

Pee Power Urinal – Microbial Fuel Cell Technology Field Trials In The Context Of Sanitation

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Abstract

This paper reports on the Pee Power urinal field trials, which are using Microbial Fuel Cells for internal lighting. The first trial was conducted on Frenchay Campus (UWE, Bristol) from February-May 2015 and demonstrated the feasibility of modular MFCs for lighting, with University staff and students as the users; the next phase of this trial is ongoing. The second trial was carried out during the Glastonbury Music Festival at Worthy Farm, Pilton in June 2015, and demonstrated the capability of the MFCs to reliably generate power for internal lighting, from a large festival audience (~1000 users/day). The power output recorded for individual MFCs is 1-2mW, and the power output of one 36-MFC-module, was commensurate of this level of power. Similarly, the real-time electrical output of both the Pee Power urinals was proportional to the number of MFCs used, subject to temperature and flow rate: the campus urinal consisted of 288 MFCs, generating 75mW (mean), 160mW (max) with 400mW when the lights were connected directly (no supercapacitors); the Glastonbury urinal consisted of 432 MFCs, generating 300mW (mean), 400mW (max) with 800mW when the lights were connected directly (no supercapacitors). The COD removal was >95% for the campus urinal and on average 30% for the Glastonbury urinal. The variance in both power and urine treatment was due to environmental conditions such as temperature and number of users. This is the first time that urinal field trials have demonstrated the feasibility of MFCs for both electricity generation and direct urine treatment. In the context of sanitation and public health, an independent power source utilising waste is essential in terms of both Developing and Developed World.

Keywords: microbial fuel cells; modular design; pee power urinal; sanitation; ceramic materials; fluidic isolation

Introduction

Microbial fuel cells (MFCs) have been receiving increased attention from the scientific community, even though the technology has been viewed with scepticism, at different levels of society. MFCs generate electrical energy directly from the break-down of organic matter via the metabolism of inhabitant microbes, with the rates of reaction being dictated by the microbial metabolic state (Ledezma et al., 2012). Electrical output is therefore thermodynamically limited by the carbon-energy metabolism of the constituent cells of the biofilm community (mono- or mixed-culture) colonising the electrode (Ieropoulos et al., 2007; Jong et al., 2006; Kim et al., 2000). Microbial reactions are inherently lower than chemical or even purely enzymatic reactions, and therefore the magnitude of the absolute power output at any given time, is typically orders of magnitude lower than those generated from conventional chemical fuel cells (Kirubakaran et al., 2009; Mekhilef et al., 2012). Be that

51 as it may, electricity generated in a MFC comes directly from waste or wastewater material,
52 which in the break-down/utilisation process is rendered cleaner and potentially suitable for
53 direct discharge to the environment (Habermann and Pommer, 1991; Ledezma et al., 2013;
54 Winfield et al., 2012). This is a competitive advantage that largely compensates for the lower
55 levels of power.

56
57 Over the years, a wide range of organic substrates has been shown to work as fuels in MFCs.
58 Without being exhaustive, these are: types of food waste such as rotten fruit and prawn
59 shells (Ieropoulos and Melhuish, 2005); various types of wastewater from the paper
60 industry, agriculture, dairy farms, municipal treatment plants, oil industry, wine distilleries
61 and breweries, and tanning industry (Pant et al., 2010); more recently, biodegradable
62 | materials (Winfield et al., 2015, 2013b) as well as human urine [and septic tank content](#), have
63 also been shown to work very well as fuels for electricity generation (Ieropoulos et al., 2013,
64 | 2012; Kuntke et al., 2012; [Yazdi et al. 2015](#)). The application of low cost ceramic membranes
65 allowed to decrease the cost of structural material, which is separating the anode and the
66 cathode, to as low as 4.14 GBP/m² (Pasternak et al., 2015). Utilising human waste directly
67 and decreasing the cost of MFCs by the use of ceramic membranes has allowed the
68 technology to be exploited in the context of sanitation, especially in countries of the
69 Developing World, which lack the basic infrastructure for clean water and sewerage
70 (UNESCO, 2009). More than 2.5 billion people lack access to an improved sanitation facility
71 while 1 billion practice open defecation (World Health Organisation, 2014). Inadequate
72 drinking water, sanitation and hygiene (WASH) are important risk factors where diarrhoeal
73 disease burden relies on access to water and sanitation facilities rather than water quality.
74 The importance of improving water and sanitation is the key for the prevention of diarrhoeal
75 diseases (Prüss-Ustün et al., 2014). In addition to the philanthropic dimension that the MFC
76 approach has, sanitation in the Developing World offers the ground for step-wise scale up
77 field trials, to evaluate the technology in the real world environment and thus assess its
78 feasibility.

