**Electricity generation and struvite recovery from human urine using microbial fuel cells**

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**ABSTRACT**

BACKGROUND: Urine is an abundant waste product which requires energy intensive treatment processes in modern wastewater treatment plants. However urine can be utilised as fertiliser in the form of struvite. Microbial fuel cells (MFCs) are a promising technology for treating waste whilst producing electricity. Combining these two approaches, a 3-stage MFC/struvite extraction process system was developed and its feasibility tested in order to maximise urine utilisation in terms of electricity generation and struvite recovery.

RESULTS: At the first stage, whilst generating electrical energy, MFCs accelerated urea hydrolysis, which was beneficial for the struvite precipitation process in the following stage. After collecting struvite by adding magnesium into the initial effluent, the supernatant was used at the final stage for additional power and more efficient COD reduction. In total, 82 % of PO43–-P and 20 % of COD of undiluted human urine were removed by the 3-stage system. Also 14.32 W/m3 (absolute power: 358 µW) and 11.76 W/m3 (absolute power: 294 µW) of power was produced from the 1st and 3rd stages of the system, respectively, during operation.

CONCLUSION: This work shows how MFCs and struvite precipitation could be integrated for both energy generation and resource recovery from urine, leading to a truly sustainable energy future.

Keywords - microbial fuel cells, struvite, source-separated urine, resource recovery

**INTRODUCTION**

The average individual human being can produce approximately 2.5 litres of urine per day, and taking into account that cattle can produce up to three times as much, gives an estimated global annual urine production of ~6.4 trillion litres 1. Urine is normally just flushed down the toilet to be treated in wastewater treatment plants (WWTPs) before returning to natural water bodies. Although urine consists of less than 1 % of municipal wastewater in volume, it contains about 50 % of total phosphorus (P) and 75 % of total nitrogen (N) in municipal wastewater 2. Phosphorus and nitrogen are two main elements that require removal from the wastewater since an accumulation of these can lead to eutrophication. The annual social and ecological damage cost of freshwater eutrophication was estimated as £75 – 114M in England and Wales only 3. Hence most modern WWTPs adapt energy intensive treatment processes for treating both phosphorus and nitrogen, which are also very costly to build and operate.

In the 1990s, various European groups started working on the concept of source-separated urine for improving the sustainability of wastewater management 4. Source-separated urine can reduce the operation cost of WWTPs and also contribute to better effluent quality of WWTPs by changing wastewater composition 2. In addition, nitrogen and phosphorus can be recovered and utilised from source points since urine has a high concentration of these elements, and phosphorus recovery through struvite precipitation has received increased attention. Struvite (magnesium ammonium phosphate, MgNH4PO4·6H2O) is usually formed in stale urine through the following chemical reaction and recovering struvite from urine has two big attractive advantages.

Mg2+ + NH4+ + PO43- + 6H2O → MgNH4PO4·6H2O

First it contains both nitrogen and phosphorus, which renders the simultaneous removal of the two compounds from the main stream of wastewater achievable. In addition to the aforementioned reduction in operation cost and improvement in effluent quality, this could also reduce pipe blockage occurrences, which are caused by struvite formation at WWTPs. Once struvite has formed and blocked water pipes, these need to be cleaned or even replaced, and in many cases other elements of WWTPs such as pumps, valves, centrifuges and aerators are also liable to fouling by struvite deposits 5,6. These ‘undesirable’ struvite deposits increase maintenance costs, and reduce the piping system capacity of WWTPs. Second, struvite can be used as a slow-release fertiliser 7–9, which is not a completely new concept since many communities have used or once used human excretion including urine for growing crops before commercial fertilisers appeared.

Further to this well-known approach of utilising urine, recently it has been presented that electrical energy can also be generated from urine with the use of the microbial fuel cell (MFC) technology 1,10. MFCs are transducers that convert chemical energy of feedstock into electricity through the metabolic activity of microorganisms. Whilst producing electricity, MFCs can also treat the feedstock by consuming nutrients through microbial metabolism. For this reason, a wide range of organic compounds have been tested for MFC power production and urine is one of the attractive options due to its abundance and natural properties such as neutral pH and high conductivity.

