# Development of a novel off-grid drinking water production system integrating electrochemically activated solutions and ultrafiltration membranes.

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## Abstract

Approximately 800 million people live without clean drinking water. Diarrhoea is responsible for between 1.7 and 2 million deaths each year (primarily children) which are the result of poor drinking water quality and sanitation. The main aim of this study was to demonstrate the production of drinking water from a raw water source using an off-grid drinking water production system. The off-grid drinking water production system (DWPS) developed at UWE Bristol, combines an ultra-filtration (UF) system with in situ generation of electrochemically activated solutions (ECAS). ECAS has two functional roles within the system; to manage biofilms within the UF system and as a disinfectant. Integrated in-situ probes (pH, oxidation reduction potential, chlorine, conductivity and dissolved oxygen) coupled with a water quality sensing network (pH, water temperature, conductivity and dissolved oxygen) enabled real time monitoring of; the operational efficiency of the DWPS, and the physicochemical parameters of both the raw water source and the produced drinking water. Spot samples of both raw and treated water were sent for independent chemical and microbial analysis at an accredited laboratory which demonstrated that the DWPS produced

biologically safe potable drinking water according to the Drinking Water Inspectorate (DWI) standards. Samples from the raw water source were shown to be consistently unsuitable for human consumption, failing several of the DWI standards for potable water supply, including coliform bacteria. This study demonstrated that the novel off-grid DWPS was capable of producing DWI standard drinking water from a heavily biologically contaminated water source.


## Keywords

Off-grid; drinking water production; electrochemically activated solutions; ultrafiltration.


## 1.0 Introduction

An estimated 800 million people worldwide do not have access to improved drinking water sources [1–3], with 1.2 billion people unable to access reliable electricity sources [4,5]. Therefore, there is a need for low energy technological solutions for the provisioning of safe drinking water. By the end of the 21$^{st}$ century the global population is expected to increase to 9 - 10 billion [6], this is likely to generate increased stress on water and power (gas and electricity) resources worldwide. Sufficient safe drinking water provisioning for an increasing population will require the development of sustainable, reliable and robust water treatment systems. The consumption of contaminated water, or poor water quality, is the cause of between 1.7 and 2 million deaths each year from diarrhoeal diseases [7–10]. The majority of these deaths are in developing or transitional countries which have inadequate sanitation conditions [11], and do not have established water distribution systems. Developing countries have economies with little industrial development, whilst aiming to improve quality of life through increasing food and water security [12]. Transitional countries often have emerging economies with a prominent secondary manufacturing industry; however, there is still considerable rural and peri-urban poverty [12]. Developed countries have established centralised water, gas and electricity (power) networks, which supply the majority of a country's population with sufficient water, gas and electricity [4]. Developing and transitional

51 countries do not have the same established water and power networks, resulting in many
52 remote, rural or temporary communities unable to access reliable and safe power and
53 drinking water [4]. In developing or transitional countries, communities which are unable to
54 access improved water sources often live in remote or transitory locations, therefore
55 'centralised' drinking water treatment facilities and distribution systems are not sustainable
56 options from a financial or resource efficient perspective.

57 Research into decentralised, or off-grid, drinking water treatment systems for developing
58 countries has gained momentum due to unfeasible practicalities with centralised provision
59 [10,13–15], and are an important element in the process of reaching the Millennium
60 Development Goals. Some decentralised systems focus on rainwater harvesting [10,16,17],
61 solar based disinfection [18,19], or the physical removal of contaminants within treated water
62 through sand bed filters [20,21] or ultrafiltration (UF) [15,22]. Since the main drinking water
63 risks in developing countries are still associated with microbial contamination, many
64 decentralised systems continue to use established disinfection techniques such as UV [18],
65 chlorination [23,24], or ozonation [14]. Even when disinfection agents (e.g. chlorine) are
66 used, the presence of suspended material and colloids in the water can reduce their efficacy,
67 ultimately enabling bacterial growth after treatment [10]. In addition, these disinfection
68 techniques require the regular purchase, transportation and storage of hazardous chemicals
69 and for developing or transitioning countries, this can prove expensive and logistically
70 challenging. A key advantage of off-grid systems is the modular capability, whereby, the
71 production of drinking water output can be increased to cope with increasing
72 populations/demand.

73 Electrochemically activated solutions (ECAS), are known by several terms, the most
74 common being electrochemically activated water (ECAW), electrolyzed water (EW),
75 electrolyzed oxidising water (EOW) and mixed oxidant (MIOX) solutions. These solutions are
76 generated by passing a weak salt solution (e.g. NaCl), through an electrochemical cell,
77 whereupon a direct current is applied. Electrochemically activated solution generated at the

anode, referred to in this paper as ECAS, is acidic in nature and possesses antimicrobial chemical species including hypochlorous acid (HClO) and other transient oxidative functional groups [25–27]. ECAS have a short environmental legacy, reverting back to a saline solution during chemical relaxation [25], and are often referred to as ‘green biocides’ [28,29]. These solutions have been shown to have a beneficial application within; the fresh produce industry [27,30–34], healthcare settings [25,26,35] and drinking water treatment [24,36,37], due to extremely fast acting kill kinetics e.g. < 10 seconds [38,39].

