Treatment of laundry wastewater by biological and electrocoagulation methods

Terelle Ramcharan and Ajay Bissessur

ABSTRACT

The present study describes an improvement in the current electrocoagulation treatment process and focuses on a comparative study for the clean-up of laundry wastewater (LWW) after each wash and rinse cycle by biological and electrocoagulation treatment methods. For biological treatment, the wastewater was treated with a Bacillus strain of aerobic bacteria especially suited for the degradation of fats, lipids, protein, detergents and hydrocarbons. Treatment of the LWW by electrocoagulation involved the oxidation of aluminium metal upon the application of a controlled voltage which produces various aluminium hydroxy species capable of adsorbing pollutants from the wastewater. The efficiency of the clean-up of LWW using each method was assessed by determination of surfactant concentration, chemical oxygen demand and total dissolved solids. A rapid decrease in surfactant concentration was noted within 0.5 hour of electrocoagulation, whereas a notable decrease in the surfactant concentration was observed only after 12 hour of biological treatment. The rapid generation of aluminium hydroxy species in the electrocoagulation cell allowed adsorption of pollutants at a faster rate when compared to the aerobic degradation of the surfactant; hence a reduced period of time is required for treatment of LWW by electrocoagulation.

Key words | biological, Biospinners, electrocoagulation, laundry wastewater, linear alkylbenzene sulphonates

INTRODUCTION

Water is a vital component for the sustainability of life on earth. With an increase in the world population and urbanisation, the demand for fresh potable water has escalated (Marcucci et al. 2002). This has accelerated the need for the development of new and more efficient wastewater recycling systems. Laundry wastewater (LWW) can be considered to be relatively less chemically polluted when compared to other industrial effluents; hence its purification and recycling would become pivotal in decreasing the demand for fresh potable water (Schouten et al. 2007). Targeting the development of new and economical treatment methods for LWW should not only be geared toward efficiency in the recycling ability but also incorporate minimal consumption of chemicals and energy. The typical composition of LWW consists primarily of the laundry detergent, inorganic species, minor organic compounds and dirt removed from soiled items (St Laurent et al. 2007). The characteristic chemicals found in laundry detergents chiefly include surfactants, builders, bleach and co-builders. Laundry detergents to a large extent contain a higher percentage of anionic surfactants and builders in comparison to other minor ingredients. Sodium dodecylbenzene sulphonate (SDS) and sodium aluminium silicates (more commonly known as zeolites) are the most common anionic surfactants and builders, respectively, utilised in laundry detergents (Duarte et al. 2006). The hydrophobic head and hydrophilic tail of the surfactant ensure effective removal of most inorganic species from LWW regardless of its hydrophilic or hydrophobic nature. On the other hand builders prevent water hardness by exchanging sodium ions with smaller cations such as magnesium and calcium. For the implementation of the recycling of LWW it is imperative to routinely monitor and analyse the surfactant level, as this is the major component of the detergent’s ingredients and is indicative of its efficacy in the removal of dirt. Most laundering facilities require a single wash cycle and two rinse cycles for the effective cleaning of soiled items. The sampling and purification of LWW after the
wash and two rinse cycles is crucial in monitoring the treatment process, as the level of surfactants is inconsistent and varies significantly. A greater total energy input is required for the recycling of wastewater after the first wash cycle when compared to the rinse cycle due to the high foaming nature of the surfactant at this initial stage of washing.

Current methods implemented in wastewater treatment plants involve the separation of the solid matrices from the liquid matrices. This is often achieved by the addition of salts such as aluminium, iron or calcium, which results in formation of larger particles by the coagulation of smaller solid particles (Guida et al. 2007). Polymer-based flocculation reagents, for example polydiallyldimethylammonium chloride, are generally used in combination with coagulating reagents (AlCl₃ and FeCl₃) to ensure formation of a larger separated mass, which increases the efficiency of the treatment of the wastewater. AlCl₃ and FeCl₃ result in the formation of gelatinous flocculants which remain suspended and are efficient in removing fine sediments from the LWW.

