Coupling UV irradiation and electrocoagulation for reclamation of urban wastewater

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Abstract

This work focuses on coupling electrocoagulation, with iron electrodes, and UV irradiation (photo-electrocoagulation) for the simultaneous removal of turbidity and E. coli from actual treated municipal wastewaters. Results show that single electrocoagulation behaves as a very efficient technology even using low current densities. E. coli is removed not only by the enmeshment of microorganisms into growing flocs, but also by the attack of electrochemically produced chlorine disinfectant species. Coupling UV irradiation to electrocoagulation with iron electrodes improves the process performance in terms of E. coli and turbidity removal. The effect of current density on process performance was evaluated, finding a synergistic interaction of both techniques at low current density (1.44 A m⁻²) but an antagonistic effect at higher values of current density (7.20 A m⁻²). This antagonistic effect is caused by the less efficient transmission of UV irradiation to the bulk solution due to the increase in the concentration of solids.
Keywords: electrocoagulation, UV irradiation, photo-electrocoagulation, integrated process, water reclamation.

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1. Introduction

During the recent years, applications of electrochemical technologies have aroused great deal of interest in wastewater treatment [1-4]. These technologies exhibit many advantages over conventional treatments [5] such as an easy automation, low waste production, small maintenance requirements and operation at mild conditions (room temperature and atmospheric pressure).

One of the most interesting electrochemical wastewater treatment technologies is electrocoagulation [6-11]. During this process, the dissolution of a sacrificial anode (usually Fe or Al) takes place in the electrochemical cell, causing the formation of coagulant species. These species interact with pollutants reducing their solubility or entrapping them into growing flocs of precipitates, thus promoting their removal by a later sedimentation, flotation or filtration stage. The efficiency of the process is strongly influenced by the concentration of Fe or Al and pH [12, 13].

In the particular case of municipal wastewater treatment, electrocoagulation has shown to be a good alternative to coagulation in the removal of turbidity [2, 14] and it also has been proven efficient in the removal of E. coli using iron and aluminium electrodes [15-17]. However, its disinfection efficiency is much lower than that reported for other conventional and even electrolytic technologies [2]. Thus, enhancing the disinfection rate of electrocoagulation could increase the potential of this technology for the reclamation of urban wastewater.

In this context, UV irradiation is a very interesting and well-known technology for the disinfection of this type of effluents. It consists of the direct irradiation of UV light to the wastewater and on the interaction of this irradiation with the organism's genetic material (DNA and RNA) [18]. When UV radiation penetrates the cell wall of an organism, it destroys the cell's ability to reproduce. The effectiveness of a UV disinfection system
depends on the characteristics of the wastewater, the intensity of UV radiation, the exposure time and the reactor configuration (lamps placement) [19].

This paper focuses on coupling electrocoagulation to UV irradiation (photo-electrocoagulation) for the simultaneous removal of turbidity and *E. coli* from actual treated municipal wastewaters. To the authors’ knowledge there is no previous experience in the combination of coagulation and UV irradiation technologies for disinfection and only a previous work has been found related to the integration of these two techniques [20], although applied to the removal of COD during the treatment of pharmaceutical wastewaters. The potential synergistic/antagonistic effects of coupling UV irradiation to electrocoagulation are assessed at different values of current density and using iron as sacrificial anode. Actual effluents from municipal wastewater treatment plants have been used to assess the technology.

2. Experimental

2.1 Analytical techniques

Turbidity was measured using a 115 Velp Scientifica turbidimeter, according to a standard method described in the literature [21].

Total iron concentration was measured off-line using an inductively coupled plasma spectrometer (Liberty Sequential, Varian) according to a plasma emission spectroscopy Standard Method [21]. To evaluate the total metal concentration, samples were diluted to 50:50 (v/v) using 4 N HNO₃ to ensure total solubility of the metal.
Faecal coliforms were estimated using the most probable number (MPN) technique [21]. Microorganism counts were carried out by the multiple-tube-fermentation technique (24 h of incubation at 44 °C) using 5 tubes at each dilution (1:10, 1:100, and 1:1000).