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80 The efficient utilization of urine through MFCs incorporated in stacks/modules would no
81 longer require conventional energy intensive treatment by the wastewater companies and
82 also result in better balanced fertiliser (Ieropoulos et al., 2013). Efficient energy harvesting
83 electronics for direct MFC usage, is also a major challenge for scale up and implementation
84 (Wang et al., 2015). So far, there have been a few MFC field trials, like for example: a ceramic
85 cascade temporarily installed in a municipal wastewater treatment plant (Winfield et al
86 2012), a multi electrode MFC system for contaminant removal (Heidrich et al., 2014) as well
87 as for winery wastewater treatment (Cusick et al., 2011), wireless sensors (Donovan et al.,
88 2008) and more recently, floating MFCs at the Nosedo, Milan wastewater treatment plant
89 (Martinucci et al., 2015).

90
91 The present study is based on previously reported novel ceramic designs developed as single
92 MFCs, showing high power performance with catholyte production and an ability to operate
93 practical applications, including direct LED lighting (Gajda et al., 2015a) and recharging a
94 mobile phone via a single MFC unit (Gajda et al., 2015c). The design gives the advantage of
95 simplicity and functionality by utilising multiple MFCs submerged in the same feedstock
96 tank. The multiplication of units in parallel would form a module, which could then be
97 connected in series or parallel with other modules, to scale-up into a flexible and robust
98 stack. The study reported herewith, funded by the Bill & Melinda Gates Foundation and
99 Oxfam, had the following aims: (i) evaluate the modular approach of stacking MFCs in a pilot
100 scale trial for energy generation; (ii) integrate the technology with the toilets that Oxfam
101 uses in refugee camps and disaster areas to demonstrate utility in terms of indoor lighting;

102 (iii) scale-up of the urinal, at a systems level, for testing during the Glastonbury Music
103 Festival 2015 and (iv) assess the efficacy of urine treatment.

104

105 **Methods**

106

107 MFC construction

108 MFC units were constructed using closed at one end terracotta caves (Weston Mill Pottery,
109 UK) as previously described (Gajda et al., 2015a). The dimensions of the ceramic cylinders
110 used in this work were 150mm long, 48mm outside and 42mm inside diameter. Anode
111 electrodes were made of 30g/m² carbon veil fibre (PRF Composites, UK) of the dimensions:
112 600 x 260mm and folded in half along its length. The carbon veil was then wrapped around
113 the ceramic cylinder and tied with a 50mm diameter stainless steel wire to secure the anode
114 in place and to provide a connection to the external circuit. Cathode electrodes were
115 prepared using activated carbon and PTFE mixture as previously described and inserted
116 inside the ceramic cylinder (Gajda et al., 2015a) as a single sheet of 130 x 140mm
117 dimensions. Stainless steel crocodile clips were then used to connect the cathode to the
118 electrical circuit.

119

120 MFC module design & Inoculation

121 | ~~Thirty six~~ 36-MFCs were fitted into a plastic container of dimensions 70 (length) x 30 (width)
122 x 16cm (depth). The anodes and cathodes were connected in a parallel electrical
123 configuration using aluminium bus bars and stainless steel wire, nuts and washers. The
124 container was inoculated with a mixture of activated sewage sludge (Cam Valley, Saltford,
125 UK) and fresh urine and operated in batch mode for the preliminary test. The total liquid
126 capacity was 25 litres. Urine was collected from healthy individuals with no known previous
127 | medical conditions, and pooled together before using as a feedstock. The pH would be ~~an~~
128 average 6.4. No pH control was applied to the MFC stacks in both urinals.