Biological treatment which is commonly used for the treatment of wastewater usually involves the addition of a cultured bacterial strain to the wastewater, which is targeted at degrading specific pollutants (Chan 2012). The advantage of using biological treatments is the negligible or reduced amount of chemicals involved as well as them being a totally environmentally friendly process. Some of the major disadvantages associated with this process are the large amount of space required for the storage of biological waste and prolonged time-periods for different effluent treatment in comparison to chemical treatment methods. Optimisation and adjustment of the biological treatment processes have to be considered for each individual effluent. In fact each effluent has to be characterised prior to a biological treatment process to determine its unique current condition. Thus the pH of the wastewater plays a significant role in the efficiency of the degradation of pollutants by bacterial means. Extreme acidity (<4) and basicity (>9) slow the metabolism of the bacteria, which eventually leads to their destruction.

Typical contaminants and stains (soil) that are found in domestic LWW generally originate from clothing items stained from food, drinks, body soil and atmospheric dust, whereas industrial LWW in general may contain high concentrations of oil, grease, heavy metals and other organic compounds (St Laurent et al. 2007). In this case the rigorous application of an efficient clean-up method for both domestic and industrial LWW has to be implemented to ensure the facile and complete removal of these compounds. Electrochemical methods such as electrocoagulation have proven successful in satisfying the criteria for the treatment of such highly polluted soils and effluents (Merzouk et al. 2011). They are known to effectively remove both organic and inorganic pollutants, particularly heavy metals, minerals, organic material and dyes, from wastewater streams.

The simultaneous production of monomeric aluminium hydroxy species during electrocoagulation such as Al(OH)²⁺, Al(OH)₃, Al₂(OH)₃⁺ and Al(OH)₄ and polymeric aluminium hydroxy species such as Al₆(OH)₁₅⁺, Al₇(OH)₁₇⁺, Al₈(OH)₂₅⁺, Al₁₃O₄(OH)₂₄ and Al₁₅(OH)₃₄ increases the efficiency of pollutant removal from wastewater (Janpoor et al. 2011). The aluminium hydroxy species are amorphous in nature with a large surface area, thus permitting effective removal of pollutants through the mechanism of adsorption, particularly on the surface (El-Khaled 2011).

The application of electrocoagulation to a wide range of wastewater streams is made possible via a pH neutralisation step during the treatment process. The major disadvantage associated with this treatment method is the formation of an overlying film on the electrodes. However, an increase in the voltage supply breaks up the film formed on the electrodes, as reported by (Wang et al. 2009), thereby increasing the efficiency of the treatment method. Consequently, this increases the cost of the overall treatment because of this additional supply of energy.

An understanding of the chemical kinetics for electrocoagulation implementation is crucial to the pilot application of wastewater treatment systems. The adsorption capacity and the rate of production of a specific adsorbent are the two most important chemical kinetic parameters required for efficient management of wastewater treatment plants. The Lagergren pseudo first-order kinetics and the Ho pseudo second-order kinetic expression are commonly utilised for determining the adsorption capacity of a solid/liquid matrix system (Ho 2006; Kumar 2006). Equations (1) and (2) below represent the linearized form of the pseudo first- and second-order reactions, respectively, where \( q_t \) and \( q_e \) correspond to the amount of analyte adsorbed (mg g⁻¹) at time \( t \) (min) and at equilibrium, respectively, and \( k_1 \) and \( k_2 \) are the kinetic constant for the pseudo first- and second-order reaction, respectively.

\[
\log(q_e - q_t) = \log(q_e) - \frac{k_1 t}{2.303}
\]

\[
\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}
\]

This paper presents the clean-up of LWW arising from each wash and rinse cycle by biological and electrocoagulation
treatment methods. For the biological treatment, a bacterial wastewater treatment product specially designed for the biological treatment of domestic, food processing and industrial wastewater was utilised. This product contains naturally occurring, non-pathogenic bacteria which are capable of producing enzymes that have the ability to degrade fats, lipids, protein, detergents and hydrocarbons. The applicability and efficiency of the treatment methods are assessed by determination of the total surfactant, chemical oxygen demand (COD) and total dissolved solids (TDS) in the LWW.