Nitrogen and chloride inorganic anions (NO$_3^-$, NO$_2^-$, Cl$^-$, ClO$^-$, ClO$_2^-$, ClO$_3^-$, ClO$_4^-$) were measured by ion chromatography using a Shimadzu LC-20A equipped with a Shodex IC I-524A column; mobile phase, 2.5 mM phthalic acid at pH 4.0; flow rate, 1.0 ml min$^{-1}$. The peak corresponding to hypochlorite interferes with that of chloride; therefore, the determination of hypochlorite was carried out by titration with As$_2$O$_3$ in 2.0 M NaOH. The same ion chromatography equipment (Shodex IC YK-421 column; mobile phase, 5.0 mM tartaric, 1.0 mM dipicolinic acid and 24.3 mM boric acid; flow rate, 1.0 ml min$^{-1}$) was used to measure the nitrogen inorganic cation (NH$_4^+$).

Chloramines were measured following the DPD standard method described in the literature [21].

Occurrence of trihalomethanes (THMs) was evaluated by gas chromatography using a SPB 10 column (30 m x 0.25 mm; macroporous particles with 0.25 µm diameter). Injection volume was set to 1 µL. Chloroform was the only trihalomethane that could be generated because chloride is the only halogen that was detected in the target wastewater.

2.2 Experimental setup

Electrocoagulation and photo-electrocoagulation tests were carried out in a bench-scale single-compartment electrochemical reactor equipped with an iron plate as anode and perforated stainless steel (SS) plate as cathode. Both electrodes were circular with a diameter of 94 mm (anode area of 69.4 cm$^2$). The electrode gap between anode and cathode was 6 mm and the internal volume of the electrocoagulation cell was 60 ml. A
power supply (0-30V, 0-10A) was used to apply current in electrocoagulation experiments (Delta Electronika ES030-10).

For coupling UV irradiation to electrocoagulation, one of the cover plates of the electrochemical cell was made of quartz and a UV lamp VL-215MC (Vilber Lourmat), \( \lambda = 254 \text{ nm} \), intensity of 930 \( \mu \text{W/cm}^2 \) and energy 4.89 eV irradiated 4 W directly to the quartz cover.

Wastewater was stored in a glass tank (5 dm\(^3\)). The system works in total recirculation mode, with a peristaltic pump (JP Selecta Percom N-M328) continuously recycling the target wastewater.

2.3. Experimental procedure

Fresh actual wastewater was collected daily at the secondary clarifiers of the wastewater treatment plant (WWTP) of Ciudad Real (small town at the centre of Spain with 80,000 inhabitants). The influent of this municipal WWTP is domestic wastewater without a significant industrial contribution. Composition of the effluent sampled in terms of chemical parameters was very uniform. However, the concentration of coliforms varies significantly from day to day. In spite of this, and after a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis, the use of any preservation method was discarded in order to purely assess the efficiency of the technologies studied. The average chemical composition of the samples is shown in Table 1.

Bench-scale electrolysis tests of 4 dm\(^3\) of wastewater were carried out under galvanostatic conditions. The current density applied ranged from 1.44–14.41 A m\(^{-2}\). Prior to use in galvanostatic electrolysis assays, the electrode was cleaned for 10 min in a 4% HCl
solution to remove any kind of impurity from its surface. Operation conditions of every experiment are clearly described in the R&D section.

3. Results and discussion

3.1. Performance of single UV light irradiation and electrocoagulation

According to the literature cited in the Introduction section, electrocoagulation is expected to influence in both, turbidity and *E. coli* concentration. Fig. 1.a shows the changes in the turbidity with the applied electric charge during the electrocoagulation of actual WWTP effluents at two different current densities. Iron dosed in both experiments is also shown in the graphs for the sake of comparison.