The main aim of this study was to demonstrate the production of drinking water from a raw water source (artificial water body) to Drinking Water Inspectorate (DWI) standards, using a decentralised, off-grid, *drinking water production system* (DWPS). The European Council set guidelines for water quality which is safe for human consumption [40], which is interpreted by each European Union member state. In the United Kingdom the Drinking Water Inspectorate (DWI) interprets and regulates drinking water quality.

## 2.0 Materials and methods

### 2.1 Off-grid drinking water production system

A technical schematic of the off-grid drinking water production system (DWPS) is shown in Figure 1. Raw water, from an artificial water body (an urban drainage holding pond, UWE Bristol, UK [N 51° 29' 56", W 2° 32' 39"]), is pumped to a settle tank within the drinking water production system through an intake submersible filter pump (115 µm) and a reverse flushing filter (100 µm). A peristaltic pump draws water from the settle tank into the UF membrane columns ([0.02 µm] LineGuard UF-100, Pentair). ECAS is generated as per details in Section 2.2, and subsequently stored in the ECAS reservoir tank (100L). ECAS is dosed directly into the DWPS pipework, immediately before (A) and after (B) the UF membrane columns via automated peristaltic dosing pumps. Treated water is then stored in the 400 L treated water tank. To monitor the health of the UF membranes, pressure gauges are installed before and after the UF membrane columns.

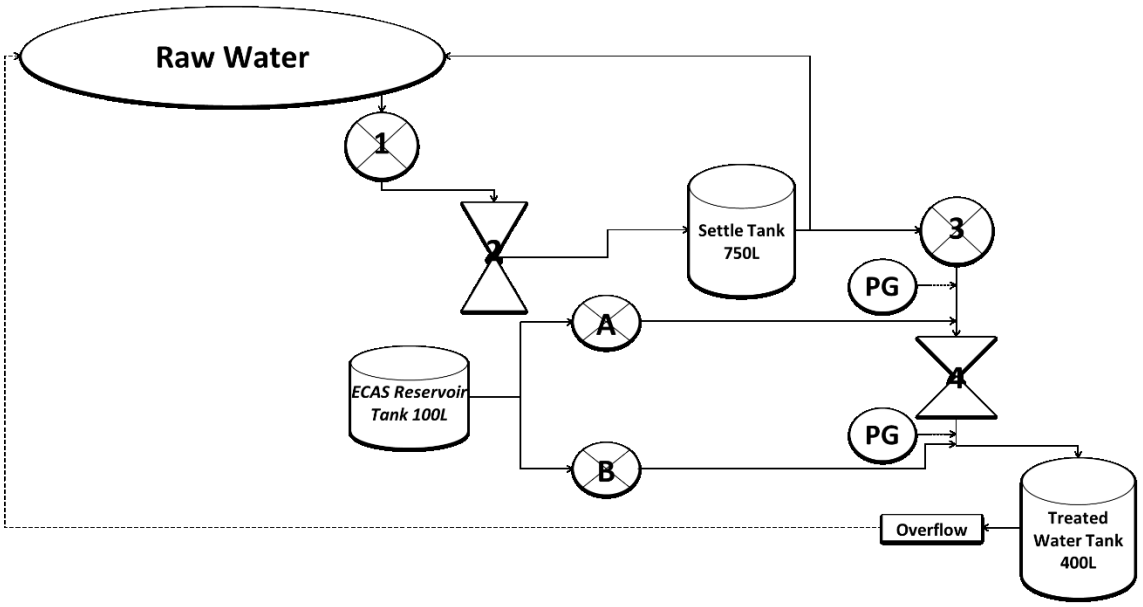


**Figure 1**: Technical schematic of the off-grid drinking water production system. Direction of arrows refer to water flow direction. (1) Submersible filter pump (115 µm); (2) Reverse flushing filter (100 µm); (3) Peristaltic pump; (4) UF membrane columns (0.02 µm); ECAS reservoir tank 100L for ECAS generated outside of the DWPS; (A) & (B) ECAS peristaltic dosing pumps for delivering ECAS into the bulk treated water stream; (PG) Pressure gauges.

## 2.2 Electrochemically activated solution (ECAS) generation

ECAS was generated using a 60 L ESOL™ generator (Bridge Biotechnology, Fife, Scotland) through the electrolysis of a 1% (w/v) NaCl solution under a direct current (Figure 2). Solutions were generated (anodic solution) to an oxidation reduction potential (ORP) of 1130 mV, and subsequently held and stored within a 100 L reservoir tank until required. Peristaltic dosing pumps enabled precise dosing of ECAS directly into the DWPS pipework pre- and post- ultrafiltration (UF) column membranes.

