ , the estimated volume of treated wastewater amounts to 1.73 and  $1.36 \text{ m}^3$  per day, respectively. For higher quantities of wastewater, a photovoltaic array of more panels is needed.

### 3.3 Increased COD removal by electrooxidation with BDD electrodes

The most powerful oxidant in water is the hydroxyl radical  $\text{OH}^*$  with a redox potential of 2.8 Volt versus normal hydrogen electrode (NHE). Chemical Advanced Oxidation Processes (AOPs) and Electrochemical Advanced Oxidation Processes (EAOPs), therefore, are characterized

by the production and use of these hydroxyl radicals for oxidative destruction of organic substances. BDD electrodes show the largest overvoltage for oxygen production and the widest potential window in water ever found for an electrode material (Troster et al., 2002; Kraft et al., 2003; Dermentzis et al., 2013). These electrodes are also chemically and mechanically stable. Therefore, BDD electrodes, compared to other electrodes, are the most suited for producing free OH\* radicals and performing EAOPs with very high current efficiencies (Dermentzis et al., 2014; Motoc et al., 2012).

In our previous works (Dermentzis et al., 2011; Stergiopoulos et al., 2014), it was shown that the electrooxidation process is pH dependent, with pH=3 being the optimum. Also, other researchers (Dogan and Turkdemir, 2005; Chatzisyneon et al., 2006; Vlyssides et al., 1999) reported that acidic electrolyte solutions favor the electrooxidation process, due to the increased oxidation power of the intermediate oxidants which are produced during the electrooxidation process according to reactions (6-9):



In order to show the dependence of the photovoltaic electrooxidation treatment from initial solution pH, electrooxidation experiments were conducted at three different initial pH values of 3, 7 and 11 using each time a 200 mL solution of 108 mg L<sup>-1</sup> COD which remained after the photovoltaic electrocoagulation treatment. Constant current density of 2.5 mA cm<sup>-2</sup> and constant electroprocessing time of 20 minutes with a BDD plate as anode and a graphite plate as cathode were used. COD could more effectively be removed. According to Table 7, the higher COD removal occurred at pH 3 (93.6%), followed by pH 7 (72.4%) and pH 11 (44.6%).

*Table 7. Removal percentage of COD by electrooxidation treatment at various solution pH values*

|                 | <i>pH=3</i> | <i>pH=7</i> | <i>pH=11</i> |
|-----------------|-------------|-------------|--------------|
| COD removal (%) | 93.6        | 72.4        | 44.6         |

#### 4. CONCLUSIONS

This paper shows the feasibility of performing electrochemical remediation of copper and COD bearing electroplating effluents by directly connecting the electrocoagulation reactor to the photovoltaic generator. The current density supplied by the PV array depends on the solar irradiation and the temperature of the photovoltaic modules. However, the PV-EC system is made versatile to instantaneous solar irradiation by adjusting the flow rate of the treated wastewater and keeping constant the ratio current density/flow rate. The removal percentage of copper remains high (>99 %) for the three tested wastewater flow rates of 0.5, 1.0 and 1.5 L/h and the three wastewater conductivities of 1500, 3000 and 4500  $\mu\text{S cm}^{-1}$ . At the same time, COD is removed by about 62 %. Higher COD removal of 93.6 % could be achieved by subsequent electrooxidation with boron doped diamond (BDD) electrodes at the optimum pH of 3. Based on the experimental results, the proposed PV-EC process could present some advantages for wastewater purification applications in isolated places with lack of electric grid. Furthermore, the process avoids problems concerning the maintenance of batteries and increases the system sustainability.

## ACKNOWLEDGEMENT

An initial version of this paper has been presented in the WASTenet Program Conference, “Sustainable Solutions to Wastewater Management: Maximizing the Impact of Territorial Cooperation”, Kavala, Greece, June 19-21, 2015.