As it can be observed, removal of turbidity is more efficient at higher current densities, which can be easily related to the much higher amount of iron dosed. This amount is even higher than expected according to the current density applied. Thus, ratio between current densities applied in the two experiments shown in the Figure is 5.0, whereas ratio between iron produced increases to 15.5. To explain this unexpected behaviour, it is important to bear in mind that the metal dissolution in electrocoagulation processes may take place by two different mechanisms: chemical dissolution (corrosion) and electrochemical dissolution [22, 23]. In the case of the highest current density, a raise in the production of protons caused by a higher overpotential (Eq. (1)) may explain a local decrease in the pH on the anode surface and the subsequent enhancement in the chemical dissolution of the electrode. Thus, in spite of the low concentration of chloride, the chemical dissolution of the iron sheet is improved by the higher concentration of protons on its surface. This corrosion process is known to be favoured under acidic conditions.

\[
\text{H}_2\text{O} \leftrightarrow \frac{1}{2} \text{O}_2 + 2\text{H}^+ + 2\text{e}^-
\]  

(1)
The electro-generated iron coagulant species are the main responsible of the turbidity removal. As previously commented, the speciation of iron mainly depends on the pH and the metal concentration [12,13,24,25]. Fe$^{2+}$ is the main oxidation product formed during the electrochemical process (Eq. (2)), but it is oxidized by dissolved oxygen to Fe$^{3+}$ (Eq. (3)).

\[
\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \quad (2)
\]

\[
2\text{Fe}^{2+} + \frac{1}{2} \text{O}_2 + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + 2\text{OH}^- \quad (3)
\]

Both species combine with hydroxyl ions to form many other species. Among them, it is worth mentioning amorphous iron (III) hydroxide because of its relevant role in the floc-enmeshment coagulation mechanism. Some of hydroxilated species typically expected are shown in Eqs. (4) - (10). Furthermore, it is important to highlight that pH during the process was naturally maintained around 8 (initial pH value of wastewater) due to the buffering behaviour inherent to electrocoagulation processes [26]. At this value of pH, the concurrence of Fe$^{3+}$, Fe(OH)$_2^+$, Fe(OH)$_2^-$ and Fe(OH)$_4$ is negligible, being iron hydroxide precipitates the dominant species and sweep flocculation the main coagulation mechanism.

\[
\text{Fe}^{2+} + 2\text{OH}^- \rightarrow \text{Fe(OH)}_2 \quad (4)
\]

\[
2\text{Fe(OH)}_2 + \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} \rightarrow 2\text{Fe(OH)}_3 \quad (5)
\]

\[
\text{Fe(OH)}_4^- + \text{H}^+ \leftrightarrow \text{Fe(OH)}_3 + \text{H}_2\text{O} \quad (6)
\]

\[
\text{Fe(OH)}_3 + \text{H}^+ \leftrightarrow \text{Fe(OH)}_2^+ + \text{H}_2\text{O} \quad (7)
\]

\[
\text{Fe(OH)}_2^+ + \text{H}^+ \leftrightarrow \text{Fe(OH)}^{2+} + \text{H}_2\text{O} \quad (8)
\]

\[
\text{Fe(OH)}^{2+} + \text{H}^+ \leftrightarrow \text{Fe}^{3+} + \text{H}_2\text{O} \quad (9)
\]

\[
\text{Fe}^{3+} + 3\text{OH}^- \leftrightarrow \text{Fe(OH)}_3 + \text{H}_2\text{O} \quad (10)
\]
In this context, low efficiency observed in the removal of turbidity during the electrolysis at 1.44 A m\(^2\) could be a direct consequence of the low amount of iron dosed and of the subsequent prevention of the floc enmeshment mechanisms of coagulation under these particular conditions. Cell voltage under these soft current density conditions is low and a passivation film can explain the lower production of coagulant.

Fig. 1.b shows the changes in concentration of *E. coli* during the electrocoagulation experiments shown before. As it can be observed, concentration of *E. coli* decreases with the applied electric charge passed (Q), being even more efficient than removal of turbidity.

Turbidity is directly related to the presence of colloids in the wastewater and indirectly to the presence of microorganisms. This means that a removal of turbidity is expected to imply an enmeshment of microorganisms in the growing flocs and, hence, a partial removal from wastewater (not killing but simply separation). However, experimental results obtained disagree in this explanation for the removal of microorganisms, because of the higher extension of the removal of *E. coli* in both experiments and also because of the very important removal obtained at the lowest current density, in which production of coagulants is low.

To explain this observation, it should be taken into account that in addition to the removal of microorganisms by enmeshment into growing flocs, some works in the literature describe the killing of microorganisms by electrolytic processes during electrocoagulation [17]. This disinfection is explained by the formation of disinfectants in the bulk. However, significance of this real disinfection in terms of *E. coli* removal is expected to be much lower than that of the separation [15, 16].