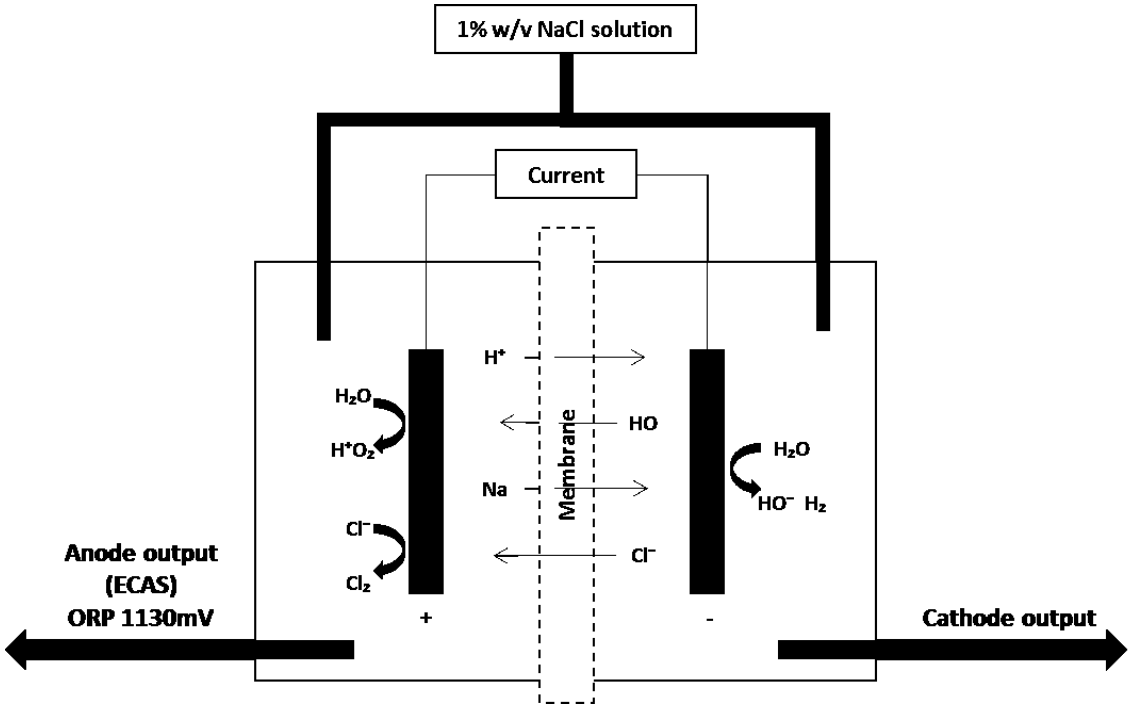


**Figure 2:** Schematic of ECAS generation. A direct current is applied across two electrodes, an anode (+) and cathode (-) separated by a permeable ion exchange membrane, allowing constant perfusion of an electrolyte solution (1% w/v NaCl). The anolyte solution generated (ECAS) has a high oxidising potential, whilst the catholyte solution has a high reducing potential.

## 2.3 DWPS Field trials

Two field trials were performed. Field trial 1 consisted of dosing 0.5% (v/v) ECAS pre- and post- UF membranes. Resulting in a total of 1% (v/v) ECAS dosed directly into the DWPS pipework. Field trial 2, the control period, had no ECAS dosed pre- and post- UF

membranes, resulting in 0% (v/v) ECAS dosage into the DWPS pipework. Both field trials were conducted over 16 operational days. The total time between the end of one field trial and the start of next was 18 days. This downtime between trials allowed for UF membranes to be thoroughly cleaned using alkaline and acid washes using sodium hypochlorite, hydrochloric acid and sodium hypochlorite.

## 2.4 Water sampling and analysis

Six water samples (both raw water and treated water) were collected and sent for analysis during each field trial. Water samples were collected from the raw water source, and the treated water outlet within the DWPS, before being immediately transported to an independent ISO 17025 accredited laboratory for standard suite analysis. See Table 1 for a full list of parameters tested within the standard suite analysis.

To determine the significant difference between raw water and treated water samples throughout field trial 1 and field trial 2, a *t-test* was performed for each parameter listed in Table 1. A $P$ value of $<0.05$ was considered significant. Graph construction and statistical analysis was performed using GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego, CA), and Microsoft Excel 2013 for Windows (Microsoft Corporation, Redmond, WA).

Real-time monitoring of treated water quality (conductivity, oxidation reduction potential [ORP], pH, dissolved oxygen and chlorine), as well as pre- and post- membrane pressures, was performed using a WebMaster data logging system (Walchem, Holliston, MA, USA).

UF membrane health was determined by calculating the pressure differential across the UF membrane column module (Equation 1 and Equation 2), and converting this to membrane permeability, the industry standard for membrane health (Equation 3).

**Equation 1**: Filtration flux.

$$\text{Filtration flux } (\mathrm{L^{-1}m^{-1}h^{-1}}) = \frac{\text{Feedflow } [\mathrm{m^3h^{-1}}] \times 1000}{\mathrm{A} \times \mathrm{B}\ [\mathrm{m^2}]}$$

155 Whereby; UF feedflow is measured on the module, A = Number of membrane housings, and
156 B = Membrane area per membrane housing [$m^2$]

157

158 **Equation 2**: Transmembrane pressure filtration.

$$\text{Transmembrane Pressure (TMP) filtration [bar]} = \mathrm{PT_{feed}} - \mathrm{PT_{permeate}}$$

159 **Equation 3**: Permeability UF module.

$$\text{Permeability UF module } [\mathrm{L^{-1}m^{-1}h^{-1}}] = \frac{\text{Filtration flux } (\mathrm{L^{-1}m^{-1}h^{-1}})}{\text{Transmembrane Pressure (TMP) filtration [bar]}}$$

160

## 3.0 Results and Discussion

### 3.1 Field trial 1: 1% (v/v) total ECAS Dosing

Field trial 1, dosing 0.5% ECAS pre- and post- UF membranes, ran for 16 operational days. Table 1 shows the biological, basic water parameters, chemical and metal analysis results for the 6 water samples taken during DWPS operation. Over the entire sampling period all raw water samples analysed prior to treatment failed to meet DWI standards, and were deemed unsafe for human consumption (Table 1). All tested parameters for the DWPS treated water samples were within the specified DWI limits. For example, Table 1 and Figure 3 demonstrate the achieved biological quality of drinking water produced using 1% (v/v) total ECAS as a disinfectant.