**METHODS**

**Chemical reagents**

HPLC grade solvent acetonitrile, sodium dodecylbenzene sulphonate, silver sulphate and nitric acid (AR 69% v/v) were purchased from Sigma Aldrich (Germany). Sulfuric acid (98% m/v) and ferrous ammonium sulfate decahydrate were purchased from SMM Instruments (South Africa). Aliquots of 1,000 mg L\(^{-1}\) ICP standards of silicon, aluminium and sulphur were purchased from DLD Scientific (South Africa). Mercuric sulphate and 1,10-phenanthroline were purchased from Merck (Germany). Potassium dichromate and sep-pak 360 mg C\(_{18}\) solid phase extraction (SPE) cartridges were purchased from SAAR Chem (South Africa) and Waters (USA), respectively. Biospinners\(^\circ\) and Em Tec-WP biological wastewater concentrate were purchased from Azapac (South Africa) and Em Tec Management Ltd (Thailand), respectively.

**Sample collection**

LWW samples were collected as reported by Ramcharan & Bissessur (2016). Samples were collected in amber glass bottles after each wash and each rinse cycle, and were refrigerated. For simplicity, the samples in this paper are referred to as W1, R1 and R2 which correspond to the water disposed from the first wash cycle, first rinse cycle and second rinse cycle, respectively.

**Treatment methods**

**Biological treatment**

Biological treatment at ambient temperature (24°C) was carried out in a 2 L glass beaker. A volume of 50 mL (100 mg L\(^{-1}\)) of the *Bacillus* strain of aerobic bacteria was added to 1 L of LWW. An adequate quantity of Biospinners was added to cover the bottom surface area of the beaker (reaction cell, Figure 1).

A consistent stream of air was purged through the wastewater with mechanical stirring. LWW was sampled after 12, 24, 48 and 72 hour treatment time periods.

**Electrocoagulation treatment**

A similar set-up (Figure 1) was utilised for electrocoagulation of the LWW. The reaction cell comprised a 2 L glass beaker, aluminium electrodes, a magnetic stirring unit and a voltage supply of 8 V to the electrodes. The dimensions of the electrodes were 180 mm × 50 mm. Figure 1 illustrates the

---

*Figure 1* | Experimental set-up for (a) biological treatment and (b) electrocoagulation of LWW.
experimental set-up for the biological treatment and electrocoagulation of LWW. LWW was sampled after 0.5, 1, 12 and 24 hour treatment time periods. Electrocoagulation was carried out at ambient temperature (24°C).

Chemical and physical analysis of LWW before and after treatment

All chemical and physical analyses were carried out in triplicate.

COD analysis

A titrimetric method with potassium dichromate and ferrous ammonium sulphate was employed for dissolved COD analysis (APHA 1975).

Inductively coupled plasma optical emission spectrometry analysis

For diagnostic purposes the LWW samples were scanned by inductively coupled plasma optical emission spectroscopy (ICP-OES) (Perkin Elmer optical emission spectrometer Optima 5300 DV) to monitor the relative intensities of persisting inorganic metal ions, and their corresponding concentrations were evaluated. LWW samples were acidified with nitric acid (69%) and diluted before analysis by ICP-OES for quantification of Al, S, and Si.

Surfactant analysis

The quantification of SDS was carried out as reported by Ramcharan & Bissessur (2016) and was analysed on a Perkin Elmer 200 series with a UV detector set at 225 nm and a 20 μL injector loop.

pH and TDS of LWW

The pH and TDS were recorded using a Metrohm 827 pH laboratory meter and a WTW TetraCon 325 TDS meter.

