Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.21024

85 (2017) 46–54
August

Grey water treatment using a solar powered electro-coagulator and vacuum membrane distillation system

Mohammad Ramezanianpour[a,b], Muttucumaru Sivakumar[a,*], Aleksandar Gocev Stojanovski[a]

[a]*Sustainable Water and Energy Research Group, GeoQuest Research Centre, School of Civil, Mining and Environmental Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong NSW 2522, Australia, Tel. +(64) 3 940 8023; email: matt.pour@ara.ac.nz (M. Ramezanianpour), Tel. +(61) 2 4221 3055; emails: siva@uow.edu.au (M. Sivakumar), ags616@uowmail.edu.au (A.G. Stojanovski)*

[b]*Department of Civil and Architectural Studies, Ara Institute of Canterbury (Poly Technique), City Campus, Christchurch 8140, New Zealand*

Received 10 December 2016; Accepted 5 June 2017

ABSTRACT

Grey water reuse has been identified as a sustainable solution to reduce the pressure on freshwater storages. Membrane distillation techniques provide high quality permeate from this insanitary source. However, grey water contains surfactants present in the form of linear alkylbenzene sulphonate (LAS) that reduces the contact angle between the feed solution and the membrane surface leads to the wetting phenomenon. Electro-coagulation (EC) with aluminium electrodes has been demonstrated as an effective technology that removes LAS significantly. The aim of this paper is to investigate the effect of the current density and circulation rate of EC unit on the permeate water quality. For this purpose, synthetic grey water was treated at different operating conditions. It has been shown that, only after 12 min of EC, the turbidity, total suspended solids, chemical oxygen demand, total organic carbon, total nitrogen, total phosphorous, electrical conductivity and faecal coliforms were reduced by an average 94.4%, 89.9%, 83.8%, 71.0%, 73.1%, 96.1%, 30.2% and 1.32log, respectively. The EC permeate was sent to the solar powered vacuum membrane distillation (VMD) to produce pure water. Photovoltaic panels and a thermal collector supplied electricity and heat, respectively, for the combination of EC and VMD in order to use renewable energy.

Keywords: Grey water treatment; Vacuum membrane distillation; Electro-coagulation; Solar energy; Membrane wetting

1. Introduction

Large-quantity production and high-potential reuse of grey water identifies treated grey water as a potential source of supplementary freshwater supply. A considerable amount of researches has been devoted towards developing alternative techniques to treat grey water. Previous studies reveal that physical processes alone are not sufficient to meet the water quality guidelines especially for the removal of organics, nutrients and surfactants [1,2]. In recent years, various combinations of biological or chemical processes with membrane filtration have been developed to achieve high quality effluent from grey water sources. On the other hand, sustainability considerations have led to the study of green technologies to produce high-quality freshwater that can be used for multiple purposes. The vacuum membrane distillation (VMD) is selected for its highest flux rate comparing with the other distillation methods. VMD produces distilled quality water due to the vaporization and condensation process. Vapour forms at lower temperatures due to the application of vacuum pressure across a hydrophobic membrane. The commercialisation requires research on new membrane development to overcome the low permeate flux and wetting problems. However, one of the major attractive features of VMD is

* Corresponding author.

its coupling to low-grade sources of energy [3]. In a recent study, evacuated tube collectors used for a cross-flow rectangular hollow fibre VMD module with membrane area of 0.25 m^2, and the flux rate of 4 L/m^2 h is achieved by 654 W/m^2 solar radiation [4]. This lab scale module was able to produce 8 L/d distilled water from 35 g/L saline water. A pilot plant VMD system working with flat plate collector and photovoltaic (PV) panels was studied for seawater desalination [5]. The system produces 210 L/d at 5.25 L m^2 h flux rate using 5 m^2 hollow fibre polyvinylidene difluoride (PVDF) module. Both electrical and thermal energies can be supplied by means of solar panels. This incorporation improves economic and energy efficiency of the VMD treatment system. The vacuum pressure also has to be controlled in order to maintain the pressure difference less than the liquid entry pressure (LEP) of the membrane. Grey water contains organic matter that can reduce the LEP of the membrane. LEP depends on the contact angle between the membrane surface and the feed solution, liquid surface tension and membrane pore size. The major cause of membrane wetting is related to the contact angle. The contact angle must remain over 90° to ensure that the feed solution does not penetrate the membrane pores.

VMD was successfully applied to treat a variety of brackish waters resulting in high quality of permeate whose water quality values were significantly below the Australian Drinking Water Guidelines and WHO guidelines [6]. Other applications of VMD include the extraction of volatile organic carbons from dilute aqueous, dilution of the alcohol water solutions, concentration of fruit juices and treatment of textile wastewater coloured with dyes [7]. The application of VMD for textile wastewater was successful in terms of dye removal [8,9]. However, treatment of other types of wastewater by means of VMD has not been studied. A tubular ultrafiltration (UF) module equipped with PVDF membranes and a polypropylene (PP) capillary membrane distillation (MD) module were incorporated for oily wastewater treatment [10]. UF process reduced the oil concentration to less than 5 ppm, and further purification by MD results in a complete removal of oil as well as 99.5% reduction of the total organic carbon (TOC) concentration. The permeate flux rate decreased from 1,300 to 875 kg/m^2 d after 50 h operation. Total dissolved solids (TDSs) concentration was removed by 2.4% and 99.96% by UF and UF/DCMD, respectively. UF performed well as a pre-treatment unit for oil removal. In this way, direct contact membrane distillation (DCMD) was protected from wetting, so high TDS removal was achieved. A commercial flat sheet polytetrafluoroethylene was used in a DCMD process to treat olive mill wastewater [11]. The effect of two pre-treatment processes, coagulation/flocculation and microfiltration (MF) were investigated on the performance of DCMD. Although MF was found to be the optimum pre-treatment unit, the permeate flux rate decreased due to the feed phenol concentration. Concentration of TS, oil and TOC were reduced more efficiently by MF; however, better removal of chemical oxygen demand (COD) concentration achieved by coagulation/flocculation. Coagulation treatment was performed with 5 g/L of $FeCl_3$ using flash mixing for 2 min, and the flocculation process was carried out by 30 min of moderate mixing. Thus, 35% water flux reduction rate observed after 76 h of DCMD experiment. Wastewater containing NaCl and protein as well as the effluents produced during the regeneration of ion exchangers was used as feed for the DCMD process [12]. The necessity of appropriate pre-treatment for removal of foulants from the feed was reported in order to treat such wastewater by the DCMD.