Water that was treated by the DWPS was shown to contain zero (0 cfu 100 $mL^{-1}$) levels of coliforms, *Escherichia coli*, Enterococci and *Clostridium perfringens*. The complete log reduction of bacteria within heterotrophic plates counts at 37°C for 48 hours was achieved for every treated water sample, except operational day 5 ([2 cfu $mL^{-1}$] Figure 3). However, all treated water samples contained significantly lower heterotrophic bacteria at 37°C than in raw water samples (Table 1), and there is no DWI maximum limit for heterotrophic plate counts (37°C) [41]. Therefore treated water within field trial 1 was deemed fit for human consumption.

The multi-step filtration within the DWPS (Figure 1) resulted in a significant reduction in turbidity between raw water samples and treated water samples, whereby treated water turbidity was within the DWI maximum limit of 4 FTU (Table 1).

The observed increase in the chloride concentration of treated water samples is due to dosing an electrolysed saline solution (ECAS) directly into the water treatment system. However, chloride concentrations for raw and treated water samples were consistently below the DWI limit of 250 mg $L^{-1}$ (Table 1). Figure 4 shows the real-time free chlorine concentration data of the treated water (using the in-line probes), whereby a reading was

187 automatically taken every minute. The frequent chlorine spikes are a result of UF
188 membranes back-flushing, which occur every 30 minutes, resulting in ECAS being dosed
189 into the DWPS pipework in the absence of bulk water flow. Despite this, free chlorine
190 concentrations within the treated water were significantly below the WHO recommended
191 concentration of 5 mg $L^{-1}$ free chlorine in drinking water.

192 It is evident from table 1, that there were significant reductions in aluminium, iron, lead,
193 manganese and zinc concentrations in the treated water compared to the raw water source.
194 The reduction in these metals is due to the multi-step filtration process within the DWPS. A
195 significant increase of sodium concentration in treated water samples is due to dosing an
196 electrolysed saline solution (ECAS) directly into the water treatment system. All metals levels
197 measured in the treated water were below the DWI limit for safe drinking water.

198 Permeability of the UF membranes initially decreased prior to stabilising, indicating no
199 significant blocking or biofouling of the UF columns during the course of this field trial (Figure
200 5). Biofouling can be a result of biofilm formation [42,43]; however, ECAS has been shown to
201 be effective in inhibiting biofilm formation [25,37,44] The regular spikes in permeability are a
202 result of UF membrane back-flushing every 30 minutes, which artificially impacts on the
203 measured pressure differential across the columns.

204 3.2 Field Trial 2: 0% ECAS Dosing (Control Period)

205 Table 1 shows the biological, basic water parameters, chemical and metal analysis results
206 for the 6 water samples taken during DWPS operation in the absence of ECAS dosing. All
207 water samples taken and analysed from the raw water source failed to meet DWI
208 specifications and were deemed unsafe for human consumption (Table 1).

209 During Field Trial 2 (in the absence of ECAS dosing), the DWPS did not produce drinking
210 water to DWI standards. Coliform bacterial counts exceeded the maximum allowance of 0
211 cfu 100 $mL^{-1}$, producing a mean result of 76.67 cfu $mL^{-1}$. Non-lactose fermenters within
212 treated water samples were significantly higher compared to raw water samples. However,

213 there were no recovered presumptive *E. coli*, *E. coli*, *Clostridium perfringens* and enterococci
214 from treated water samples (Table 1).

215 Table 1 demonstrates that multi step filtration within the DWPS resulted in a significant
216 reduction in turbidity between the raw water and the treated water, bringing the treated water
217 sample to within DWI limits. No significant difference was observed between the raw water
218 and treated for any of the measured chemical parameters (ammonium, chloride, nitrate,
219 nitrite, orthophosphate, silica and sulphate), and were within the DWI limits. The free
220 chlorine concentration of treated water over the 16 operational days was below the limit of
221 reliable detection for the in-line sensor (< 0.12 mg $L^{-1}$), which is expected since no ECAS
222 was dosed into the DWPS.

223 Metal analysis of the raw and treated water samples resulted in significant reduction of
224 aluminium, iron, lead and zinc (Table 1). Since this was observed in both field trials
225 (presence and absence of ECAS dosing), it can be concluded that reduction is due to the
226 multi-step filtration process alone within the DWPS.