RESULTS AND DISCUSSION

Composition of LWW

From previous studies it has been reported that polydimethylsiloxane, SDS and sodium aluminium silicate (zeolite), mainly, have been found to be the most abundant reagents utilised as anti-foam reagents, surfactants and builders, respectively, in laundry detergents.

In this study, analysis of LWW from W1, R1 and R2 by ICP-OES showed abundance in sulphur, silicon and aluminium (Table 1). As the majority of the pollutants in the LWW are removed after the first wash cycle, there is a distinct decrease in the levels of S, Si and Al from W1 to R2. This accounts for the subsequent drops in pH for W1, R1 and R2 of LWW from 9.58 to 8.04 and finally to 7.55, respectively. According to the South African quality guidelines, reported levels of Si and sulphate for reuse as utility water in the domestic sector (South African Quality Guidelines 1996) should be within a range of 0–200 mg L⁻¹ and 0–20 mg L⁻¹, respectively. The amounts of Si and total sulphur in R2 were below these prescribed levels. In the case of Al it is not regarded to be harmful in reuse utility water in the domestic sector.

Biological and electrocoagulation treatments of LWW

The objective of applying both these treatments was targeted at mainly removing SDS as it is one of the major chemical components remaining after W1, R1 and R2. It is envisaged that the treatments will remove SDS (to varying degrees), thus restoring the rinse water to a re-usable state.

The high organic content in the LWW serves as a nutrient medium for the bacterial strain added to the LWW. Consumption of the organic matter in the presence of oxygen results in the production of carbon dioxide and generation of new microbes (Von Sperling 2007). The biological treatment method, although proved to work successfully, did not initially proceed effectively. Adjustments and modifications to the process to enhance its efficiency required purging with a steady stream of air and the addition of Bio-spinners to the reaction cell. Bio-spinners, which are cylindrical plastic objects with multiple grooves, have the ability to support a biofilm. These objects were introduced to the reaction cell to enhance the treatment method by providing a greater surface area for cultivation of bacteria.

| Average concentration of S, Si and Al in LWW |
|-----------------|-----------------|-----------------|
| Si (mg L⁻¹)     | Sb (mg L⁻¹)     | Al (mg L⁻¹)     |
| W1              | 89.56 ± 2.69    | 309.8 ± 3.87    | 11.74 ± 3.91    |
| R1              | 7.2 ± 3.46      | 124.6 ± 5.01    | 9.72 ± 3.42     |
| R2              | 6.18 ± 3.83     | 19.34 ± 5.05    | 3.4 ± 4.97      |

aAnalysis of sample triplicates with reported relative standard deviation.
bTotal sulphur content made up of sulphates and sulphonates.
In this way the oxidative environment for efficient degradation of SDS was increased and conditions for growth of the aerobic bacteria were made more conducive.

In the case of LWW treatment by electrocoagulation, formation of multiple aluminium metal hydroxy species was crucial to the measure of the success of the process. The generation of the metal hydroxy species was confirmed by the visible appearance of a grey flocculant in suspension. Mechanical stirring throughout the electrocoagulation process was pivotal in ensuring complete adsorption of pollutants.

The pH of the LWW is crucial to the success of electrocoagulation as the formation of metal hydroxy species is dependent on values exceeding pH 7.

The implementation of a pH neutralisation step during electrocoagulation extends its application to a wider range of wastewater samples. An indication of a pH neutralisation step is observed for W1 where there is an initial increase in pH followed by a decrease, while for R1 and R2 there is a constant increase in pH (Figure 3).

One of the major disadvantages of electrocoagulation treatment at high pH is the passivation of the aluminium anode. This protective metal oxide film is due mainly to the production of a combination of aluminium hydroxy chloride species. Under extreme basic conditions such as that in W1, generation of Al(OH)₄⁻ species is unfavourable as it forms a protective film over the anode. Upon completion of the electrocoagulation process there was a larger amount of the overlying film for W1 when compared to R1 and R2. Improvement to the current electrocoagulation method was implemented by the addition of Biospinners to the electrocoagulation cell.