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130 Pee Power Oxfam urinal- UWE campus

131 Eight modules (288 MFCs in total) as described above were fluidically connected using
132 plastic elbow connectors and pipes to create a series loop and air gaps between the boxes.
133 This was to allow the 8 modules to be connected in a series electrical configuration. They
134 were inserted under the men's urinal unit installed at the Frenchay Campus, University of
135 the West of England, as shown in Figure 1. The structure was built to accommodate two
136 urinal bowls directly feeding the MFC modules fitted underneath the structure. The urinal on
137 the University campus resembles toilets produced by Oxfam and used in refugee camps to
138 make the trial as realistic as possible. Inside the cubicle, LED light modules were fitted to be
139 energised by the MFC stack via a capacitor bank consisting of 4x3000F capacitors in a series
140 parallel configuration (BCAP3000 p270, Maxwell Technologies). The lighting consisted of 4x
141 4.5W modified LED modules (Dial MR16-3H-WH-A1 12V-50Hz 530mA 4.5W 14W20). The
142 purpose of modification was to reduce the LED forward voltage from ~12V to ~3V and so
143 better suit the requirements of the MFC system. With this modification, the 4 LED modules
144 were consuming approximately 1.2W. The switching of the LED lights was controlled using a
145 low power passive-infra-red (PIR) sensor and a low power microcontroller (Microchip
146 PIC24F16KA102). This also allowed for a 3V backup power supply in the case of MFC system
147 failure. The holding tank was fitted as the initial (inlet/buffer) tank at the beginning of the
148 stack, providing feedstock for the MFC modules. There was also a collection tank fitted at the
149 outlet of the MFC stack. The operational time was 3 months starting in 05/03/15 – 31/05/15
150 and the analytical data presented herein were collected over the period of 5 weeks to assess
151 power and nutrient removal. Urine was donated voluntarily by the campus student and staff
152 population.



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Figure 1. (a) Pee Power field trial funded by Oxfam at the UWE campus in February –May 2015; (b) 3D representation of the MFC stack with the inlet and outlet tanks underneath the urinal.

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Pee Power field trial – Glastonbury

161 A field trial was performed at the Glastonbury Music Festival, England, between 22/06/15 –
162 30/06/15. A specially adapted urinal (Dunster House, UK) was installed in the “Sacred
163 Space” (aka “Stone Circle”) field. The urinal structure was fitted with 3 troughs which
164 collected the urine from festival-goers and was used to 'feed' the MFC modules. Next to the
165 urinal, an educational information point was used to interact with the public explaining the
166 ideas and the technology behind the project. The men’s urinal was installed as shown in
167 Figure 2 where 12 MFC modules (8 from the Oxfam Pee Power urinal + 4 new ones) were
168 installed giving in total 432 MFCs in the stack and 300 litres of working volume. Similar to
169 the previous trial, supercapacitors (10x3000F in a series parallel configuration giving
170 7500F) were used as an energy store. The same LEDs as the ones used in the Oxfam system,
171 but a higher number of 6, were used, due to the larger urinal facility. The total power
172 consumption of the 6 LED modules was 1.8W. Due to the high number of users (between
173 825-1000 per day) the estimated flow rate was approximately 330 l/day and the hydraulic
174 retention time was 0.9 days.

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179 **Figure 2.** (a) Pee Power field trial in Glastonbury Music Festival, June 2015; (b) Urinal
180 assembly and MFC stack arranged in 12 modules.