Fig. 2 shows disinfection reagents produced in both cases. As it can be observed, not only hypochlorite but also chloramines are produced in the bulk and detected at relevant
concentrations. Both types of disinfectants come from oxidation of chlorides contained in wastewater. Chloride ions are commonly contained in any urban wastewater, typically at a not negligible concentration because they are associated with excretion products and they may also be contained in the supply water.

The product of the electrolysis is chlorine (Eq. (11)) but it rapidly disproportionates to hypochloric acid and chloride, being the overall reaction represented in Eq. (12). Hypochloric acid is partially deprotonated to hypochlorite anion depending on the pH (Eq. (13)), meaning that in the bulk, there is a mixture of three oxidants electrochemically produced with different oxidation capabilities: chlorine, hypochloric acid and hypochlorite. As it can be observed, the hypochlorite concentration follows the same trend regardless the current density applied: there is an initial increase due to the chloride electrooxidation, followed by a decrease. This decrease can be related to different processes that occur in the electrochemical cell: the attack to E. coli (causing their death), the electrochemical oxidation of hypochlorite to chlorate and perchlorate (Eqs. (14-15)) or the reaction with other species such as ammonium (Eqs. (16-18)) to form chloramines. However, the maximum concentration of hypochlorite is higher at low current densities (1.44 A m$^{-2}$). This unexpected behaviour is mainly due to its high reactivity with other species present in wastewater.

The production of hypochlorite will be higher when the current density increases (high electric potential). However, higher concentrations of hypochlorite will also promote its rapid reaction with other species such as ammonium to form chloramines. In this context, the production of chloramines is much higher when working at 7.20 A m$^{-2}$ and therefore, it implies a decrease in the hypochlorite concentration observed. On the other hand, the presence of chlorine species in high oxidation state has been discarded by ion chromatography regardless the current density applied. This fact was expected because,
according to the literature [17], iron anodes do not lead to the generation of chlorine compounds in high oxidation state (ClO$_2^-$, ClO$_3^-$, ClO$_4^-$).

\[
\text{Cl}^- + 2e^- \rightarrow \text{Cl}_2 \quad (11)
\]

\[
\text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HClO} + \text{Cl}^- + \text{H}^+ \quad (12)
\]

\[
\text{HClO} \leftrightarrow \text{ClO}^- + \text{H}^+ \quad (13)
\]

\[
2\text{HClO} + \text{ClO}^- \rightarrow \text{ClO}_3^- + 2\text{H}^+ + 2\text{Cl}^- \quad (14)
\]

\[
\text{ClO}_3^- + \text{OH}^- \rightarrow \text{ClO}_4^- + \text{H}^+ + e^- \quad (15)
\]

Chloramines are also known to be disinfectants but are less reactive and less aggressive to human health than hypochlorite. Chloramines formation (Eqs. (16)-(18)) is clearly explained in a previous work of our group [28-30] because of the interaction with hypochlorite of ammonium ions contained in the effluent of municipal WWTP or produced by cathodic nitrate reduction [31] during the electrolytic process.

\[
\text{NH}_3 + \text{HClO} \leftrightarrow \text{NH}_2\text{Cl} + \text{H}_2\text{O} \quad (16)
\]

\[
\text{NH}_2\text{Cl} + \text{HClO} \leftrightarrow \text{NHCl}_2 + \text{H}_2\text{O} \quad (17)
\]

\[
\text{NHCl}_2 + \text{HClO} \leftrightarrow \text{NCl}_3 + \text{H}_2\text{O} \quad (18)
\]

Occurrence of both disinfectants is a clear indicative of the relevance of the oxidation mechanisms in the disinfection that follows electrocoagulation processes and explains that not only enmeshment is responsible for removal of *E. coli* from wastewater. At this point, it is important to bear in mind that the role of oxygen in coagulation processes is not limited to the oxidation of iron (II) to iron (III) but it may also be reduced on the cathode surface to hydrogen peroxide. Presence of iron (II) in high concentrations could explain that this oxidant is not detected in the bulk because of the rapid combination to form hydroxyl radicals (Fenton reagents) but its action on disinfection could be
interesting and it should be at least proposed at this point. This topic could be of interest for future research, although it is out the scope of the present work.