Precipitation of wastewater components on the membrane surface during the MD process operation and the reduction of contact angle and surface tension of the feed solution are the main obstacles in this area. The main impediments of MD for wastewater treatment are the wetting and fouling phenomena. In this way, grey water treatment by means of MD techniques requires suitable pre-treatment units. It has been shown that the chemical processes are able to remove the suspended solids, organic materials and surfactants in low strength grey water. On the other hand, anaerobic processes are not sufficient for removal of organic substances and surfactants. The aerobic biological processes are suitable for medium and high strength grey water treatment [13]. Since the removal of surfactant is the main aim of this research, either a chemical process or an aerobic biological process is the most feasible solution for pre-treatment of grey water.

A large portion of grey water contains laundry discharge that is largely contaminated with residual surfactants. The critical micelle concentration occurs at which the concentration of surfactant increased to the level that cause the aggregation of the surfactant molecules into a cluster with the hydrophobic groups located at the centre of the cluster and the hydrophilic head groups [14]. UF was suggested as an effective process for surfactant removal [15]. However, high concentration of surfactant results in the reduction of the permeate flux and critical micelle concentrations. Among the selected UF membranes, polysulfone and polyethersulfone type of membranes were successful for surfactant removal; however, their efficiency was decreased by 4% and 7%, respectively, at higher concentration. The application of the ion-exchange process was also performed and indicated that the magnetic resin removes anionic surfactant successfully [15]. UF followed by the ion-exchange unit was also suggested for surfactant removal. A bipolar electro-coagulation (EC)/electro-flotation process was carried out to treat laundry wastewater [16]. The bipolar design achieved acceptable removal of turbidity, COD, total phosphorous (TP) and surfactants in a wide pH range (5–9) at a short hydraulic retention time (5–10 min.). Eight pieces of Ti plates and 21 pieces of Al plates were incorporated in the EC unit. The reactor volume and the effective area of each electrode were 2.8 L and 50 cm^2, respectively. This application removed 80% COD concentration, 95% linear alkylbenzene sulphonate (LAS) concentration and 99.9% turbidity. From a sustainability point of view, EC is more preferred than a chemical type of coagulation unit due to its flexible operation, avoiding the use of chemicals and EC lends itself to the application of solar power.

2. Electro-coagulation, a suitable pre-treatment for MD

Surfactant is rejected by means of either the reaction between charged ionic species with ion of the opposite charge or with a flocculation by means of metallic hydroxides. Iron or aluminium is usually selected as electrodes, so the following chemical reactions occur at anode and cathode:

Anode: $M_{(s)} \rightarrow M^{n+}_{(aq)} + ne^-$

Cathode: $2nH_2O + ne^- \rightarrow nH_2 + 2nOH^-$

In the case of Al electrodes, the reactions in EC generate different types of ionic species at various pH levels including Al^{3+}, $Al(OH)^{2+}$, $Al(OH)_2^+$ and $Al(OH)_4^-$. Aluminium ions are transformed into aluminium hydroxides at appropriate pH range near 7 [17]. Coagulation is performed by aluminium hydroxides such as $Al(OH)_4^-$ and $Al(OH)_3$ due to adsorption of the particles to neutralise the colloidal charges. On the other hand, hydrogen bubbles produced at the cathode may adhere to the flocculated species and induce flotation. Moreover, dense flocculated species can settle in the solution.

The operating parameters that affect EC include electrolysis time, current density, rate of agitation, number and distance between electrodes, retention time, type of power supply, type and shape of electrode and pH level. The concentration of aluminium released into the solution is a significant factor to build up the optimum ratio of Al:TP and Al:total nitrogen (TN) [18]. The released concentration is calculated by Faradays law as shown in Eq. (1) [19].

$$C_{\mathrm{Al}} = \frac{ItM_{\mathrm{Al}}}{ZFV} \tag{1}$$

where C_{Al} is the concentration of aluminium (g/L), I is the current through electro-coagulator (A), t is time (s), M_{Al} is the molar mass of aluminium (26.98 g/mol), Z is the number of electrons involved in the reaction (Z_{Al} = 3), F is Faradays constant (96,485 A s/mol) and V is the volume of electro-coagulator (L).

Current density is the most significant parameter of EC that influences the rate of coagulant dosage, rate of bubble production and size and growth of the flocculated species [19]. An increase in the current density dissolves aluminium ions rapidly, which results in the increase of metal hydroxide substances followed by the production of flocculated species. Surfactant removal efficiency is also a function of electrolysis time. An increase in electrolysis time generates a larger number of metal hydroxides. However, further operation after the optimum electrolysis time has no effect on the pollutant removal efficiency [20].

Surfactant removal was determined through the detergent compounds measurement by the solvent extraction-spectrophotometric unit. The jar test experiment was carried out using ethyl violet method for the coagulation/flocculation of industrial wastewater [21]. The effective dosage and pH control tests were performed in order to determine the optimum conditions for the removal of surfactants, COD and turbidity. Effective pH range between 7 and 9 was observed for treatment with $FeCl_3$. The process successfully removed surfactants and COD by 99% and 88%, respectively. A positive correlation between COD and surfactants removals was also illustrated. The cations Fe^{3+} attached to a micelle simultaneously prevent repulsion between micelles flocculating them, and effectively remove surfactant from the solution where they interconnect organic compounds and the flocculated species.

The EC process was used to remove nitrogen and phosphorus from synthetic yellow water [18]. The removal efficiency for phosphate was approximately 98% at pH 8 for the ratio 1:1 of Fe/nutrient. Small reduction of TOC showed that its concentration reached to 26% of the initial value. It has been concluded that the EC processes are competitive technologies with conventional N/P removal methods because of less or no chemicals usage, simple equipment requirements and easy operation. The major achievement of EC is its effective application for nutrient removal.

Effects of operating parameters for the EC process such as electrode type (Al or Fe), initial pH (2–10), current density (5–80 A/m^2) and operating time (0–50 min) were investigated to determine the optimum operating conditions of the EC performance for treatment of paint manufacturing wastewater [19]. In terms of electrode type, Al electrodes were more successful than the Fe type with removal efficiencies of 94% and 89% for COD and TOC, respectively. These results were achieved for the optimum operating conditions of pH 6.95, current density of 35 A/m^2 and operating time of 15 min.