227

**Table 1**: Analytical results of the raw water samples and treated water samples. Field trial 1: 1% total ECAS dosing UF membrane. Field trial 2: Control, 0% ECAS UF membrane. Results shown are the calculated mean from the independent ISO 17025 accredited laboratory reports (n=6 ±SD). Significant difference (Sig. diff) calculated through an unpaired, two tailed t-test, with a confidence interval of 95% (*** = p<0.001; ** = p<0.01; * = p<0.05; ns = not significant). **Bold figures** = Above DWI limit value.

| | | FIELD TRIAL 1 (1% total ECAS dosing) | | | | | FIELD TRIAL 2 (Control; 0% ECAS dosing) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Water type** | | **Raw water** | | **Treated water** | | | **Raw Water** | | **Treated water** | | | |
| | UNIT | Mean | SD | Mean | SD | Sig. diff | Mean | SD | Mean | SD | Sig diff. | *DWI Limit* |
| BIOLOGICAL | | | | | | | | | | | | |
| Plate count (2 day @ 37°c) | /ml | 538.83 | 753.19 | 0.33 | 0.82 | *** | 672.60 | 778.93 | 457.33 | 518.80 | ns | |
| Plate count (3 day @ 22°c) | /ml | 2685.33 | 770.77 | 2690.67 | 757.71 | ns | 12769.40 | 11209.42 | 2330.00 | 596.80 | ns | |
| Non-lactose fermenters | /100ml | 33.33 | 51.64 | 1.17 | 2.86 | *** | 0.00 | 0.00 | 13.67 | 33.48 | *** | |
| Presumptive coliform bacteria | /100ml | 49.17 | 43.19 | 0.00 | 0.00 | *** | 1913.33 | 3977.37 | 86.50 | 66.51 | ns | |
| Coliform bacteria | /100ml | **12.00** | 8.29 | 0.00 | 0.00 | *** | **1913.33** | 3977.37 | **76.67** | 73.55 | ns | *0* |
| Presumptive *E.coli* | /100ml | 1.50 | 0.71 | 0.00 | 0.00 | *** | 573.33 | 832.99 | 0.00 | 0.00 | *** | |
| *Escherichia coli* | /100ml | 1.50 | 0.71 | 0.00 | 0.00 | *** | 573.33 | 832.99 | 0.00 | 0.00 | *** | |
| *Clostridium perfringens* | /100ml | **95.83** | 11.70 | 0.00 | 0.00 | *** | **115.33** | 82.65 | 0.00 | 0.00 | *** | *0* |
| Enterococci | /100ml | **52.67** | 42.04 | 0.00 | 0.00 | *** | **88.67** | 88.59 | 0.00 | 0.00 | *** | *0* |
| BASIC WATER PARAMETERS | | | | | | | | | | | | |
| Alkalinity | | 139.00 | 2.65 | 131.50 | 7.78 | ns | 155.00 | 31.11 | 154.00 | 31.11 | ns | |
| Colour (spectrophotometer) | mg $L^{-1}$ Pt/Co | 5.60 | 0.55 | 4.00 | 1.79 | ns | 8.33 | 1.37 | 7.67 | 1.53 | ns | |
| Colour estimated | Deg Hazen | 5.00 | 0.00 | 5.00 | 0.00 | ns | 5.00 | 0.00 | 5.00 | 0.00 | ns | |
| Conductivity | µS $cm^{-1}$ @ 20°C | 708.00 | 69.80 | 764.17 | 151.18 | ns | 610.33 | 53.71 | 613.17 | 52.53 | ns | *2500* |
| pH | | 8.88 | 0.18 | 8.70 | 0.37 | ns | 8.33 | 0.66 | 8.22 | 0.69 | ns | *6.5 - 10* |
| Total hardness | Mg Ca $L^{-1}$ | 118.67 | 13.31 | 114.93 | 16.75 | ns | 109.00 | 11.33 | 102.93 | 8.23 | ns | |
| Turbidity | FTU | 15.60 | | 0.34 | 0.27 | *** | 27.33 | 6.86 | 0.19 | 0.13 | *** | *4* |
| CHEMICAL ANALYSIS | | | | | | | | | | | | |
| Ammonium | mg $L^{-1}$ | 0.05 | 0.04 | 0.03 | 0.01 | ns | 0.27 | 0.29 | 0.21 | 0.16 | ns | *0.5* |
| Chloride | mg $L^{-1}$ | 96.50 | 7.66 | 137.50 | 5.54 | *** | 63.17 | 3.54 | 62.17 | 3.54 | ns | *250* |
| Nitrate | mg $L^{-1}$ | 3.50 | 0.46 | 3.77 | 0.42 | ns | 1.02 | 0.55 | 1.08 | 0.71 | ns | *50* |
| Nitrite | mg $L^{-1}$ | 0.05 | 0.01 | 0.04 | 0.01 | ns | 0.06 | 33.68 | 0.38 | 33.21 | ns | *0.5* |