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182 Analysis

183 Power performance was monitored with a multi-channel Agilent 34972A, LXI Data
184 Acquisition Unit (Farnell, UK) and were then processed using the Microsoft Excel and
185 GraphPad Prism software packages. Parameters such as pH and conductivity were measured
186 with a Hanna 8424 pH meter (Hanna, UK) and 470 Jenway conductivity meter (Camlab, UK)
187 respectively. Dry weight was determined by drying 1 mL of catholyte over 72 h in ambient
188 temperature and weighing the dry mass.

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190 COD was analysed using the potassium dichromate oxidation method (COD HR test vials,
191 Camlab, UK) with an MD 200 photometer (Lovibond, UK) where 0.2 mL samples were taken
192 before and during MFC treatment and filter-sterilised prior to analysis. Total Nitrogen (TN)
193 was measured using MD 500 colorimeter (Lovibond, UK) and Vario Tube Test (0.5-25 mg/L)
194 on diluted samples. The concentration of anions in the anolyte (inlet, outlet) and catholyte
195 samples was determined by ion chromatography using a 930 Compact IC Flex (Metrohm,
196 UK). The samples were diluted with ultrapure water before they were collected by the 858
197 professional sample processor and introduced into the ion chromatograph.

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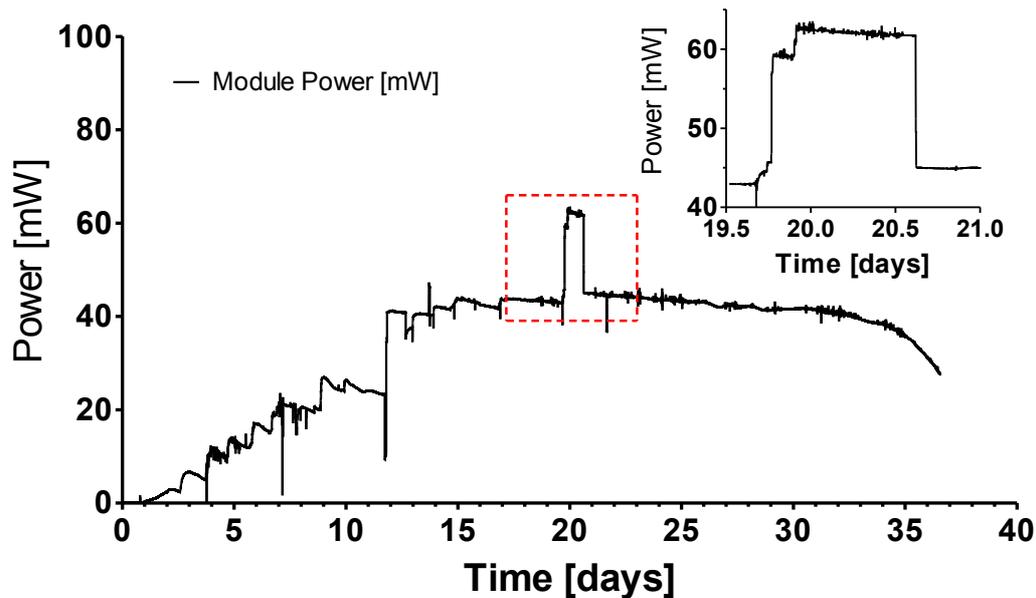
199 **Results and Discussion**

200

201 Initial MFC module testing

202 A single box assembled with 36 MFCs was initially tested under laboratory conditions. After
203 inoculation the MFC module was connected to a fixed resistor load and it was supplemented
204 with fresh and/or old urine daily. The resistor load was adjusted between 2.3 and 3.3 Ω with
205 stable performance achieved under a 3.3 Ω load. The module reached steady state
206 performance at 40 mW, however, when the resistor was adjusted to 2.3 and with some
207 modification and improvement of the cathode current collector, the peak power reached 62
208 mW (Figure 3), which is consistent with the individual ceramic MFC performance of up to
209 2.58 mW under controlled conditions. Multiple individual MFC units were also previously
210 tested in series and parallel configurations. These preliminary experiments constituted the
211 first tests of multiple MFC units in the same anodic feedstock, which simplified the
212 realisation of an MFC collective.