The EC process was successful for treatment of various wastewaters. A high removal rate was achieved for surfactants through coagulation/flocculation. This has been performed using Al electrodes. In order to treat grey water with a certain pH by EC, appropriate current density and operating time needs to be selected.

3. Experimental set-up and tests

The grey water treatment system consists of an electro-coagulator as a pre-treatment unit followed by the VMD process. In order to determine the appropriate operating configuration, various operating times and densities were carried out for the independent EC unit. An on-site solar powered electro-coagulation and vacuum membrane distillation (SECVMD) system was designed and developed for this purpose. In this paper, the performance of this system was studied for a wide range of water quality parameters.

The average angle between the left and right end points is contact angle between a liquid droplet on a sheet of membrane. It was calculated via 200-F1 Goniometer (Ramè-Hart, USA) using a camera and computer software. The accuracy of the instrument is ±0.1°. A two-dimensional profile was imported to the software for the measurement of the angle formed between the membrane surface and droplet. For each test, three contact angles were measured and the average has been used as a reported data. The water quality parameters comply with the duplicate engineering experimental tests.

3.1. Electro-coagulation

Five parallel aluminium plates (200 × 200 × 3 mm) were employed in the electro-coagulator unit that have a total active area of 0.16 m^2. The aluminium plates were held in the first reactor that has a weir to allow the coagulated water to spill over into the flocculation chamber. The volume of the first chamber is 1.19 L. Online and alternative measurements of TDS and contact angle were performed in this research. Thus, various recirculation rates were carried out rather than the time of operation that results in the agitation rate increase. Thus, a circulating pump transfers grey water into the first chamber as shown in Fig. 1. To adjust the current through the electro-coagulator, an ISO-Tech (IPS-1820D) DC variable power supply is utilised.

In this paper, only the effect of the current density and circulation rate has been determined. Five different current densities (12.5, 25, 37.5, 50, 62.5 A/m^2) and five circulation

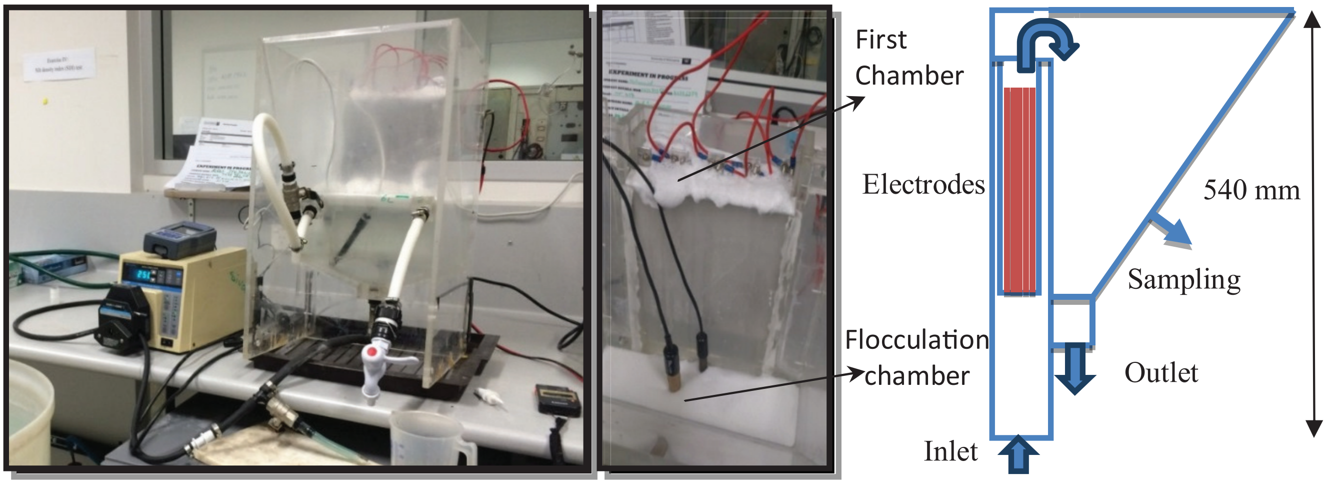

Fig. 1. Electro-coagulator using Al electrodes for grey water treatment.

rates (0.25, 0.50, 0.75, 1.00, 1.25 L/min) were selected based on the literature data. For all 25 tests, pH and electrical conductivity were monitored online. Contact angle with a PP membrane was determined for each water sample collected in duplicates at 2, 4, 6, 8, 10, 30 and 60 min intervals of operation time. Other water quality parameters such as turbidity, TP, TN, TOC, COD and faecal coliforms were also measured for the raw water sample and the treated effluent at the end of each test.

3.2. Solar powered electro-coagulation and vacuum membrane distillation

An SECVMD system is shown schematically in Fig. 2. This system consists of two separate flow loops and a distillate channel. Electricity for the pumps and the EC unit is supplied by the two PV panels. Grey water is directed through the first loop from the feed tank through the glass coil condenser in order to increase the temperature of the feed solution. The condenser contains three cavities of glassware, so the cold stream inside the middle tube condenses vapour completely. The second loop recirculates water through the EC unit followed by the solar collector and the membrane. During the experiment, the amount of water extracted through the membrane (permeate flux) is replaced by the feed water from the loop 1. The floating valve shown on Fig. 2 controls the level of water in EC tank. The EC unit not only treats grey water to achieve the required level of contact angle, but also heats the feed solution. When the feed solution passes through the thermal collector, additional heat is added before feed arrives at the membrane module. A three-way thermostatic valve bypasses the solar collector when feed water reaches the ultimate temperature (65°C). The valve sensor reads the temperature of the container and leads water directly to the membrane if necessary. A hollow fibre PP membrane module, MD02CP2N (MICRODYN, Germany) consists of 40 capillaries with 0.2 μm pore size, 70% porosity, 0.47 m length and 0.1 m^2 area was used in the VMD process. Vacuum pressure (7 kPa) is then applied on the permeate side of the membrane through the distillate channel to extract vapour by means of pressure difference. The N820 KNF laboratory vacuum pump (Javac, Australia) used to operate this pressure at flow rate of 20 L/min. Heated feed solution is vaporised at the hydrophobic membrane surface. An online data acquisition system has been developed to monitor pressure, temperature, selected water quality and meteorological parameters during the treatment process.