| Water type | | FIELD TRIAL 1 (1% total ECAS dosing) Raw water | | Treated water | | | FIELD TRIAL 2 (Control; 0% ECAS dosing) Raw Water | | Treated water | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | UNIT | Mean | SD | Mean | SD | Sig. diff | Mean | SD | Mean | SD | Sig diff. | *DWI Limit* |
| Orthophosphate | mg $L^{-1}$ | 0.10 | 0.02 | 0.12 | 0.02 | ns | 0.09 | 0.08 | 0.12 | 0.08 | ns | |
| Silica | mg $L^{-1}$ | 0.40 | 0.20 | 0.45 | 0.35 | ns | 0.50 | 0.74 | 0.41 | 0.58 | ns | |
| Sulphate | mg $L^{-1}$ | 158.00 | 40.31 | 156.83 | 36.86 | ns | 126.00 | 13.53 | 129.00 | 13.00 | ns | *250* |
| METAL ANALYSIS | | | | | | | | | | | | |
| Aluminium | µg $L^{-1}$ | **256.67** | 183.16 | 16.67 | 5.16 | ** | **463.33** | 124.85 | 23.33 | 5.77 | *** | *200* |
| Cadmium | µg $L^{-1}$ | 0.12 | 0.04 | 0.10 | 0.00 | ns | 0.10 | 0.00 | 0.10 | 0.00 | ns | *5* |
| Calcium | mg $L^{-1}$ | 103.45 | 11.07 | 100.28 | 14.07 | ns | 95.50 | 9.78 | 92.40 | 6.22 | ns | |
| Copper | mg $L^{-1}$ | 0.01 | 0.00 | 0.01 | 0.00 | ns | 0.01 | 0.00 | 0.01 | 0.01 | ns | |
| Iron | µg $L^{-1}$ | **316.67** | 180.85 | 10.00 | 0.00 | *** | **548.33** | 160.18 | 10.00 | 0.00 | *** | *200* |
| Lead | µg $L^{-1}$ | 5.38 | 2.43 | 0.62 | 0.26 | *** | 8.57 | 2.38 | 0.37 | 0.20 | *** | *25* |
| Magnesium | mg $L^{-1}$ | 9.28 | 1.36 | 8.95 | 1.67 | ns | 8.22 | 0.91 | 7.50 | 0.66 | ns | |
| Manganese | µg $L^{-1}$ | 21.00 | 3.85 | 4.33 | 1.97 | *** | 62.67 | 32.96 | 25.40 | 23.89 | ns | *50* |
| Nickel | µg $L^{-1}$ | 2.00 | 0.00 | 2.00 | 0.00 | ns | 1.68 | 0.78 | 1.70 | 0.73 | ns | |
| Potassium | mg $L^{-1}$ | 3.90 | 0.49 | 3.65 | 0.57 | ns | 3.87 | 0.38 | 3.58 | 0.34 | ns | |
| Sodium | mg $L^{-1}$ | 53.17 | 4.02 | 75.83 | 3.66 | *** | 37.50 | 1.87 | 36.83 | 1.33 | ns | |
| Zinc | µg $L^{-1}$ | 35.00 | 13.78 | 11.67 | 4.08 | ** | 36.00 | 15.17 | 18.00 | 8.37 | * | |

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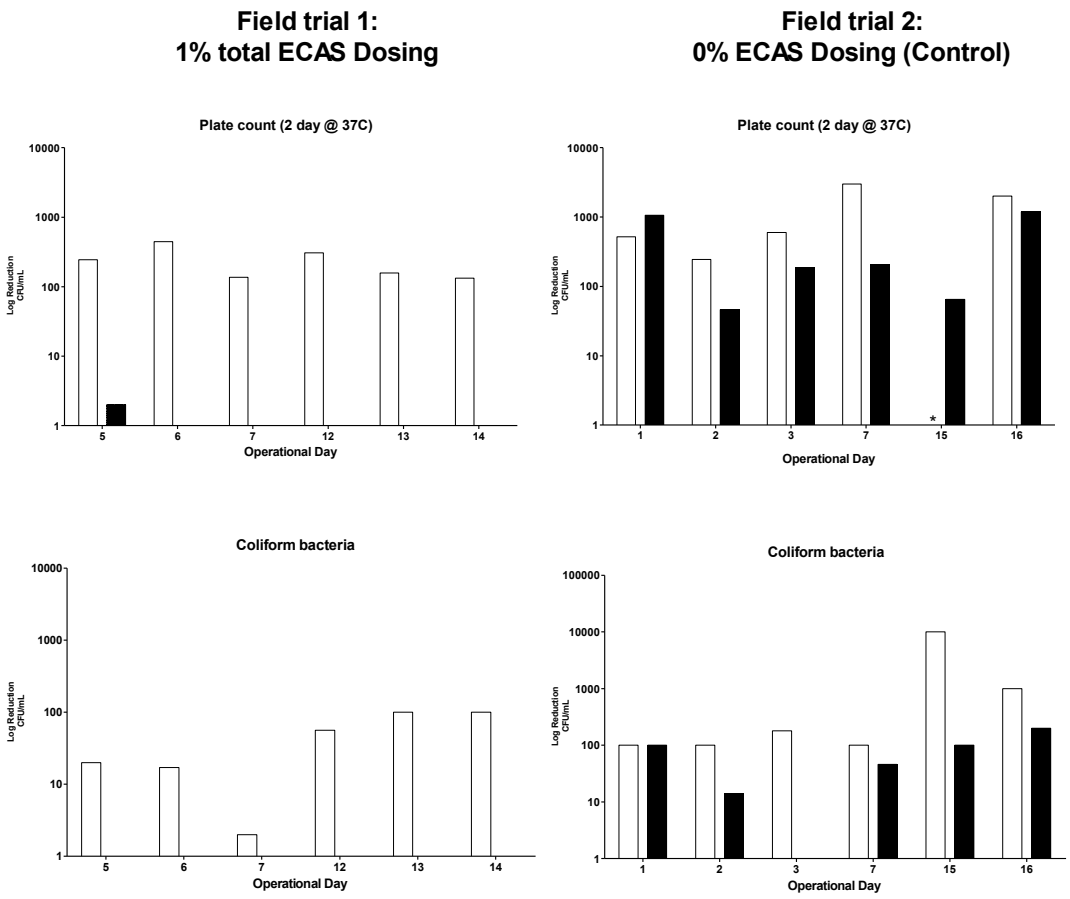