Once discussed the main processes occurring during the single electrocoagulation, it is interesting to focus on the effects of UV irradiation. Fig. 3 shows the changes in the *E. coli* concentration and turbidity during the UV irradiation of actual WWTP effluents.

As it can be observed, and as expected, turbidity remained constant during the process because the energy irradiated with UV light is not high enough to modify the superficial charge of the colloids contained in the raw wastewater. Obviously, no other coagulation mechanisms can be activated or promoted under irradiation of light, because the formation of precipitates is not supported under these conditions.

Opposite, the influence of UV irradiation on the faecal coliforms is very relevant. Their concentration decreases with the exposure time to UV radiation following a first-order kinetic. This behaviour is expected according to literature [19, 32] and it is explained because of the modification of genetic material of microorganisms, which helps destroying their ability to reproduce [33].

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**3.2. Performance of the photo-electrocoagulation process**

Fig. 4.a shows turbidity removal and production of iron during the simultaneous electrocoagulation and UV light irradiation (photo-electrocoagulation) of actual wastewaters at 1.44 and 7.20 A m², same conditions selected for single electrocoagulation.

As it can be observed, and comparing these results to those of Fig. 1 (single electrocoagulation at the same current densities), there is a much important decrease in turbidity operating at low current densities, which can be easily related to an increased
production of iron coagulants in the cell and, hence, to an enhanced electrocoagulation process. As explained before, this fact could enhance the removal of *E. coli* by enmeshment in growing iron hydroxide precipitates. Regarding the photo-electrocoagulation at 7.20 A m\(^{-2}\) no significant changes are observed and production of iron coagulant and removal of turbidity seems not to be affected by UV irradiation (just a small improvement).

Fig. 4.b shows the changes in the concentration of *E. coli* during these photo-electrocoagulation experiments. As it can be observed, in the 1.44 A m\(^{-2}\) electrolysis, *E. coli* is depleted at an applied electric charge as low as 0.005 Ah dm\(^{-3}\). This value of applied electric charge is much lower than that required for the single electrocoagulation process (Fig. 1.b). This result is especially relevant if it is taken into account that the initial *E. coli* concentration in this test was around eight times the one in the corresponding electrocoagulation experiment (electrocoagulation with the same current density). An increase in the removal of turbidity can help to explain it, but only partially, because *E. coli* is fully depleted whereas turbidity only decreases down to a 30% of the initial value.

Regarding the experiment at 7.20 A m\(^{-2}\), there is also an improvement in the *E. coli* removal rate (complete depletion is obtained at 0.025 Ah dm\(^{-3}\) in the irradiated technology while it requires more than 0.04 Ah dm\(^{-3}\) in single electrocoagulation). In this case, no effect of turbidity removal can be accounted, as turbidity removal was almost kept within the same values in both irradiated and not irradiated experiments. Thus, the improved removal of *E. coli* should be explained only in terms of other disinfection mechanisms.

Fig. 5 focuses on the main disinfectant species formed during the photo-electrocoagulation. Again, as it can be observed, hypochlorite and chloramines are the main species produced. Maximum concentrations of hypochlorite and chloramines are 0.014 and 0.005 mmol Cl dm\(^{-3}\), for the photoelectrocoagulation carried out at 1.44 A m\(^{-2}\).
and 0.015 and 0.018 mmol Cl dm$^{-3}$ for the experiment at 7.20 Am$^{-2}$. These concentrations are even lower than that detected during single electrocoagulation experiments. At this point, it is important to note that light irradiation can promote the production of hydroxyl and chlorine radicals by means of hypochlorite decomposition as it is shown in Eqs. (19)- (20) [34, 35]. These radicals production can help to explain the higher effect of the combined photo–electrocoagulation technology on the removal of *E. coli* and the simultaneous lower detection of disinfectants.

\[
\text{ClO}^- \xrightarrow{hv} \text{O}^- + \text{Cl}^-
\]  
(19)

\[
\text{O}^- + \text{H}_2\text{O} \rightarrow \text{OH}^- + \text{OH}^-
\]  
(20)

It also helps to explain the estrange differences in the behaviour of turbidity removal between the single and the UV irradiated electrocoagulation. These radicals contribute to the chemical dissolution of the iron electrode, helping to remove passive layers which can be formed in the lowest current density experiment.