4. Results and discussion

The experimental results and discussion of the EC tests and SECVMD performance are presented separately. Online measurement of pH and electrical conductivity as well as the internal measurement of the contact angles are illustrated. The removal efficiency of the EC for selected water quality parameters are calculated and discussed. Finally, the optimum operating conditions in regard to the energy consumption is reported followed by the performance of the SECVMD system.

4.1. The EC influence on contact angle, pH and electrical conductivity

The average contact angle of the synthetic grey water was found to be 76° for the PP membrane and this value was unacceptable for the VMD technique. The EC was carried out for 60 min. The results for contact angle of samples taken alternatively illustrate the role of coagulation and flocculation in improvements of the contact angle. The synthetic grey water with the average electrical conductivity 432 μS/cm was injected into the EC unit. Electrical conductivity of the sample was monitored online and was plotted in Fig. 3 during the operation time. The effect of EC on pH was also monitored and graphed for each test.

Contact angle values are graphed at specific operating times in Fig. 3. The rate of increase is dependent on the circulation rate and current density. Higher current density and higher circulation rate achieved more increase in the contact angle. Fig. 3 depicts that for all tests, the contact angle increased sharply for the first 5–10 min of operation depending on the circulation rate. Afterwards, these increase rates are reduced from the average 24%–5%. The results show that a minimum operation time of 5–10 min is required to achieve a contact angle above 100°. Higher circulation rate and higher current density reduce this time; however, the

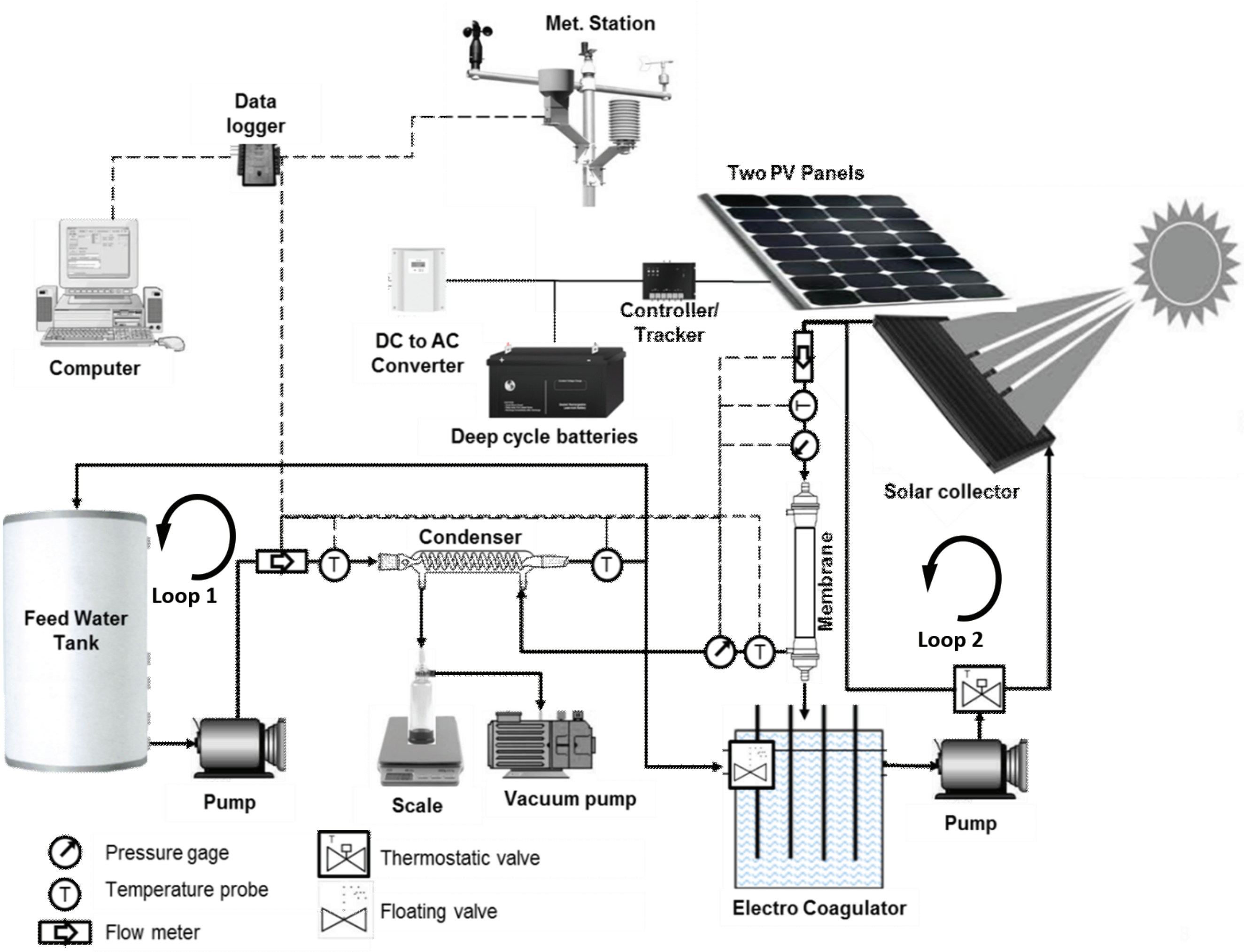

Fig. 2. Solar powered electro-coagulation and vacuum membrane distillation system.

membrane characteristics have to be kept constant. The circulation rate of 0.25 L/min required 60 min of treatment to reach 100° contact angle in the case of the highest current density application as shown in Fig. 3(a). The circulation rate of 0.5 L/min significantly increased the contact angle from an average 78°–100° in 50, 19, 8, 5 and 6 min of treatment for 12.5, 25, 37.5, 50 and 62.5 A/m^2, respectively as shown in Fig. 3(b). Similar improvement was observed for the circulation rate of 0.75 L/min where the contact angle increased from an average 78°–100° in 44, 14, 8, 5 and 5 min for 12.5, 25, 37.5, 50 and 62.5 A/m^2, respectively, as shown in Fig. 3(c). The problem of membrane fouling decreased the contact angle between PP and grey water samples taken from tests with circulation rates 1.00 L/min and 1.25 L/min. The grey water contact angle was 71° and 70° before the tests with 0.75 L/min and 1.25 L/min circulation rates, respectively. In order to compensate this effect, the increase rates of the contact angle were compared together for various current density applications as shown in Fig. 4. The comparison is performed for the results obtained by current density 25 A/m^2 at different circulation rates. Regardless of the result for the lowest current density the other applied current densities were successful in achieving the aim of pre-treatment.