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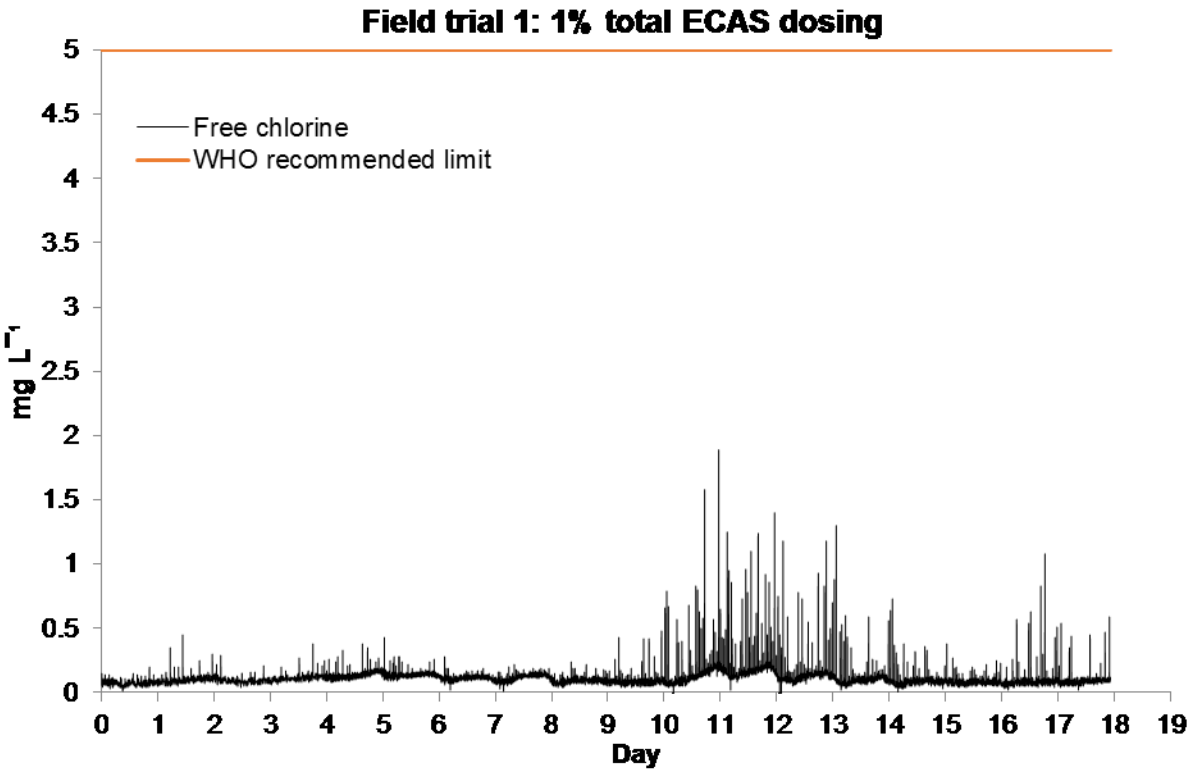
236 **Figure 3:** Heterotrophic plate count and coliform bacteriological results for water samples taken
237 during Field Trial 1 (1% total ECAS dosing) and Field Trial 2 (control; no dosing). White bars
238 represent raw water samples. Black bars represent treated water samples. Data taken from
239 independent ISO 17025 accredited laboratory reports (n=1 per sampling day).

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241 **Figure 4**: Free chlorine concentration (mg $L^{-1}$) of treated water samples (as recorded by the in-line
242 DWPS probe) for Field Trial 1 (1% total ECAS dosing).