In comparison to the current method of electrocoagulation, a greater percent removal in the surfactant, COD and TDS removal is noted for electrocoagulation upon addition of Biospinners for W1 (Figure 4). The main objectives of adding the Biospinners were to provide a greater surface area for the aluminium hydroxy species, a greater rate of aeration and partial removal of the overlying film on the electrodes. The additional aeration provided to the electrocoagulation cell had significantly increased the COD removal.

The removal of the overlying film on the electrodes was crucial to permit further dissolution of the aluminium electrodes, thus increasing the aluminium hydroxy content in the LWW and adsorption sites for pollutants. Similar results and trends in the surfactant concentration, COD and TDS were observed for R1 and R2.

The application of electrocoagulation used in pilot wastewater treatment plants requires kinetic data in order to ascertain the rate at which aluminium hydroxy species are generated, thus establishing the adsorption capacity of the aluminium hydroxy species. This has a direct consequence on the removal of surfactants and other contaminating chemical species that are present within the matrix. The rate of formation of the aluminium hydroxy species followed a first-order reaction given by Equation (3) below:

\[
\ln \left( \frac{[A]}{[A]₀} \right) = -kt
\]  

Figure 2 | Image of a Biospinner.

Figure 3 | pH of various rinse samples of LWW at different stages of electrocoagulation treatment.

Figure 4 | Average* percentage removal of surfactant, COD and TDS with and without Biospinners. *Analysis of sample triplicates.
where [A]₀ and [A], respectively, correspond to the initial and specific concentration of the aluminium hydroxy species at time t. The concentration of the aluminium species was performed in triplicate at time t, with a percentage relative standard deviation <5, thus highlighting the precision of the results obtained. A plot of ln([A]/[A]₀) vs t displayed a linear regression given by the $R^2$ value of 0.9637 (Figure 5), and the slope generated the rate constant of 0.0016 min⁻¹. The linear regression (Figure 5) confirms that the rate of formation of the aluminium hydroxy species follows a first-order reaction; hence it is suggested that a doubling in the mass of the aluminium would result in doubling the concentration of aluminium hydroxy species.

The concentration of the aluminium hydroxy species generated during electrocoagulation was determined based on three different calculation methodologies:

1. the mass difference of the electrodes before and after electrocoagulation;
2. mass of Al calculated using Faraday’s Law (Equation (4));
3. mass of Al(s) in the LWW calculated from ICP-OES analysis

$$n_A = \frac{Q}{nF} \quad (4)$$

where $Q$ = charge of electrolytic cell, $n_A$ = number of moles of Al, $n$ = number of electrons and $F$ = Faraday’s constant (96487).

The mass of Al(s) determined by the difference in mass of electrodes before and after electrocoagulation (0.36 g) varied significantly when compared to the mass of Al(s) determined using Faraday’s law (0.434 g) and ICP-OES (0.449 g).

The gravimetric determination of the aluminium hydroxy is highly dependent on:

(a) complete formation of aluminium hydroxy with no free $Al^{3+}(aq)$ remaining;
(b) careful and complete removal of the deposited aluminium hydroxy film.

The low quantity of Al(OH)₃ generated by the gravimetric method was due to the error-prone removal of the film from the electrodes.

Hence the mass of Al(s) generated during electrocoagulation is best calculated using Faraday’s law and ICP-OES analysis, given by the closeness of the mass of Al(s) obtained. The adsorption capacity for surfactant removal in W1, R1 and R2 by the aluminium hydroxy species was assessed using the Ho pseudo second-order kinetic expression.

A plot of $t/q_t$ vs $t$ showed that the reaction followed a pseudo second-order reaction given by the $R^2$ values >0.99 and the similarity of experimental and calculated $q_e$ values (Figure 6).