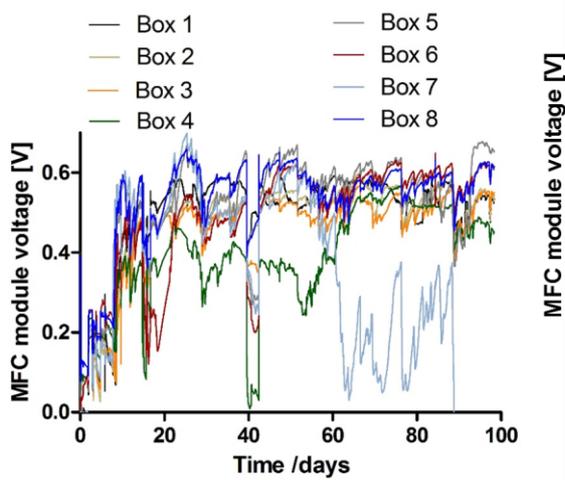
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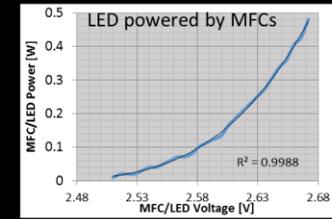
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 215 **Figure 3.** Real time power output from a single module of 36 MFCs connected in parallel.
 216 Inset graph is a magnification of the marked area, where the load was changed to 2.3Ω for
 217 approximately 24 hours.

218
 219 Campus (Oxfam) Trial

220 The pilot field trial ran for a total of three months. After inoculation with 1:1 activated sludge
 221 and urine mix, MFC modules were installed in the urinal and fed with neat fresh urine. The
 222 MFC voltage output of all eight modules is shown in Figure 4 (a) and the capacitor voltage in
 223 Figure 4 (b), where the inset presents the calibration curve for the LED lights directly
 224 connected to the MFC stack (i.e. by-passing the supercapacitors); during this time, the
 225 maximum power generated by the MFCs to power the lights was 0.4W for 75 hours. As can
 226 be seen from the graph on the left, 7 of the 8 MFC boxes were more consistent, in terms of
 227 performance, for the majority of the time (with the exception of when the LEDs were
 228 powered directly by the MFCs) and even with 1 of the boxes underperforming, the system
 229 was still operational without any polarity reversal; this demonstrated the robustness of the
 230 collective MFC modules under adverse conditions. As a joint project with Oxfam, it was
 231 hoped that electricity generated by MFCs will provide light for cubicles in refugee camps.
 232 The successful trial demonstrated that MFCs have got this capability (the campus Pee Power
 233 urinal has been re-started and it was still running successfully at the point of submitting this
 234 paper). Over the three month period, there was an estimated 5-10 users/day, which resulted
 235 in the processing of 2.5L-5L of urine daily. The hydraulic retention time for the whole stack
 236 was estimated to range between 2-3 weeks. The total catholyte synthesised (Gajda et al.,
 237 2015a) during the 3 month period for the 288 MFCs of 100mL internal volume was ca. 34L.
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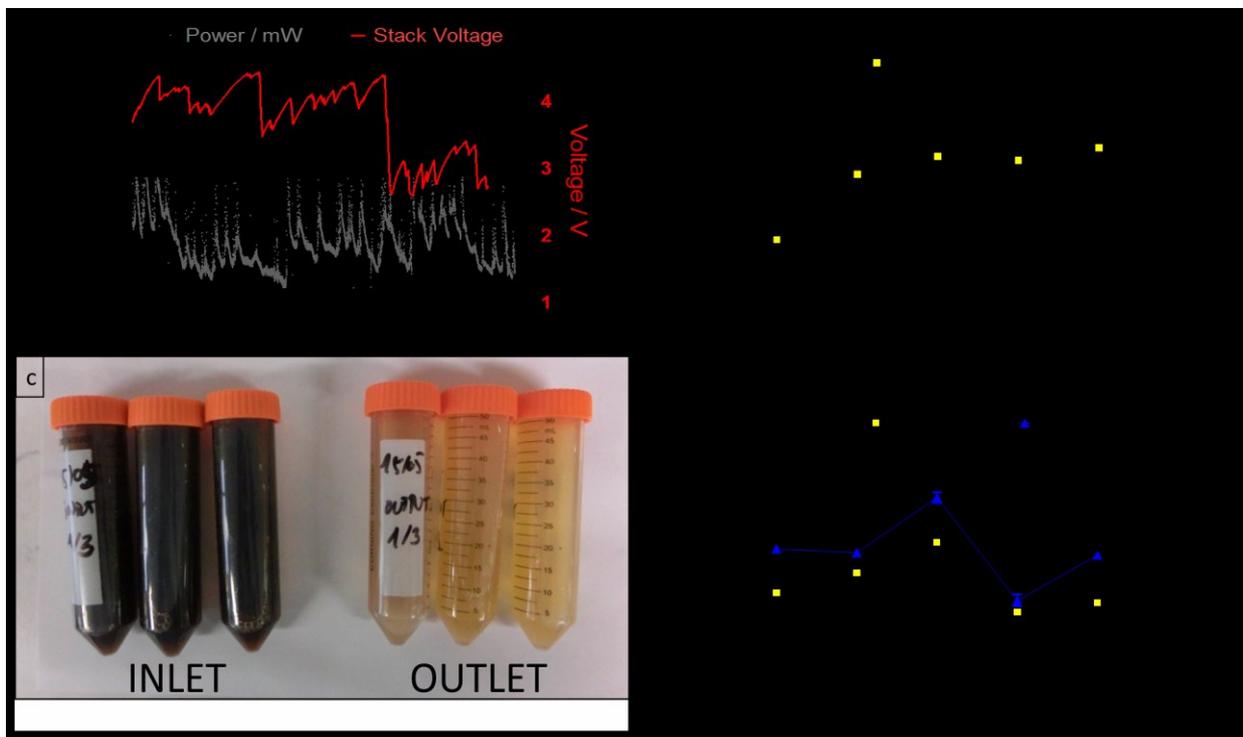