## REFERENCES

- Adhoum N., Monser L., Bellakhal N., Belgaied J-E. (2004) Treatment of electroplating wastewater containing  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$  and  $\text{Cr(VI)}$  by electrocoagulation. *Journal of Hazardous Materials*, B112: 207-213.
- Alvarez-Guerra E., Dominguez-Ramos A., Irabien A., (2011) Design of the Photovoltaic Solar Electro-oxidation (PSEO) process for wastewater treatment. *Chemical Engineering Research and Design* 89: 2679-2685.
- Caprarescu S., Vaireanu D. I., Cojocaru A., Maior I., Purcara V., (2011) A 3-cell electro dialysis system for the removal of copper ions from electroplating wastewater. *Optoelectronics and Advanced Materials – Rapid Communications* 5: 1346-1351.
- Chatzisyneon E., Xekoukoulotakis N.P., Coz A., Kalogerakis N., Mantzavinou D. (2006) Electrochemical treatment of textile dyes and dyehouse effluents. *Journal of Hazardous Materials*, B137: 998-1007.
- Dermentzis K., Davidis A., Papadopoulou D., Christoforidis, K. Ouzounis, (2009) Copper removal from industrial waste waters by means of electrostatic shielding driven electrodeionization. *Journal of Engineering Science and Technology Review*, 2: 131-136.
- Dermentzis K., Marmanis D, Valsamidou E, Christoforidis A, Ouzounis K. (2011) Electrochemical decolorization treatment of nickel phthalocyanine reactive dye from wastewater, *Environmental Engineering and Management Journal*, 10: 1703-1709.
- Dermentzis K., Marmanis D., Christoforidis A., Ouzounis K., (2013) Electrochemical reclamation of wastewater resulted from petroleum tanker truck cleaning, *Environmental Engineering and Management Journal*, 13: 2395-2399.
- Dogan D. and Turkdemir H. (2005) Electrochemical oxidation of textile dye indigo, *Journal of Chemical Technology and Biotechnology*, 80: 916-923.
- Emamjomeh M. M., Sivakumar M, (2009) Denitrification using a monopolar electrocoagulation/flotation (ECF) process, *Journal of Environmental Management*, 91: 516-522.
- Fornari P. and Abbruzzese C., (1999) Copper and nickel selective recovery by electrowinning from electronic and galvanic industrial solutions, *Hydrometallurgy*, 52: 209-222.
- Irfan A.A., (1997) Photovoltaic Application in Remote Areas, Asian Institute of Technology, Bangkok, Thailand.
- Koby M, Can O. T., Bayramoglu M., (2003) Treatment of textile wastewaters by electrocoagulation using iron and aluminium electrodes, *Journal of Hazardous Materials*, B100: 163-178.
- Kraft A., Stadelmann M., Blaschke M. (2003) Anodic oxidation with doped diamond electrodes: a new advanced oxidation process, *Journal of Hazardous Materials*, B103: 247-261.
- Motoc S., Manea F., Pop A., Baciu A., Burtica G., Pode R, (2012) Electrochemical mineralization of reactive red 147 dye on boron-doped diamond electrodes, *Environmental Engineering and Management Journal*, 12: 509-516.
- Ortiz J.M., Exposito E., Gallud F., Garcia-Garcia V., Montiel V., Aldaz A., (2007) Electrodialysis of brackish water powered by photovoltaic energy without batteries: direct connection behavior, *Desalination*, 208: 89-100.
- Ren Q., Liao W., Wu Z.-C., (2013) Continuous electroextraction and concentration technology, *Journal of Electrochemistry (J)*, 19: 454-459.
- Stergiopoulos D., Dermentzis K., P. Giannakoudakis, S. Sotiropoulos, (2014) Electrochemical decolorization and removal of indigo carmine textile dye from wastewater, *Global NEST Journal*, 16: 499-506.
- Troster I, Fryda M., Herrmann D., Schafer L., Hanni W., Perret A., Blaschke M., Kraft A., Stadelmann M. (2002) Electrochemical advanced oxidation process for water treatment using DiaChemR electrodes, *Diamond Related Materials*, 11: 640-645.
- Valero D., Ortiz J.M., Exposito E., Montiel V., Aldaz A., (2008) Electrocoagulation of a synthetic textile effluent powered by photovoltaic energy without batteries: Direct connection behavior, *Solar Energy Materials and A. Solar Cells*, 92: 291-297.
- Vasudevan S, Lakshmi J, Sozhan G, (2009) Studies on the removal of iron from drinking water by electrocoagulation – A clean process, *Clean: Soil, Air, Water*, 37: 45-51.
- Verma, S., Khandegar, V., Saroha, A., (2013) Removal of chromium from electroplating industry effluent using electrocoagulation, *Journal of Hazardous Toxic Radioactive Waste*, 17: 146–152.
- Vlyssides A.G., Loizidou M., Karlis P.K., Zorbas A.A., Papaioannou D., (1999) Electrochemical oxidation of a textile dye wastewater using a Pt/Ti electrode, *Journal of Hazardous Materials*, B70: 41-52.
- Zhang S., Zhang J., Wang W., Li F., Cheng X., (2013) Removal of phosphate from landscape water using an electrocoagulation process powered directly by photovoltaic solar modules, *Solar Energy Materials and Solar Cells*, 117: 73-80.