Fig. 3 also shows the reduction of electrical conductivity with 1 h test for different current densities and circulation rates. Higher current density reduced electrical conductivity of the grey water solution more rapidly. High current density increased the concentration of Al and more Al flocs resulting in a greater removal of TDS. However, as time progresses, the electrical conductivity value of the effluent from the first chamber seems to level off. This is attributed to the fact that the chemical reactions reduced by the increase of pH value. On the other hand, the subsequent produced Al ions remained in the solution without any chemical reactions. The TDS removal rate decreased by increase of pH values since hydroxide ions were oxidised at the anode at the pH values greater than 8. The results depicted that the rate of increase for pH values are reduced during the operation. This is ascribed to the fact of temperature rise during operation. In addition, Figs. 3(a)–(e) illustrate that the circulation rate does not appear to affect the reduction of electrical conductivity to any significant extent. The electrical conductivity reduced to 310 and 330 μS/cm in all conditions except for the circulation rate 0.25 L/min. The only effect is on agitation of the solution since in the first few minutes the electrical conductivity did not reduce. The agitation is more important than the contact

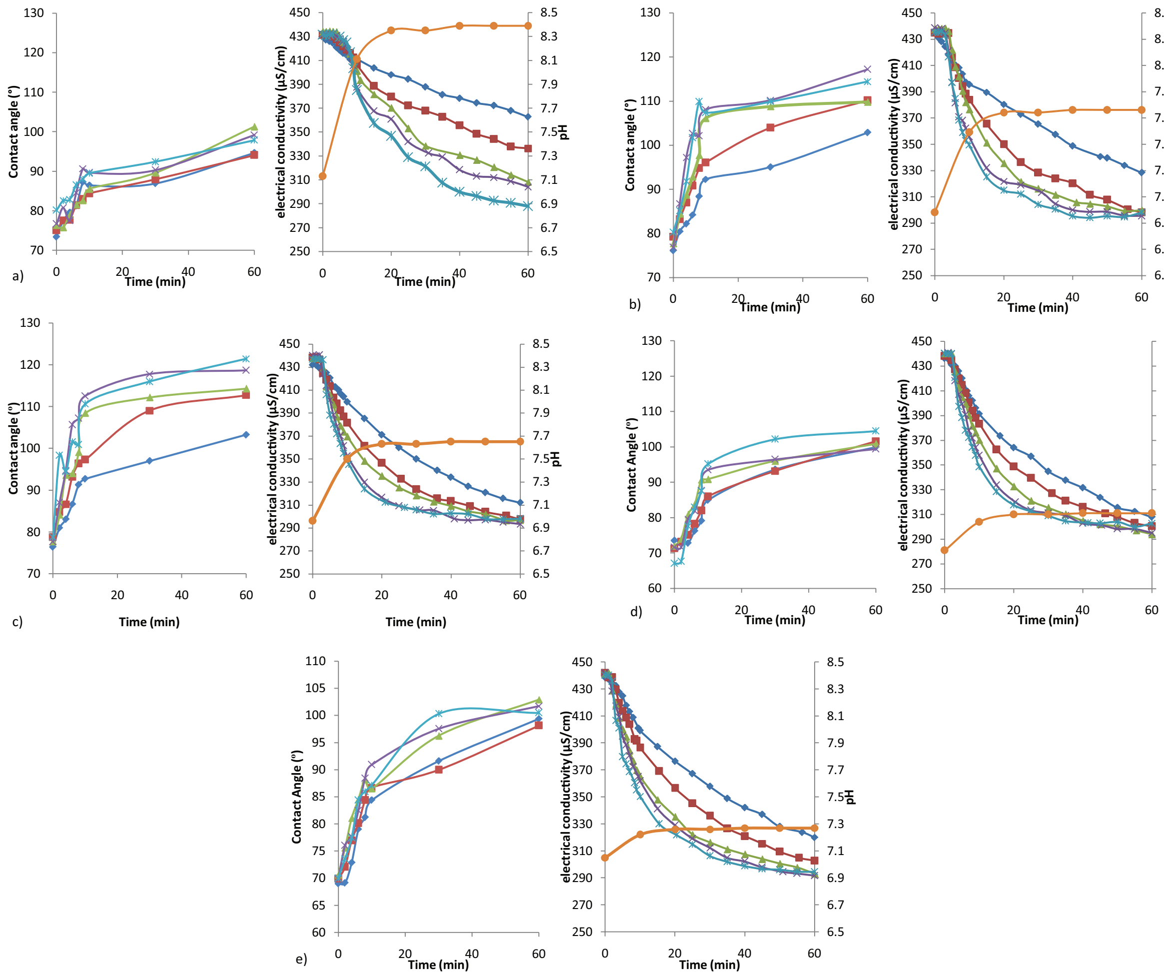

Fig. 3. Electrical conductivity, pH (●) and contact angle measurements with operation time for (a) 0.25 L/min, (b) 0.5 L/min, (c) 0.75 L/min, (d) 1.00 L/min and (e) 1.25 L/min circulation rate at various current densities 12.5 A/m² (♦), 25 A/m² (■), 37.5 A/m² (▲), 50 A/m² (×) and 62.5 A/m² (*).

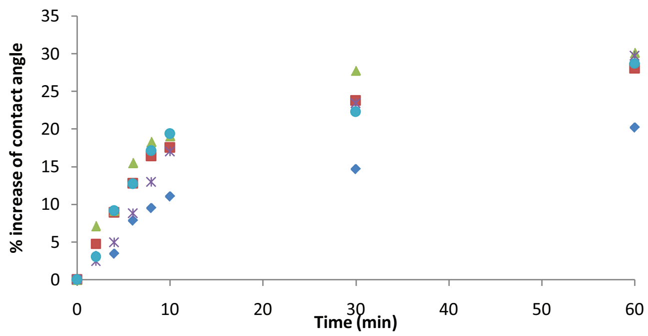

Fig. 4. Contact angle increase rate at current density 25 A/m² for circulation rate (♦) 0.25 L/min, (×) 0.5 L/min, (▲) 0.75 L/min, (■) 1.00 L/min and (●) 1.25 L/min.

time. For different circulation rates, the contact time is always the same for a given operating time.