Once described the main processes occurring during the irradiation of UV light and electrocoagulation of the effluents of municipal WWTP, it is interesting to focus on the effect of the current density (main operating parameter in electrocoagulation processes) on the performance of the process.

Fig. 6 shows changes in the concentration of *E. coli* during the photo-electrocoagulation of actual wastewater at different current densities as a function of reaction time (t) and specific current charge passed (Q). As it can be observed, the concentration of *E. coli* decreases during the experiment, following the same trend regardless the current density applied, although rate and efficiency seem to be clearly influenced by this parameter.

Regarding the plot concentration vs. Q (Fig. 6.a), there is a negative effect of increasing current density on the efficiency of the removal, meaning that coagulant dosed is not
efficiently used when high production rates (high current efficiencies) are applied. This observation can be explained in terms of the less efficient way in which the coagulant dose increase with current density (lower g Fe/ Ah). Hence, the coagulation resulting from this dosing process is affected. This worse behaviour is observed in the complete range of current densities assessed and it may suggest a more effective enmeshment of *E. coli* on slowly growing hydroxide precipitates.

Regarding the plot concentration vs. time (Fig. 6.b), the removal rate exhibits an estrange behaviour with current density, increasing with this parameter at low current densities and reversing the trend at higher values (suggesting an optimum in the operation current density). To explain this observation, it should be taken into account that flocs behaves as particles which interferes light waves transmission, decreasing the efficiency of the disinfection processes that are only associated with single UV irradiation as a consequence of the absorption of light in particles [19]. As joined UV irradiation and electrocoagulation also promote other removal mechanisms, combination results in a complex output.

To further assess this interesting behaviour, as data fit well an exponential model, first order kinetic constants were obtained for the removal of *E. coli*. Fig. 7 shows these elimination rate constants for the single UV irradiation, single electrocoagulation and photo-electrocoagulation experiments. As it can be observed, there is a synergistic effect when coupling UV radiation and electrocoagulation when working at low current densities as the constant rate of the combined process (*k* = 0.0757 min⁻¹) is higher than the sum of the constant rates of both process by themselves (UV: 0.0479 min⁻¹; EC: 0.0134 min⁻¹).

For higher current densities, the behaviour observed is the contrary. The elimination rate constant is 0.029 min⁻¹ when working at a current density of 7.20 A m⁻² and UV radiation,
meanwhile the constants during the UV radiation and electrocoagulation themselves are 0.048 and 0.043 min\(^{-1}\), respectively. This fact indicates that there is an antagonistic effect when the photo-electrocoagulation is carried out at higher current densities, caused by the increase in the concentration of solids and subsequently a less efficient transmission of UV radiation to the bulk solution.

Fig. 8 shows the remaining turbidity and the metal concentration during the electro-, photo- and photo-electrocoagulation processes at different current densities. Regarding the differences between electro- and photo-electrocoagulation processes, the removal of turbidity and the amount of iron dissolved are higher during the photo-electrocoagulation process at low current densities (1.44 A m\(^{-2}\)), as described above. On the contrary, this promotion is not observed at higher current density (7.2 A m\(^{-2}\)). This dissimilar behaviour can be explained in terms of the powerful oxidants than are produced when UV irradiation is coupled to the EC system (Eqs. 19 and 20). These oxidants enhance the chemical dissolution of the anode and increase the efficiency in the production of coagulant species and in the removal of turbidity. When higher current densities are applied, the electrochemical production of iron species dominates over the chemical dissolution, the maximum concentration of solids is higher and the effect of coupling UV with electrocoagulation becomes negligible.

However, a further increase in the current density does not lead to an improvement on the photo-electrocoagulation performance in spite of the higher concentration of iron coagulant species dissolved. This fact indicates that the photo-electrocoagulation process with iron electrodes allows decreasing the turbidity in wastewaters but there is a residual turbidity that is refractory to this technique.