Only recently recovery of resources whilst treating waste using bioelectrochemical systems (BES) including MFCs and microbial electrolysis cells (MECs) has begun to gain attention. Recent progress and findings can be found in a comprehensive review11. In the case of resource recovery from urine, nitrogen recovery in the form of ammonium (both NH3 and NH4+) from the cathode have been attempted using MFCs and MECs12,13. Zang et al.14 reported that phosphorus and nitrogen recovery in the form of struvite from stale urine is compatible with MFC operation. However the current study’s thesis is that more effort should be made for better understanding the processes and implementing the systems especially when dealing with fresh urine such as a MFC system directly connected to urinals.

In order to maximise urine utilisation in this work, a 3-stage MFC/struvite extraction process system that generates electricity whilst collecting phosphorus and nitrogen in the form of struvite was proposed and its feasibility was tested. With this system, electricity generation is maximised, thus increasing the consumption of organic matter, and high concentrations of nitrogen and phosphorus are recovered through the struvite precipitation process. Furthermore this can be easily integrated with existing source-separated urinals. Therefore, the aim of this study was to combine the MFC electricity production with struvite recovery and investigate whether the two processes can complement each other. This work could contribute to a sustainable urine treatment process through recovery of resources and generation of energy as well as treating urine from the point of source.

**EXPERIMENTAL**

**MFC design**

The MFCs consisted of 6.25 mL anode chambers and open-to-air cathodes as previously described15. The anode compartments had inlets and outlets, which allowed the anolyte to fill up from the bottom and then overflow from the top; the overflow anolyte fed into the downstream MFC. Plain carbon fibre veil electrodes (PRF Composite Materials, UK) with 12 layers of 4.18 cm2 (width: 2.2 cm, length: 1.9 cm) were used for the anodes. A cation exchange membrane (CMI-7000, Membrane International, USA), 25 mm diameter, was sandwiched between the anode and cathode frames. The cathode electrodes, which were identical for all MFCs, were made of hot-pressed activated carbon onto carbon fibre veil and had a total macro surface area of 4.9 cm2. Nickel-chromium (0.45 mm thickness) wire was used for connection and current collection.

**Urine and inoculum**

Neat (untreated without dilution) human urine was used for this work since the final MFC/struvite extraction process system is aimed to fit directly into urinals. Urine was donated from male and female healthy individuals, on a normal diet and without any medical conditions, and pooled together prior to use. Unless otherwise stated, urine was used on the day of donation.

The anodes were inoculated with activated sewage sludge supplied from the Wessex Water Scientific Laboratory (Saltford, UK). Sludge was mixed with 0.5 % yeast extract and 1 % tryptone (both Sigma-Aldrich) as an initial feedstock. Following the inoculation of the MFCs and the maturing of the biofilm communities on the anodes for a week, neat human urine was provide as the sole energy source (fuel).

**Proposed system operation**

For a more efficient use of urine with MFCs in terms of power production and nutrient recovery, a system of MFCs which could be fitted into urinals was developed. This proposed system consisted of two MFC groups and each group had four MFC units. In each group, four MFCs were cascaded and had a single flow of substrate, which was provided continuously, using a 16-channel peristaltic pump (205U, Watson Marlow, UK). The four MFCs were connected in a series/parallel configuration (MFCs 1 & 4, and MFCs 2 & 3 were connected in parallel, and the two pairs were connected in series) in order to produce sufficient power for demonstration of a practical application. An external load of 1K Ω was applied to both groups.

In the first stage, untreated urine was supplied to Stage 1 (see Fig.1) at a flow rate of 96 mL/hr, which resulted in 16 minutes of hydraulic retention time (HRT) for all 4 MFCs. Once the effluent was collected, magnesium chloride hexahydrate (MgCl2·6H2O, Fisher Scientific) was added in Stage 2 and mixed using a magnetic stirrer at 100 rpm for 5 min. Following this, the mixing was stopped and the solution was allowed to settle for 45 min before the supernatant was fed into the last stage (Stage 3) of the treatment. The amount of magnesium addition was 1.2 times the phosphate presented in the initial effluent in molar ratio 16. In the final stage, the MFCs treated the struvite-deprived effluent (2nd stage effluent) at a flow rate of 42 mL/hr (HRT: 38 min). The final effluent was collected for analysis.

Figure 1 shows the whole system operation. All experiments were carried out in a temperature controlled laboratory, with 22 ± 2 °C and repeated at least 3 times.