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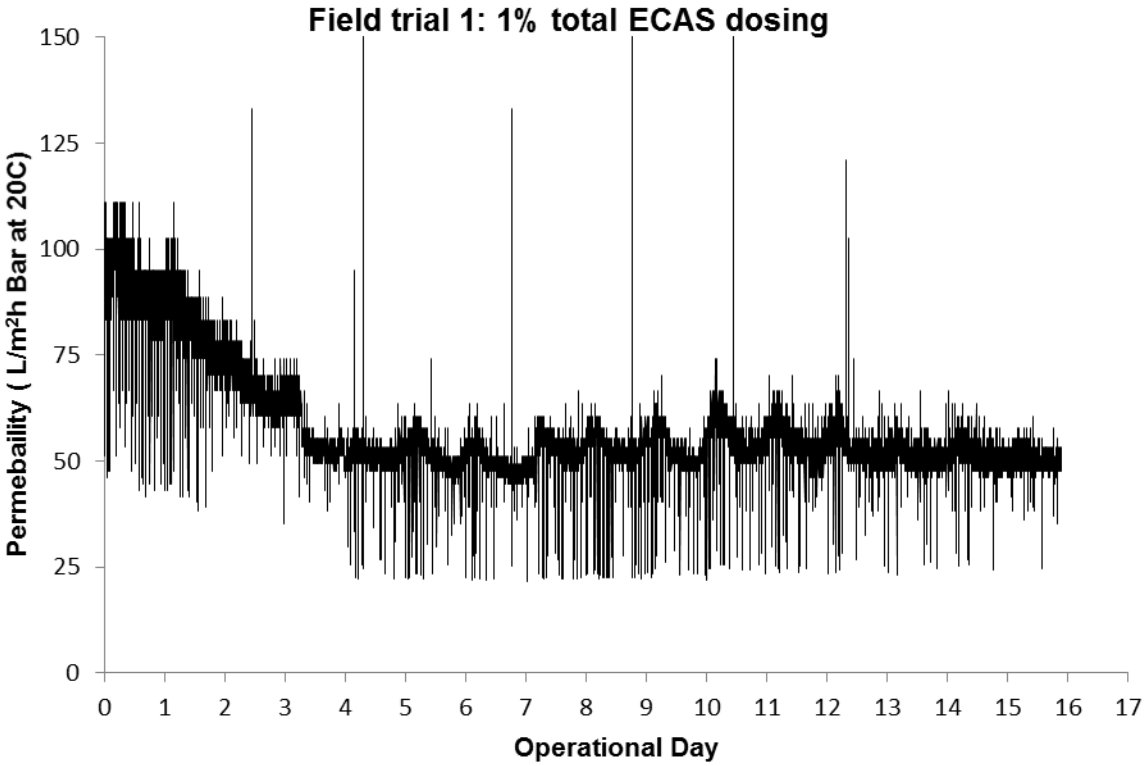


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246 **Figure 5:** UF membrane column permeability within the drinking water production system during Field
247 trial 1 (1% total ECAS dosing).

248

## 4.0 Conclusions

Two field trials were conducted over two 16 day periods to evaluate the off-grid drinking water production system shown in Figure 1. Field trial 1 performed direct dosing of 1% (v/v) total ECAS into the DWPS pipework, pre- and post- UF membranes. Field trial 2 was a control period, whereby the DWPS was operated in the absence of ECAS (0% ECAS dosing) pre- and post- UF membranes.

All raw water source samples taken throughout the two field trials failed to meet DWI standards and were deemed unsafe for human consumption.

During the control period (Field trial 2) all treated water samples were within DWI limits for basic, chemical and metal parameters. However, the treated water produced was not biologically safe due to the presence of coliform bacteria (Table 1 and Figure 3).

The analysis of all treated water samples resulting from field trial 1, demonstrated that the off-grid DWPS was consistently capable of producing DWI standard drinking water, with all basic, biological, chemical and metal parameters falling within the DWI threshold limits (coliform bacteria, C*lostridium perfingens,* enterococci, conductivity, pH, turbidity, ammonium, chloride, nitrate, nitrite, sulphate, aluminium, cadmium, iron, lead and manganese).

In particular, the microbiological results from field trial 1 treated water samples demonstrated the importance of ECAS dosing in the production of biologically safe drinking water to DWI standards.

The stable permeability of the UF membranes during field trial 1 (whereby 0.5% (v/v) ECAS was dosed pre-UF membranes), indicates that ECAS may help manage biofilm formation on the UF membranes. During Field trial 2 (control; no dosing) greater fluctuations in permeability within the UF membranes was observed, indicative of less stability, and possible biofilm formation (data not shown). This inference of reduced biofilm formation,

reducing the possibility of biofouling using 0.5% (v/v) ECAS dosing pre-UF membranes, requires further investigation.

Through a systems based hazard analysis the critical control points of the DWPS focus on the in-line monitoring parameters, specifically ORP and free chlorine. Two key critical variables are continuously measured in the WebMaster data logger, chlorine and ORP, ensuring the risks of biological and physicochemical contamination in the DWPS final treated water are minimised. The guideline value for chlorine is 5 mg $L^{-1}$, a European requirement for ensuring adequate residual disinfection within distribution systems. In addition, due to the nature of ECAS as a disinfectant; high ORP (+1130 mV), low free chlorine concentration, compared to conventional chlorination, and very fast acting kill kinetics (< 10 seconds), ORP is a key parameter to ensure production of biologically safe drinking water. Regular spot sampling of the treated water for biological, basic, chemical and metal analysis is required to ensure DWI compliance. A complete assessment regarding the hazards and critical control points of the DWPS shall be carried out as part of any future work.

This study has shown that a novel off-grid drinking water production system can produce DWI standard drinking water from a heavily biologically contaminated water source, when a 1% (v/v) total ECAS dosing regimen is implemented. The DWPS was developed with the intention of use in a wide variety of applications and locations, such as developing and transitional countries, many of which lack established centralised water treatment networks. The potential modular and scalable capability of the DWPS could be beneficial in remote, rural or temporary communities, which can have fluctuating populations. The self-contained nature of the DWPS, all filtration and disinfection processes are within the DWPS (except for intake filter pump), could be beneficial for temporary communities such as long-term research expeditions, or during disaster relief efforts. Long-term field trials are now required to obtain data for more representative applications, such as raw water sources from surface and ground waters, which have differing ‘contaminants’ (e.g. fertilisers, heavy metals, faecal contamination), ensuring the DWPS is capable and versatile in a wide variety of applications.

Investigations into the energy requirements for the DWPS are currently being conducted to ensure that the DWPS is robust and reliable for long-term operation.

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