4.2. The EC influence on quality of the permeate

Raw grey water temperature prior to treatment was in the range of 22°C–24°C, and after 60 min of operation, the temperature reached 25.6°C, 29.1°C, 31.5°C, 36.2°C and 42.0°C at current densities 12.5, 25, 37.5, 50 and 62.5 A/m², respectively. There is a direct relationship between energy consumption and the temperature of the solution. The relevant water quality parameters were measured for synthetic grey water. The procedure for making grey water was outlined by Commonwealth Scientific and Industrial Research Organisation [22]. Water quality parameters were measured before and after treatment by the EC unit. The results are shown in Table 1.

The EC process removed 94.4% of turbidity from the untreated water sample, which had an initial turbidity value of 25.5 NTU. Flocculation followed by either sedimentation or flotation will reduce the concentration of suspended solids. This significant reduction is the result of adsorption of aluminium hydroxides onto the dissolved and suspended matter. Results illustrate that increases in the circulation rate and current density beyond 0.25 L/min and 12.5 A/m², respectively, have a negligible effect on turbidity removal. Total suspended solids (TSS) also reduced from 180 mg/L to average 3.90 mg/L at all current densities except for 12.5 A/m².

TOC concentration was reduced by 71.0% from 54.5mg/L for raw grey water. Grey water COD concentration also decreased from 404.5 to 65.5 mg/L which illustrates the

Table 1
Quality of grey water before and after EC treatment

Sample type	Parameter								
	Circulation rate	Current density	Turbidity	COD	TSS	TOC	TN	TP	Faecal coliform
	L/min	A/m^2	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	cfu/100 mL
Grey water	–	–	60.8	664	180	54.5	2.67	39.4	700
EC treatment and the removal rate	0.25	12.5	3.52	128	12.5	20.97	1.2	6.55	310
			94.2	80.7	93.1	61.5	55.1	83.4	0.35
	0.25	25	2.45	97.5	3	19.36	1.15	7.58	90
			96.0	85.3	98.3	64.5	56.9	80.8	0.89
	0.25	37.5	1.76	87.5	1	16.12	1.22	3.43	90
			97.1	86.8	99.4	70.4	54.3	91.3	0.89
	0.25	50	1.42	81	2	15.46	0.96	6.2	5
			97.7	87.8	98.9	71.6	64.0	84.3	2.15
	0.25	62.5	5.25	72	2	13.95	1.01	3.78	5
			91.4	89.2	98.9	74.4	62.2	90.4	2.15
	0.50	12.5	1.12	90	10	19.43	0.896	0.45	423
			98.2	86.4	94.4	64.3	66.4	98.9	0.22
	0.50	25	1.05	54	3	17.84	0.65	2.39	110
			98.3	91.9	98.3	67.3	75.7	93.9	0.80
	0.50	37.5	0.58	49	6	18.43	0.8	3.18	70
			99.0	92.6	96.7	66.2	70.0	91.9	1.00
	0.50	50	0.73	52	6	17.73	0.508	1.42	7.5
			98.8	92.2	96.7	67.5	81.0	96.4	1.97
	0.50	62.5	3.37	47.5	4	13.74	0.374	0.4	2.5
			94.5	92.8	97.8	74.8	86.0	99.0	2.45
	0.75	12.5	0.79	74.5	9	20.43	0.895	3.52	393
			98.7	88.8	95.0	62.5	66.5	91.1	0.25
	0.75	25	0.31	46.5	4	16.12	0.617	1.59	55
			99.5	93.0	97.8	70.4	76.9	96.0	1.10
	0.75	37.5	0.34	46.5	6	14.2	0.331	2.5	40
			99.4	93.0	96.7	73.9	87.6	93.7	1.24
	0.75	50	1.11	33.5	14	13.6	0.254	9.71	10
			98.2	95.0	92.2	75.0	90.5	75.4	1.85
	0.75	62.5	9.4	37.5	3	8.35	0.356	2.61	8
			84.5	94.4	98.3	84.7	86.7	93.4	1.94
	1.00	12.5	1.05	80.5	0	22.2	0.955	3.5	208
			98.3	87.9	100.0	59.3	64.2	91.1	0.53
	1.00	25	0.54	59	2	22.9	0.82	4.9	60
			99.1	91.1	98.9	58.0	69.3	87.6	1.07
	1.00	37.5	0.56	51	2.5	18.9	0.82	4.7	58
			99.1	92.3	98.6	65.3	69.3	88.1	1.08
	1.00	50	0.64	44	2.5	16.7	0.63	3.6	5
			98.9	93.4	98.6	69.4	76.4	90.9	2.15
	1.00	62.5	0.75	63	1.5	9.3	0.69	0.2	3
			98.8	90.5	99.2	82.9	74.2	99.5	2.37
	1.25	12.5	1.07	87.5	16.5	19.2	0.8	3.18	305
			98.2	86.8	90.8	64.8	70.0	91.9	0.36
	1.25	25	0.783	73.5	2	15.1	0.66	2.15	135
			98.7	88.9	98.9	72.3	75.3	94.5	0.71
	1.25	37.5	0.662	63.5	2	13.1	0.58	0.568	40
			98.9	90.4	98.9	76.0	78.3	98.6	1.24
	1.25	50	0.433	59.5	3.5	13.4	0.45	4.43	3
			99.3	91.0	98.1	75.4	83.1	88.8	2.37
	1.25	62.5	1.183	59	8	7.8	0.33	0.965	3
			98.1	91.1	95.6	85.7	87.6	97.6	2.37

removal of organic matter from the solution. The most effective results are observed during the circulation rate of 0.75 L/min, whereas the least effective results are achieved by the 0.25 L/min circulation rate for all current densities. Agitation is the main reason of this achievement. The COD and TOC concentrations were reduced by the increase of current density as shown in Fig. 5. This is mainly attributed due to the increase in size of precipitates, increased rate of bubble generation and decreased bubble size when current density increases [19]. In a similar manner, effectiveness of TOC removal was more dependent on the current density with the best results achieved at 62.5 A/m^2. Higher temperatures also assist in destruction of the oxide film on the anode surface results in the improvement of the EC performance.