**Chemical & physical analysis**

The pH, redox potential (ORP) and conductivity of the suspension were measured using a pH/ORP meter (pH 209, Hanna Instruments, UK) and conductivity meter (470 Cond Meter, Jenway, UK). For measuring soluble elements such as COD, NH4+–N and PO43–-P, urine samples were filtered through 0.45 µm filters (Millex, USA) and then analysed according to the standard methods 17.

Characterisation of the dried crystals from the struvite precipitation stage was performed by X-ray diffraction (XRD) (D8 Advance Diffractometer, Bruker, UK) and the results were analysed using the EVA software package (Bruker). The precipitates were filtered through 0.45 µm filters, and then dried at 40 ºC prior to analysis. Microscopic images of the precipitates were also taken by a digital microscope (KH-7700, Hirox, Japan).

**Electrical measurement and power output calculations**

Power output of the MFCs was monitored in real time in volts (V) against time using a HP Agilent multiplex logging system (34907A, HP, USA). Polarisation experiments were performed periodically by connecting a decade variable resistor box (Centrad Boite A Decades De Resistances DR07, ELC, France) between the anode and cathode electrodes and varying the external resistance from 30 kΩ to 10 Ω in time intervals of 5 minutes after the MFCs had established a steady-state open circuit voltage. The current (I) in amperes (A) was determined using Ohm’s law. Power density (PD) and current density (ID) were calculated according to the anodic chamber volume; PD = P/v, ID = I/α, where α is the anode chamber volume in cubic metres (m3).

**RESULTS AND DISCUSSION**

**Effect of struvite collection on the MFC performance**

Before operating the 3-stage MFC/struvite extraction process system, the effect of struvite collection on the MFC performance was investigated in two steps. First, in order to observe the effect of naturally occurring struvite on MFC performance, untreated neat urine as a fuel was provided to both MFC groups continuously at a flow rate of 21.2 mL/h (HRT: 18 min for individual MFCs) for 5 days. During this period, the MFCs were operated individually without inter-connection and the urine was stored at room temperature in an open container. Power performance and struvite precipitation were monitored and shown in Fig. 2a. In these 5 days, urine pH rose naturally due to urea hydrolysis, which resulted in increased precipitation. Furthermore, soluble phosphate concentration decreased accordingly since part of it went into the precipitate. Power output from individual MFCs remained relatively stable suggesting that it was not significantly affected by the change of pH or phosphorus concentration in the feedstock. Hence naturally occurring struvite precipitation did not seem to have an effect on MFC performance as long as the same untreated urine was provided.

For the second step of this work, rapid struvite precipitation from fresh urine was pursued by manually changing the pH and adding MgCl2·6H2O. Sodium hydroxide (NaOH) pellets were used for increasing the pH to 11 and 0.5 M H2SO4 solution was used for bringing the pH back to its initial value after removing the precipitate. The two MFC groups were fed both with untreated freshly collected urine as well as with struvite-deprived urine at a flow rate of 21.2 mL/h. Using this method, 20 % of NH4+–N (from 363 mg/L to 290 mg/L) and 82 % of PO43–-P (from 202 mg/L to 36 mg/L) were recovered in the form of precipitate (Table 1). ORP and conductivity increased whilst the pH decreased slightly. In both cases of neat- and struvite-removed urine, the change in pH, ORP and conductivity between feedstocks and effluents, demonstrated a similar pattern. The degree of change was proportional to the initial value of the influent. It was also observed that the power output was higher from the struvite-removed urine than from the neat urine. This is thought to be the result of conductivity increase of the anolyte after adding magnesium - MgCl2·6H2O (molar ratio; Mg2- : PO43–-P = 1.2 : 1).

Thus from the two tests, it was suggested that a decrease of phosphorus concentration in urine through struvite precipitation did not significantly affect the MFC power performance. This finding can be useful when designing a MFC system that can be connected to urinals. For MFC operation, reducing any insoluble matter in the feedstock solution is preferred for minimising blockages of the anode or membrane. Since the amount of precipitate in urine increases with time, precipitate removal or fresh urine (in both cases of undiluted and diluted urine) is required before adding into MFCs. Relatively high ammonium concentration of urine have been reported not to hinder the MFC power performance12,14. However no published information was found on the inter-relationship between MFC operation and high phosphorus concentration of urine. These findings demonstrate that it is possible to remove the precipitate before the MFC system without negatively affecting the power output.