MFC module voltage [V]



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Figure 4. (a) Individual MFC module voltage performance of the 8 Oxfam stack boxes and (b) voltage output of the connected capacitor. The decreases in the voltage data curves are from when volunteers were visiting the urinal, and hence activating the lights to switch ON. The magnitude and length of decrease is an indication of the length of time the lights were ON. Figure 4B (inset) shows a calibration curve for the power consumed by the LED lighting at a given voltage. As can be seen the MFC stack gave a maximum power of approximately 0.4W for 75hrs.



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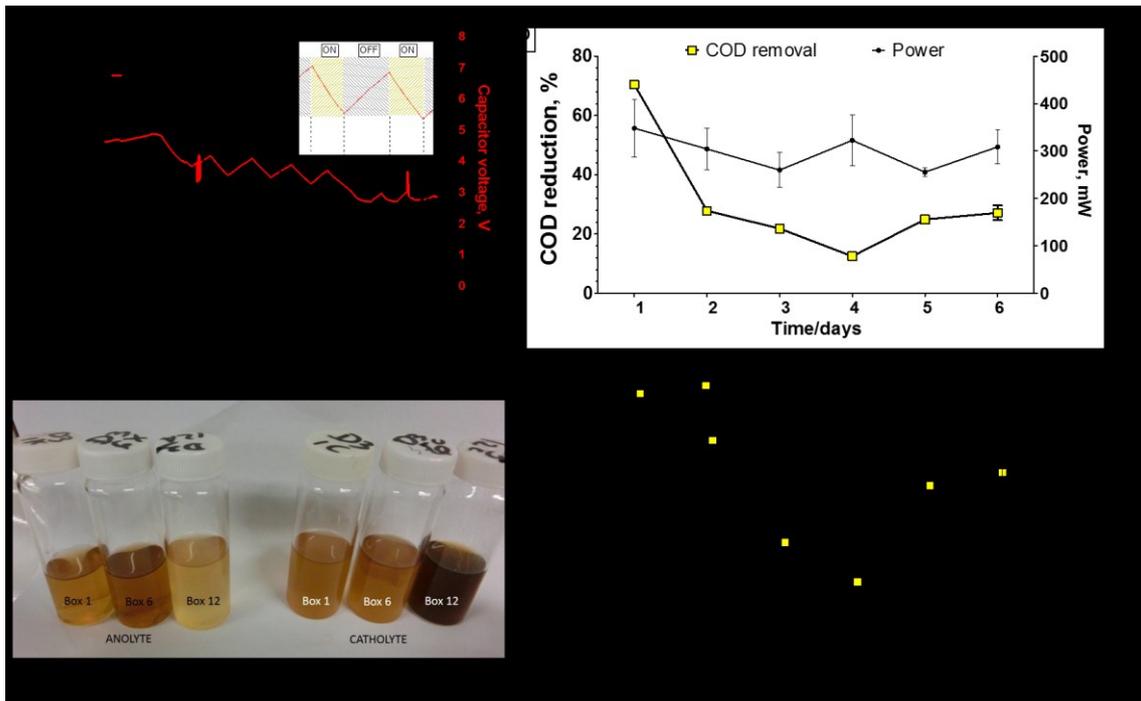
Figure 5 a) Power and Voltage performance over the 5 week analysis period; b) COD reduction in the system with reference to the power of the stack; c) Samples collected from the inlet and the outlet tanks on the 15/05/2015 (week three); d) Reduction of the total nitrogen from the outlet and catholyte samples compared to the inlet, with reference to the power performance.

258 The power behaviour in Figure 5a demonstrates the dynamic nature of the system, and the
259 response to the lights switching ON when people were entering the urinal, and OFF after a
260 period of 3 minutes (based on a pIR sensor, also powered by the MFC stack). The peak values
261 during this 5 week period were reaching, on average 75mW, and the highest value recorded
262 was ca. 160mW; the variation in performance was due to natural temperature conditions as
263 well as frequency of uses. The COD reduction is shown to be >90% reaching a maximum of
264 98%, which was mainly due to the long HRT, and this high reduction level was maintained
265 throughout the trial. This is also evident from the colour of the inlet and outlet samples
266 collected (Fig.5c), which clearly showed that the urine was being treated during the process.
267 The highest total nitrogen reduction was >50% for the anolyte and the lowest was <20%,
268 which was the same for the synthesised catholyte (Fig.5d). For the catholyte, the maximum
269 total nitrogen reduction was approximately 80%. Increased TN reduction in the catholyte
270 was probably due to the MFC electrochemical operation stimulating pH increase in the
271 cathodic chamber (Supporting Information, Figure S1a) that allowed ammonia stripping
272 (Kuntke et al., 2012) and more efficient nitrogen removal.

273 274 Glastonbury Trial

275