TN and TP concentrations decreased by an average 73.1% and 96.1%, respectively. The main reaction is between phosphate and nitrate with aluminium. The phosphorous removal rate was very significant. It has been found that in wastewater treatment, significant removal of phosphorous can be achieved if the ratio of metal Al to TP by weight is between 2.05 and 6.25 [23]. The Al:TP ratios were 1.32, 2.65, 3.97, 5.23 and 6.62 for the 12.5, 25, 37.5, 50 and 62.5 A/m^2 current densities, respectively.

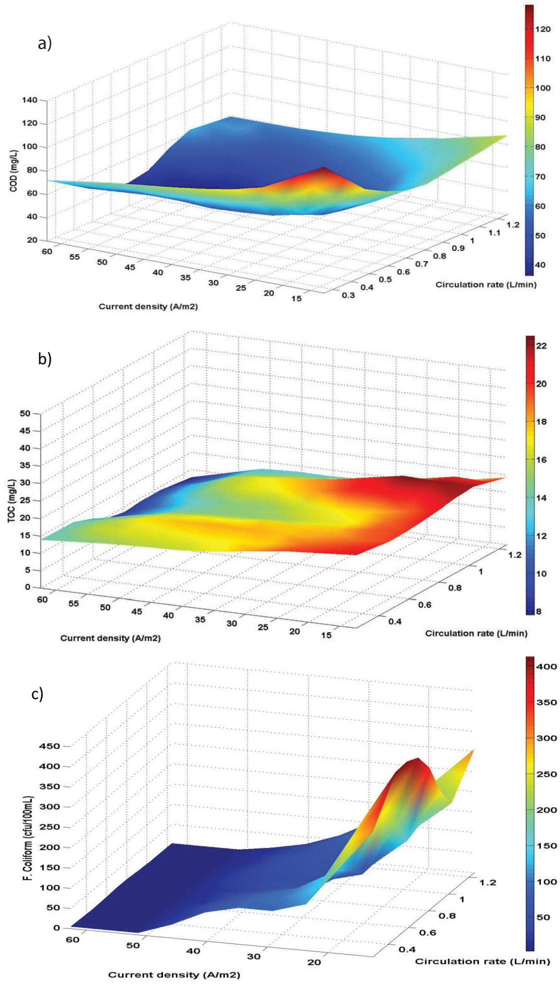

Fig. 5. Permeate water quality for a variety of circulation rates and current densities (a) COD (mg/L), (b) TOC (mg/L) and (c) faecal coliform (cfu/100 mL).

The EC process also showed a low 1.32log removal of faecal coliforms. It was found that as the current densities increased the contaminants quantity decreased as shown in Fig. 5. Faecal coliform counts significantly decreased to 328, 90, 60, 6 and 4 cfu/100 mL for current density 12.5, 25, 37.5, 50 and 62.5 A/m^2, respectively, due to higher temperature released to the solution at higher current density.

4.3. Optimum operating conditions

Total energy consumption of each test was determined by the energy consumption of the circulation pump and DC current source. The power required to maintain each current density varied from 7.36 to 145.8 W, and the peristaltic pump requires 17–50 W power for relative circulation rate. Total power required to carry out the EC experiment is the summation of the power required for the separate components. The energy consumption for each test was then determined using the total power and operating time required to reach a contact angle above 100°.

The optimum operating condition is determined based on two parameters: energy consumption and contact angle value of the permeate water. The calculation was performed for the results of two tests running at different current densities. This decision has been made since the most effective increase rate of the contact angle was observed for 25 and 37.5 A/m^2. The results have been plotted in Fig. 6 along with a trend line in order to achieve the lowest energy consumption value. The lowest energy consumption is 9.12 W h for operating EC at a circulation rate of 0.5 L/min and current density of 43.5 A/m^2 with an operating time of 5 min.

4.4. Solar powered combination of EC and VMD

Based on EC effective removal of several water quality parameters, EC was selected as a pre-treatment for VMD. Experimental results of the permeate water from EC permit the solution to pass through the hydrophobic membrane. The EC unit was located before the thermal panel as shown in Fig. 2. The two significant parameters, operating time and temperature variation, have to be considered in order to efficiently incorporate the EC unit. The EC unit was placed after the condenser to increase the temperature of the solution in the second loop. The EC unit was performed at the optimum condition. In order to apply this condition to the SECVMD system, the rate of the second circulation loop was adjusted to 0.5 L/min. The EC unit was also operated at the optimum

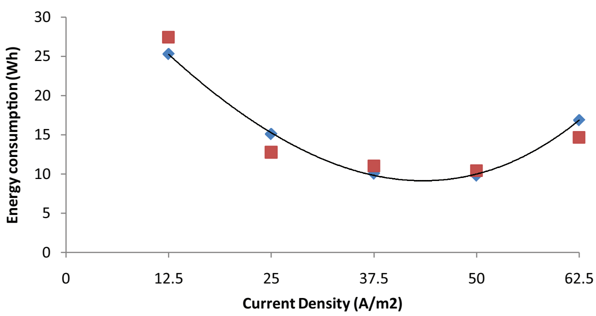

Fig. 6. Energy consumption of the EC unit for (♦) circulation rate 0.5 L/min and (■) circulation rate 0.75 L/min.

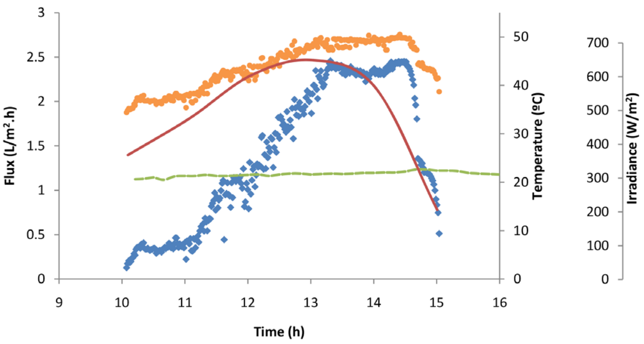

Fig. 7. The permeate flux (♦) for SECVMD, solar irradiance (—) and ambient temperature (--) and feed water temperature (●) during a day.

current density of 43.5 A/m². Grey water was treated through the SECVMD system for 5 h as shown in Fig. 7. The treatment system was located in a relatively shaded area where the availability of direct solar input was limited to only 5 h during the day. The maximum flux rates about 2.4 L/m² h were achieved between 13:15 and 14:15 h due to the highest solar radiation at 13:00 h which increased the temperature of the feed solution. The feed solution temperature increased marginally from 38°C to 49°C between 11:00 and 13:00 h. This is attributed to the shape of solar irradiance. Since, the vacuum pressure was constant, the temperature was the significant parameter in variation of the permeate flux rate. The ambient temperature was relatively constant at 21°C, so there is less effect by this parameter in the variation of the feed water temperature.