Struvite removal with Mg addition has the added advantage of higher phosphorus recovery rates in shorter periods of time. Approximately 38 % of PO43–-P was removed in 5 days of storage (Fig. 2a) whereas 82 % of PO43–-P was recovered through the Mg addition process, which required a period of less than 1 hour. In terms of struvite recovery, struvite precipitation using additional magnesium is a very well established and efficient way to remove phosphorus from urine. A previous study18 reporting struvite recovery from the cathode electrode observed deterioration of electricity generating performance due to struvite deposition on the cathode and membrane which impedes the mass transfer of ions and oxygen. Therefore in the case of utilising urine which has high concentration of phosphorus, phosphorus recovery through struvite precipitation process seems more convenient and efficient way to pursue.

**Urea hydrolysis acceleration by microbial activity of MFCs**

Figure 2b shows the general pattern of pH change occurring in undiluted urine that was stored on a laboratory bench in ambient temperature. The initial pH of 6.4 did not significantly change for approximately the first 10 hours (less than 0.2 pH units), but then increased relatively rapidly for the next 20 hours. After 30 hours of storage, the pH stayed at approximately 9.2, which is consistent with previous reports 19.

As shown in Table 1, the pH of untreated urine however, rose to the same level after running through a group of 4 MFCs in only 72 min (HRT of the whole group). This clearly showed that MFCs accelerated urea hydrolysis, which was not attributed solely to the electricity generating activity of microorganisms in the MFCs, since a similar degree of pH increase was also recorded for the same MFCs without an external load (open circuit condition). Therefore the acceleration effect could be the result of urine being exposed to a higher population of microorganisms for a given time.

The pH of urine naturally increases as a result of urea hydrolysis by ubiquitous microorganisms 20. It is very likely that electricity generating microorganisms existing in MFCs could also hydrolyse urea. Further investigation is needed to confirm if they are the same species to the urease-positive bacteria that hydrolyse urea in urine and if their activity is affected. Nevertheless it seems that introducing MFCs to fresh urine shortens the time for urea hydrolysis thus increases the pH of urine rapidly.

Previous studies 8,21,22 proposed an optimum pH range of 8 - 9 for struvite precipitation. Since the effluent pH is in this range, no additional NaOH is necessary for pH adjustment. This could be an added advantage when struvite collection is expected from both cases of diluted or undiluted urine. Most studies on struvite recovery from urine used either stored urine for allowing the pH of urine to increase naturally or fresh urine but increasing the pH by adding alkalis like NaOH. In both cases, large storage capacity or high cost for pH increase is required, and it seems that both operational costs can be significantly reduced, by accelerating the pH increase through MFC systems.

**Urine treatment and nutrient recovery**

Based on the above findings, a 3-stage MFC/struvite extraction process system was designed. The first stage, running the 1st group of MFCs, was for generating power and increasing the pH for struvite removal. The second stage centred on the struvite precipitation process by adding Mg. In the third and final stage, the 2nd group of MFCs was fed with the supernatant from Stage 2 at a slower flow rate in order to further reduce COD and generate electricity. Change of pH, conductivity, NH4+–N, PO43–-P, COD and power output from each stage is shown in Figure 3.

After the first stage of treatment, the pH of urine increased to 9.37 and conductivity rose by 11.8 mS/cm, which implied a considerable amount of urea hydrolysed within 15.6 minutes of HRT. At the same time, NH4+–N concentration increased almost 7 times whilst PO43–-P concentration decreased 26 %. Again the increase in NH4+–N concentration was a result of urea hydrolysis accelerated by microbial activity in MFCs and it led to pH increase. The PO43–-P concentration reduction could probably be explained by solubility decline of phosphate due to pH increase, and bacterial uptake for growth. Struvite solubility depending on pH value is well described in the literature 23; generally solubility decreases with increasing pH and this results in struvite precipitation within the system. In addition, phosphorus is one of the essential elements for microbial growth thus it could be absorbed by microorganisms in MFCs. However this phosphate behaviour was not consistent in repeated tests as also has been the case in previous reports 24,25. The biological phosphorus removal process adapted in modern WWTPs uses specific microbial species, so called, polyphosphate accumulating organisms(PAOs) under certain environmental conditions, switched from anaerobic to aerobic 26,27.

Once neat urine was treated in the first stage, magnesium was added without any pH adjustment. This addition brought about a decrease in pH, NH4+–N, PO43–-P and COD but an increase in conductivity. Since the PO43–-P concentration was much lower than NH4+–N concentration in the 1st stage effluent (thus a limiting factor for precipitation), the recovery rate of PO43–-P was far higher than the recovery rate of NH4+–N. Approximately 7 % of NH4+–N and 78 % of PO43–-P were recovered by collecting the precipitate.