276 The data presented in Figure 6a shows the stack power performance over the period of 8
277 days. The first two days of data show the system in charge mode only in preparation for the
278 festival proper. On the 23rd of June the light in the cubicle was switched on (Further
279 controlled by a PIR sensor) and it is represented by the supercapacitor voltage drop. From
280 this point the lighting system was disabled during daylight hours (Figure 6a, inset) to allow
281 the system to recharge and then re-enabled during the night. Stack power had increased
282 from the system start date until the 24th of June (first day of the festival) reaching up to 400
283 mW total power output and showed good and stable power performance through the time of
284 the festival due to high usage and constant fast flow of fresh feedstock. The long decrease in
285 capacitor voltage between the 27th-28th June is when the lights were intentionally left ON
286 for 24 hours. As can be seen, at the end of this 24hr period, the system had almost reached
287 equilibrium (MFC power-in = LED power-out). The spike between the 29th-30th June is
288 when the supercapacitors were disconnected and the data following this (going into the 30th
289 June) are from when the MFCs were directly powering the lights. The peak power output was
290 up to 800mW, which is equivalent to 19.2Wh over 24hrs, and showed a mean output of
291 1.85mW/MFC, which is consistent with the laboratory data. Power output is significantly
292 higher than the power levels recorded for the campus Pee Power Oxfam trial, which might be
293 due to the increased number of modules (from 8 to 12), very high flow rate at the festival
294 and elevated temperature due to the direct sunlight exposure. The catholyte generated
295 during this trial was approximately 43 litres as each of the MFC units produced 0.1L of
296 catholyte. The very high flow rate and reduced HRT, did however affect the COD reduction
297 capability of the system as a whole, recording a maximum of ca. 70%, a minimum of 15% and
298 mean for the majority of the time of 25%. The same effect was observed for the total
299 nitrogen reduction of the system, where the maximum recorded was 79% and the minimum
300 was 6%. The high usage did however result in struvite accumulation inside the connecting
301 pipes, as a result of the inlet tank not holding urine for the required amount of time. The
302 colour of the collected (anolyte) inlet and outlet samples, also confirmed the reduced
303 treatment performance.