The $q_t$ values were calculated by the determination of the efficiency of adsorption (% E) given in Equation (5), whereby $C₀$ and $C$ correspond to the initial and specific concentration of the surfactant at time $t$. The adsorption efficiency at equilibrium ($q_e$) and rate of adsorption ($k_2$) was calculated according to Equations (6) and (7), respectively. The rate of adsorption of the surfactants is significantly lower for W1 when compared to R1 and R2 (Table 2). This demonstrates the reduced amount of time required for the treatment of LWW resulting from R1 and R2.

$$\%E = \frac{C_0 - C}{C_0} \times 100 \quad (5)$$

![Image](https://iwaponline.com/wst/article-pdf/75/1/84/456517/wst075010084.pdf)
Figure 7 shows the concentration of the surfactant in W1, R1 and R2, and the concentration of the aluminium hydroxy species throughout the electrocoagulation process. The concentration of the surfactant in W1 exceeds the concentration of the aluminium hydroxy species during the first 12 hours. Therefore, the rate of adsorption is significantly lower when compared to the rate for R1 and R2, as the rate of adsorption of the surfactant depends on the production of the aluminium hydroxy species.

In order to gauge the efficacy of the biological and electrocoagulation treatment methods, SDS (surfactant), COD and TDS removal was monitored after applying these two methods. The concentrations of SDS for W1, R1 and R2 are shown in Figure 8, where a shorter period of time was required for surfactant removal from the LWW treated by electrocoagulation.

Although both treatment processes display significant decreases in the SDS concentration, the drop in SDS occurs to varying degrees as seen in Figure 8.

The electrocoagulative process is shown to have a more pronounced effect than the biological process, with sharp decreases in the SDS concentration over extremely short periods. A comparative time frame shows an 80% decrease in SDS using the electrocoagulative treatment for W1 within a half-hour while a 12 hour biological treatment only decreased the SDS concentration by 40%.

The electrocoagulative treatment resulted in lower SDS levels than did the biological treatment for all wash and rinse LWW. The biological treatment initially showed a gradual drop followed by a plateauing off to a minimum. This was expected as the microbial growth, especially in R1 and R2, is initially gradual and afterwards (usually a 12 hour period) results in exponential growth of the bacteria which subsequently imposes its full oxidative strength. On the other hand the electrocoagulative treatment is immediate and provides ongoing oxidation that drives the formation of the aluminium hydroxy species which are primarily responsible for the clean-up of the LWW. The

Table 2 | The Ho pseudo second-order kinetic parameters for adsorption of surfactants by aluminium hydroxy

<table>
<thead>
<tr>
<th>Kinetic parameter</th>
<th>W1</th>
<th>R1</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental $q_e$</td>
<td>77.60</td>
<td>67.27</td>
<td>60.69</td>
</tr>
<tr>
<td>Calculated $q_e$</td>
<td>77.52</td>
<td>68.97</td>
<td>57.47</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.997</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>$k_2$</td>
<td>$8.53 \times 10^{-4}$</td>
<td>$2.53 \times 10^{-3}$</td>
<td>$2.21 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

$$q_e = \frac{1}{\text{slope}} \quad (6)$$

$$k_2 = \frac{\text{Slope}^2}{\text{intercept}} \quad (7)$$

**Figure 7** | Concentration of surfactant in W1, R1 and R2, and aluminium hydroxy species during electrocoagulation (Stage 1 – 0.5 hour; Stage 2 – 1 hour; Stage 3 – 12 hour; Stage 4 – 24 hour).

**Figure 8** | Surfactant concentration sampled at (a) 12, 24, 48 and 72 hours for biological treatment and (b) 0.5, 1, 12 and 24 hours for electrocoagulation.
superiority of the electrocoagulation treatment of LWW is further evidenced and enhanced from a comparison of the COD shown in Figure 9, especially upon treatment of W1 LWW whereby a slow but gradual increase in COD is observed. The pH of the wastewater evidently promoted the destruction of the bacteria, as the dead bacterial cells increased the organic content in the wastewater, which consequently increased the COD in W1 (Figure 9(a)). Contrastingly an immediate drop in COD is attained for the electrocoagulative technique.