X-ray diffraction (XRD) analysis showed this precipitate had a similar pattern to struvite (Fig. 4). Also the microscopic image showed that the precipitate consisted of mainly transparent rod-like crystals, which is a typical orthorhombic structure of struvite 21. However the purity of struvite needs to be investigated further. In a process like this, besides struvite, other minerals such as montgomeryite (Ca4Al5(PO4)6(OH)5·11H2O, Ca4MgAl4(PO4)6(OH)4·12H2O), epsomite (MgSO4·7H2O), and brucite (Mg(OH)2) may also be formed depending on the amounts of other divalent or trivalent metal cations available 28.

During the final stage of treatment, pH and conductivity slightly increased again due to the hydrolysis of urea that remained from the previous treatment. Consequently NH4+–N concentration also increased which was in contrast to previous studies reporting NH4+–N reduction in the anodic chamber of MFCs12,14. This is thought to be due to different conditions of substrate and MFC operation (fresh neat urine without dilution and continuous feeding mode in this study). Also PO43–-P concentration increased slightly this time. However, the phosphate behaviour at the final stage was - as in the first stage - inconsistent. The inconsistent phosphorus behaviour might be attributed to the dynamic physical-chemical reactions and equilibrium conditions of the system as well as bacterial activity. In the case of COD, the highest removal of 15.6 % was achieved at this stage. Longer HRT of the stage was thought to be one of the reasons for the higher COD removal. After the 3-stage system treatment, COD was still relatively high (above 5000 mg/L), which could make further utilisation of urine as a MFC substrate possible.

In total, 82 % of PO43–-P and 20 % of COD were removed by the 3-stage system.

**Electricity generation**

During the first treatment, 358 µW of power (PD = 14.32 W/m3) was generated by the 1st MFC group. The 2nd MFC group produced 294 µW (PD = 11.76 W/m3) from the 2nd stage effluent. However it cannot be concluded that untreated urine always gives higher power than the 2nd stage effluent. In order to evaluate urine as a fuel source at different treatment stages, several factors need to be considered. Firstly, any differences in the microbial community developed at each stage need to be taken into account. In each group, microorganisms had different environmental conditions such as pH, conductivity and salts concentration of the feedstock thus there could have been changes in the abundance and diversity of the complex microbial community in the system. This may have caused differences in the performance between the two MFC groups. In this case, the 1st group was better performing than the 2nd group as shown in Figure 5. Therefore the 1st group was expected to produce higher power than the 2nd group if the same urine was supplied. When the same untreated urine was provided to the 2nd group, the output was 291 µW (PD = 11.64 W/m3) which was almost identical to the output generated from the same MFC group fed with the 2nd stage effluent. In repeated tests, the power output from the same group fed with untreated urine was similar or only slightly higher than the 2nd stage effluent. Moreover, when the position of the two groups was swapped, higher power was produced by the 1st MFC group at the 3rd stage.

An important aspect to consider is the flow rate of urine supply resulting in different HRT, and in this study different flow rates were set for the MFC processes. The higher flow rate (96m L/hr) for the first stage was in order to prevent precipitation inside the system but still result in a good level of power. For operating MFC systems in continuous feeding mode, the flow rate of feedstock needs to be optimised since too low or high flow rate can cause performance decline 29. Different flow rates were tested in order to find the optimum flow rate for the system used in this work and with the flow rate of 42 mL/hr the system showed the maximum power output. For this reason, this was the flow rate used during the final stage. Therefore more power could be expected from the 3rd stage, if all other conditions were identical. It is also important to give consideration to the concentration change of readily available organic matter. In most cases, the second MFCs in each group produced higher output than the first units when they were monitored individually. It is likely that the amount of readily available organic matter increased after the first MFC units. In a similar fashion, effluent from the 1st stage might have had more easily utilisable organic matter than untreated urine. A similar pattern has been witnessed in previous studies using complex feedstocks where the downstream MFCs outperformed the upstream30,31. Therefore the optimum flow rate, HRT, group positioning and amount of magnesium addition need to be chosen accordingly when designing a MFC system for maximising power output and nutrient recovery.