Finally, the energy consumption per unit volume was calculated by means of the specific electrical charge passed (Q, kAh m\(^{-3}\)) and the average potential difference between anode
and cathode for the electrocoagulation process (Eq. (21)). In the case of UV irradiation, the energy consumption has been calculated by means of the light power irradiated (w = 4W) following Eq. (22) (considering 100% efficiency of UV lamp).

\[ W \ (\text{kWh m}^{-3}) = Q \cdot V \]  
\[ W \ (\text{kWh m}^{-3}) = w \cdot \frac{t}{v} \]

The results are shown in Table 2. It can be observed that it is necessary to apply 0.0085 and 0.085 kWh m\(^{-3}\) to achieve the maximum percentage of *E. coli* removal for current densities of 1.44 A m\(^{-2}\) and 7.20 A m\(^{-2}\), respectively. The differences observed in the required energy consumption can be related to the higher electric potential when current density increases and/or to the differences between the initial concentrations of microorganisms (j: 1.44 A m\(^{-2}\), *E. coli*\(_0\): 750 CFU 100ml\(^{-1}\); j: 7.20 A m\(^{-2}\), *E. coli*\(_0\): 7000 CFU 100ml\(^{-1}\)). However, the energy consumption necessary to obtain a reclaimed water is lower than 0.1 kWh m\(^{-3}\) regardless the current density applied and the initial characteristics of the wastewater. On the other hand, the energy consumption required to achieve the complete disinfection of the effluent with the UV irradiation is much higher (around 1 kWh m\(^{-3}\)). This result means that the main energy consumption of the combined process is related to the electricity consumed by the UV lamp. This point should be optimized and will be confronted in future works.

Nevertheless, it is worth noting that the required time to disinfect the effluent is three times lower when working coupling UV to the EC process. This improvement is more marked when working at low current densities, taking into account that the initial concentration of *E. coli* in the test with UV irradiation was three fold that for single EC. In terms of the process economics, this enhancement would imply lower residence time for a hypothetical continuous process of water disinfection and, as a consequence, smaller equipment (lower investment cost) for the same treatment flow rate.
4. Conclusions

From this work, the following conclusions can be drawn:

- Electrocoagulation with iron electrodes is an efficient technology for the removal of turbidity and *E. coli* in urban wastewater reclamation. Enmeshment into growing flocs and oxidation by electrochemically (hypochlorite) and chemically (chloramines) produced species are the key processes in this technology.

- A synergistic effect was found during the UV irradiation of electrocoagulation processes (photo-electrocoagulation) at low current densities for both the disinfection rate and the removal of turbidity. The turbidity and *E. coli* removal performance improves due to the promotion of the formation of hydroxyl and chlorine radicals by UV radiation.

- Application of high current densities during the photo-electrocoagulation of urban wastewater reduces the process efficiency due to an increase in the solids concentration, which causes a decrease in the transmission of the UV irradiation to the bulk.

Acknowledgements

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References


List of Tables

Table 1. Composition of target wastewater.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Concentration (mg dm$^{-3}$)</th>
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<tr>
<td>Chloride (Cl$^-$)</td>
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<tr>
<td>Nitrate (NO$_3^-$)</td>
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<tr>
<td>Sulphate (SO$_4^{2-}$)</td>
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<tr>
<td>Ammonium (NH$_4^+$)</td>
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Table 2. Energy consumption.

<table>
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<th></th>
<th>Electrocoagulation (1.44 A m$^{-2}$)</th>
<th>UV irradiation (7.20 A m$^{-2}$)</th>
<th>Photo-electrocoagulation (1.44 A m$^{-2}$)</th>
<th>Photo-electrocoagulation (7.20 A m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E. coli_0$ (CFU/100 ml)</td>
<td>750</td>
<td>7000</td>
<td>2200</td>
<td>5400</td>
</tr>
<tr>
<td>Q (kAh m$^{-3}$)</td>
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<td>0.042</td>
<td>-</td>
<td>0.006</td>
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<td>Time (h)</td>
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<td>1</td>
<td>1</td>
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<td>Energy consumption (kWh m$^{-3}$)</td>
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</tbody>
</table>

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Figure 3
Figure 4

(a) Turbidity vs. $Q / \text{Ah dm}^{-3}$

(b) E. coli vs. $Q / \text{Ah dm}^{-3}$
Figure 5

Chlorine species (Cl) / mmol dm$^{-3}$ vs $Q$ / Ah dm$^{-3}$
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Figure 8