5. Conclusion

The stand-alone SECVMD system was successful in treating grey water using solar energy. The effect of solar radiation and ambient temperature on the feed solution temperature and correspondingly the permeate flux rate was observed, whereas other parameters such as pressure and feed flow rate remained constant. Extraction of vapour on the permeate side of the membrane illustrated the successful removal of LAS from grey water. This was achieved by only 5 min of electro-coagulation at 43.5 A/m² and 0.5 L/min circulation rate. It was concluded that the EC unit not only performed well as a pre-treatment process to treat the permeate water by the PP hydrophobic membrane but also it has improved the water quality of the grey water. Over 90% removal of TSS concentration, TP concentration and turbidity value were achieved by means of EC. These advantages can result in a higher permeate flux rate and higher membrane life time due to fouling. The concentration of TSS, TDS, COD, TOC, TN and TP were reduced by 92.2%, 32.3%, 85.8%, 71.0%, 73.8% and 95.7%, respectively after EC. The contact angle was over 100° for the permeate solution from the EC unit. This permeate was heated by the thermal panel before it goes into the membrane. Distillate flux reached to 2.4 L/m² h due to the increase of solar radiation before 13:00 h. The permeate flux variation was the result of changes in feed–water temperature since the vacuum pressure and the flow rate remained constant.

References

[1] F. Li, K. Wichmann, R. Otterpohl, Review of the technological approaches for grey water treatment and reuses, Sci. Total Environ., 407 (2009) 3439–3449.

[2] E. Eriksson, K. Auffarth, M. Henze, A. Ledin, Characteristics of grey wastewater, Urban Water, 4 (2002) 85–104.

[3] M.R. Qtaishat, F. Banat, Desalination by solar powered membrane distillation systems, Desalination, 308 (2013) 186–197.

[4] Y. Wang, Z. Xu, N. Lior, H. Zeng, An experimental study of solar thermal vacuum membrane distillation desalination, Desal. Wat. Treat., 53 (2015) 887–897.

[5] S. Gabsi, N. Frikha, B. Chaouachi, Performance of a solar vacuum membrane distillation pilot plant, for seawater desalination in Mahares, Tunisia, Int. J. Water Resour. Arid Environ., 2 (2013) 213–217.

[6] M. Sivakumar, M. Ramezanianpour, G. O'Halloran, Brackish Water Treatment for Reuse Using Vacuum Membrane Distillation Process, 9th IWA International Conference on Water Reuse, IWA, Windhoek, Namibia, 2013, pp. 1–8.

[7] M. Khayet, T. Matsuura,Vacuum Membrane Distillation, Chapter 12, Membrane Distillation, Elsevier, Amsterdam, 2011, pp. 323–359.

[8] F. Banat, S. Al-Asheh, M. Qtaishat, Treatment of waters colored with methylene blue dye by vacuum membrane distillation, Desalination, 174 (2005) 87–96.

[9] A. Criscuoli, J. Zhong, A. Figoli, M.C. Carnevale, R. Huang, E. Drioli, Treatment of dye solutions by vacuum membrane distillation, Water Res., 42 (2008) 5031–5037.

[10] M. Gryta, K. Karakulski, A.W. Morawski, Purification of oily wastewater by hybrid UF/MD, Water Res., 35 (2001) 3665–3669.

[11] A. El-Abbassi, A. Hafidi, M. Khayet, M.C. García-Payo, Integrated direct contact membrane distillation for olive mill wastewater treatment, Desalination, 323 (2013) 31–38.

[12] M. Gryta, M. Tomaszewska, K. Karakulski, Wastewater treatment by membrane distillation, Desalination, 198 (2006) 67–73.

[13] F. Li, K. Wichmann, R. Otterpohl, Evaluation of appropriate technologies for grey water treatments and reuses, Water Sci. Technol., 59 (2009) 249–260.

[14] S.K. Tripathi, R. Tyagi, B.K. Nandi, Removal of residual surfactants from laundry wastewater: a review, J. Dispersion Sci. Technol., 34 (2013) 1526–1534.

[15] I. Kowalska, Surfactant removal from water solutions by means of ultrafiltration and ion-exchange, Desalination, 221 (2008) 351–357.

[16] J. Ge, J. Qu, P. Lei, H. Liu, New bipolar electrocoagulation-electroflotation process for the treatment of laundry wastewater, Sep. Purif. Technol., 36 (2004) 33–39.

[17] K. Bensadok, S. Benammar, F. Lapicque, G. Nezzal, Electrocoagulation of cutting oil emulsions using aluminium plate electrodes, J. Hazard. Mater., 152 (2008) 423–430.

[18] H. Inan, E. Alaydın, Phosphate and nitrogen removal by iron produced in electrocoagulation reactor, Desal. Wat. Treat., 52 (2013) 1396–1403.

[19] A. Akyol, Treatment of paint manufacturing wastewater by electrocoagulation, Desalination, 285 (2012) 91–99.

[20] V. Khandegar, A.K. Saroha, Electrochemical treatment of distillery spent wash using aluminum and iron electrodes, Chinese J. Chem. Eng., 20 (2012) 439–443.

[21] M.A. Aboulhassan, S. Souabi, A. Yaacoubi, M. Baudu, Removal of surfactant from industrial wastewaters by coagulation flocculation process, Int. J. Environ. Sci. Technol., 3 (2006) 327–332.

[22] C. Diaper, M. Toifl, M. Storey, Greywater Technology Testing Protocol, 2008, CSIRO.

[23] J.-Q. Jiang, N. Graham, C. André, G.H. Kelsall, N. Brandon, Laboratory study of electro-coagulation-flotation for water treatment, Water Res., 36 (2002) 4064–4078.