**Practical application**

For demonstration purposes, it was attempted to operate a commercially available electronic air freshener with the 2 groups of 4 MFCs (8 in total) used in this study. The air freshener originally required two D sized batteries to operate. The original circuit board of the automatic air freshener was modified with a 240 mF super-capacitor (Cellergy, Israel) which would allow a maximum voltage of up to 4.2 V. When the charged voltage of the capacitor reached 2.8 V, the air freshener operated the integrated motor, which actuated to press the nozzle of an inserted compressed air spray can. After the firing motion, the voltage of the capacitor decreased to 2.1 V, the system stopped and the capacitor began to charge again. The 4 MFCs within each group were connected as already described above, and the two groups were then connected in series.

Figure 6 shows the temporal profiles of the MFC stack whilst operating the automatic air freshener. Each trough and peak represent one charge/discharge cycle where the MFC stack voltage increased as the capacitor was charged. When the capacitor discharged at 2.8 V, the voltage of the stack dropped to 2.1 V then quickly started charging up again. This charge/discharge cycle repeated every 15-25 minutes for 4 weeks continuously. This exemplar practical application demonstrated successfully the capability of the MFC stack, with only 8 MFCs of 6.25 mL anodic volume each.

**CONCLUSIONS**

In this work, a 3-stage MFC/struvite extraction process system demonstrated how the MFC technology and struvite precipitation could be integrated and beneficial to each other in this integration for both energy generation and resource recovery from urine. Three major conclusions were drawn in this study.

1. Placing MFCs before the struvite precipitation process helps struvite collection by accelerating urea hydrolysis, and removing struvite from urine before the MFCs helps by minimising the element of system blockage without hindering the MFC performance.
2. With the 3-stage system proposed in this work, 82 % of PO43–-P, 20 % of COD of undiluted human urine were removed and 14.32 W/m3 (absolute power: 358 µW), 11.76 W/m3 (absolute power: 294 µW) of power was produced, which was put to practical use.
3. Besides the potential benefits of the proposed system concept, several design factors such as flow rate and amount of magnesium addition are suggested for further consideration, which can be the first steps to a truly sustainable energy future.

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**Table legend**

Table 1. Comparison of neat urine and struvite removed urine as a feedstock in terms of pH, ORP, conductivity, NH4+–N, PO43–-P and power output. Data presented as the mean and error (n=2 for NH4+–N and PO43–-P, n=4 for power output).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | untreated urine(neat) | treated urine from group 1 | treated urine from group 2 | untreated urine(struvite removed) | treated urine from group 1 | treated urine from group 2 |
| pH | 6.57 | 9.28 | 9.24 | 6.49 | 9.25 | 9.23 |
| ORP (mV) | -14 | -171 | -166 | -2 | -165 | -163 |
| Conductivity (mS/cm) | 12.3 | 23.0 | 22.5 | 13.5 | 24.4 | 24.2 |
| NH4+–N (mg/L) | 363 ± 8 | 3268 ± 10 | 3246 ± 15 | 290 ± 6 | 3114 ± 14 | 3106 ± 12 |
| PO43–- -P (mg/L) | 202 ± 6 | 254 ± 11 | 244 ± 6 | 36 ± 2 | 36 ± 1 | 36 ± 2 |
| Power (µW) |  | 101 ± 7 | 82 ± 3 |  | 104 ± 6 | 86 ± 4 |

**Figure Captions**

Figure 1. Schematic diagram of the 3-stage MFC/struvite extraction process system. The diagram also illustrates how this can be implemented in real life.



Figure 2. Urine pH change with time and its use as a substrate for MFCs (a) profile of influent pH, soluble phosphate and MFC power output. Data are based on mean values (n=2 for PO43--P, n=4 for power output). (b) typical pH behaviour of urine when stored in a bottle at room temperature; pH was measured *in situ* every 30 minutes for 50 hours.



Figure 3. Profile of pH, conductivity, PO43–-P, NH4+–N, COD and power output of each stage. Data presented as the mean and range (n=3).



Figure 4. XRD analysis of the struvite precipitate (grey line: standrard struvite, black line: precipitate sample from the 2nd stage). The inset shows the microscopic image of the struvite.



Figure 5. Polarisation curves of MFC group 1 and MFC group 2; each group consisted of 4 MFC units in cascade.



Figure 6. Temporal profiles of the MFC stack when connected to a commercial electronic air freshener; charge/discharge cycle in voltage, current and power (from the top).