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308 **Figure 6.** a) Real time performance of the urinal stack with voltage. The inset represents a 2-
309 day charge-discharge cycle of the capacitors when the LED lights were turned OFF (day) and
310 ON (night); b) COD reduction and power performance over the 6 days of the field trial; c)
311 anolyte and catholyte samples collected on day 3; d) Total Nitrogen (TN) reduction rates in
312 Box 1, 6 and 12 in relation to stack power performance.

313

314 MFC electrochemical treatment is actively changing the chemistry of the treated substrate
315 favouring pH and ion separation (see Supporting information), which leads to the recovery
316 of slow-release fertiliser and electricity from urine (Zang et al., 2012). Porous terracotta has
317 been reported to allow ionic movement from the anodic chamber to the cathode surface
318 (Ghadge and Ghangrekar, 2015a), however when the cathode is exposed as part of an
319 outside surface (as opposed to a secluded inner surface used in the Pee Power examples),
320 might also lead to chemical scaling (salt deposition) and consequently biofouling (Ghadge
321 and Ghangrekar, 2015b) of the outer cathode.

322

323 Ceramic is a cost effective replacement for the cation exchange membrane (Behera et al.,
324 2010; Winfield et al., 2013a) and it proved once again to be a valid building block for MFCs.
325 Moreover, it is a functional medium for the electroosmotic flow of ions induced by the MFC
326 electric field (Gajda et al., 2015a). It promotes extraction and ion separation essential for
327 elemental recovery and recycling. This electro-kinetic function of MFCs depends on power
328 performance (Gajda et al., 2015b), which implies that the more efficiently the systems
329 perform, the more improved the elemental extraction with the added advantage of direct
330 monitoring of effluent quality (Chouler and Di Lorenzo, 2015). Environmental sustainability
331 is an integral part of the design, maintenance and operation of a urinal facility, promoting the
332 awareness of environmental issues, whilst providing the tools and incentives to address
333 them. Such field trials are essential so that the technology can be further advanced and
334 applied at larger scale.

335

336 The decreased treatment performance of the Glastonbury Pee Power urinal can easily be
337 rectified with the appropriate fluidic arrangements, to allow the same number of users, but
338 elongate the hydraulic retention time of the collective MFCs, so that higher COD and TN

339 reduction efficiencies can be achieved. This was not done in this case, due to the timing and
340 location constraints of the MFC stack, which was mainly for demonstration purposes. The
341 high number of users, resulting in a high throughput, implies that a further scaled-up Pee
342 Power urinal will be more efficient in treating higher urine volumes and at the same time
343 maintain a high level of power performance.

344

345 **Conclusions**

346 The provision of safe water, adequate sanitation and hygiene, is critically important for
347 promoting individual and community-level health in the Developing World. MFC based
348 technologies prove to be a sustainable solution even in remote locations, improving
349 sanitation and hygiene, and opening the way to elemental recycling. The Pee Power urinals
350 are perhaps one example of how these can be achieved.

351

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363

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