COD levels for R1 and R2 were consistent for both treatment methods (Figure 9); however, an initial drop in the COD was observed for R1 only, whereas the change in the COD levels for R2 was almost negligible for the duration of the implemented treatment. The overall percentage decrease in COD for R1 (41.36%) was much sharper over a shorter period of time (24 hours) for the electrocoagulative treatment, while a decrease in COD of 32.51% was observed for the biological treatment over a 72 hour period.

The presence of the SDS is directly linked to the COD in that its effective removal by the electrocoagulative treatment rapidly decreased the organic content present; thus a rapid decrease in the COD is observed (Figure 9(b)).

As reported by Scott & Jones (2000), SDS is susceptible to degradation under aerobic conditions; hence it is presumed that the decrease in surfactant levels for W1 observed for biological treatment (Figure 8(a)) can be solely attributed to oxidative degradation by aeration as no bacteria are expected to persist under these pH conditions (Scott & Jones 2000).

SDS was qualitatively determined by Ramcharan & Bissessur (2001) as the major surfactant in LWW; hence oxidative degradation of SDS was further investigated by purging a standard SDS solution with air over a period of 2 days. A notable decrease in the SDS concentration (Figure 10) was observed, hence showing that SDS is susceptible to degradation in an oxygen-rich environment with no added bacteria. This accounts for the decrease in the surfactant concentration in W1 treated by the biological method.

A 44.63%, 33.08% and 8.46% decrease in the TDS was noted for W1, R1 and R2, respectively, treated by electrocoagulation, while there was a 49.19%, 64.55% and 67.02% increase in the TDS for W1, R1 and R2, respectively, treated by the biological method (Figure 11).

A larger percentage increase is observed for R1 and R2, as the favourable conditions promoted growth of bacteria within the LWW.

A longer period of time is required for the bacteria to form a larger settleable mass; hence an increase rather than a decrease in the TDS was observed in the LWW. For the electrocoagulation method, formation of a large settleable flocculant (aluminium hydroxyl species) allows for effective TDS removal from LWW within a short period of time when compared to the biological treatment method. Figure 11(b) shows a continuous decrease in the TDS of the LWW after 12 hours of electrocoagulation.
This displays the coalescing of smaller aluminium hydroxy species, which increases the efficiency of the filtration procedure of the treated wastewater.

Despite being a more demanding energy process, treatment of LWW by electrocoagulation, compared with the biological method, shows higher efficiency and greater success, in addition to being applied to a wider range of samples at a much reduced treatment time. Increase in energy consumption could possibly be circumvented by the implementation of solar energy, thus enhancing the favourability of the method.

**CONCLUSION**

Both biological and electrocoagulation treatment methods were effective in decreasing the level of the surfactant concentration in LWW for W1, R1 and R2. Electrocoagulation proved to be the far more efficient method in which the levels of the surfactant, COD and TDS decreased over a much shorter period of time and with an application to a wider range of samples. Modification of the electrocoagulation treatment process with the addition of Biospinners significantly improved the current method by increasing aeration, surface area and removal of the overlying film formed on the electrodes.

Kinetic studies showed the adsorption of SDS to the aluminium hydroxy species occurred at a significantly lower rate for W1, when compared to R1 and R2. This highlighted the need for the isolated treatment of LWW discarded from W1, R1 and R2, as a reduced period of treatment would decrease the total output cost of the treatment method.

**REFERENCES**


Schouten, N., van der Ham, L. G., Eeuveink, G. J. & de Haan, A. B. 2007 Selection and evaluation of adsorbents for the
removal of anionic surfactants from laundry rinsing water. 
Water Research 41 (18), 4233–4241.

First received 21 April 2016; accepted in revised form 21 September 2016. Available online 20 October 2016