Electricity and fertilizer production using microbial fuel cell stacks for hydroponics

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Abstract

Earlier investigation on cylindrical ceramic MFC fed with human urine revealed that, along with electricity, catholyte is accumulated with highly concentrated nitrogen, phosphate, and potassium (N, P, K) sources, which could be used as liquid fertiliser. However, this concept has not been scaled up to produce liquid fertiliser from sewage. Here, we stacked 40 ceramic microbial fuel cells in two plastic trays (MFC tray-1 and MFC tray-2) to produce both electricity and liquid fertiliser directly from raw sewage. MFC tray-1 and MFC tray-2 produced ca. power of up to 21.78 mW and 18.89 mW, respectively, with synthetic urine. Maximum power output values were 19.1 mW (63.82 mA) and 14.9 (56.38 mA) for sewage-fed MFC Tray-1 and MFC Tray-2, respectively. Therefore, each ceramic MFC unit in both trays achieved a power of up to 1.02 mW and 0.85 mW with synthetic urine and raw sewage, respectively. The rate of catholyte (fertiliser) production in each MFC tray was 1.2 L of catholyte/48 h from 2.5 L of sewage. The catholyte from sewage-fed MFCs has been observed to have antimicrobial properties, and it is composed of NO_3^-, PO_4^{-2}, and K^+ at concentrations of 25 ± 1 [mg/kg], 9 ± 3[mg/kg], and 95 ± 14 [mg/kg], respectively. Ceramic-microbial fuel cell stacks therefore efficiently harness electricity and produce liquid fertiliser from sewage, offering seamless integration with hydroponics to grow vegetables in a self-powered, hygienic, and sustainable manner.

Keywords: *Ceramic Microbial Fuel Cell; Electroosmotic; Electricity; Liquid fertilizer; Sewage*

1. Introduction

Global effort is undertaken to tackle climate change issues and encourage the use of greener, carbon-neutral technologies, for a balanced carbon/nitrogen (C/N) future. Wastewater is one of the major contributors to climate change and C/N imbalancing issues, which directly affect humans, plants, and all living organisms on this planet [1]. Globally, ~380 billion m^3 (380 trillion liters) of wastewater is generated per year, and it is expected to increase by 24% by 2030 and 51% by 2050 [2]. Out of the 380 billion m^3, more than 60% of sewage is discharged without treatment due to a lack of wastewater treatment infrastructure [1]. The discharge of untreated sewage leads to the spread of waterborne diseases, as witnessed during the COVID-19 pandemic [1]. In India, almost USD 600 million (48.60 billion INR) is invested annually to address waterborne diseases [3]. In the U.S., the cost of secondary treatment of sewage ranges from less than \$5 to \$45 per gallon, and for both secondary and tertiary conventional treatment, it ranges from less than \$5 to nearly \$70 per gallon [4].

Alternatively, wastewater is replete with organic matter (mostly carbon and nitrogen), thus recovery and reuse of these nutrients could be a promising approach instead of their treatment through conventional processes. Wastewater contains 16.6 Tg (Tg = million metric tons) of nitrogen, 3.0 Tg of phosphorus, and 6.3 Tg of potassium [2]. It is estimated that the nutrients recovered from wastewater could meet 13.4% of the global agricultural demand, while the energy in wastewater could power 158 million households [2]. Wastewater treatment using MFCs has been reported to cost €1700 to €2300/yr, which is significantly less expensive than the existing technologies [5]. Furthermore, it is calculated that a methane-fed microbial fuel cell (MFC) integrated with an anaerobic digester can generate up to 1.386 kWh of electrical energy per kg of chemical oxygen demand (COD) utilised during wastewater treatment [6]. It is thus becoming increasingly obvious that wastewater is a resource rather than a burden to be disposed of.

In this context, a Pee Power® urinal (based on stacking ceramic MFC) was demonstrated on the Frenchay Campus (UWE, Bristol) and during the Glastonbury Music Festival at Worthy Farm, Pilton in consecutive years [7]. This urinal-MFC generates power for internal lighting from a large festival audience (~1000 users per day). Another investigation on stack module design with 22 ceramic MFCs produced up to 21.4 mW (11.9 W/m^3) after 580 days, whereas the 3-module cascade achieved up to 75 mW (13.9 W/m^3) of power after 446 days of operation. The COD removal efficiency has achieved more than 92% in these ceramic-MFC cascades [8]. Besides the potential of MFC for carbon removal from wastewater, it can be used to recover potassium as caustic potash (KOH) from wastewater along with electricity production, making it a carbon-negative technology [9,10].

Moreover, the catholyte produced *in situ* in these urine-fed ceramic MFCs through an electro-osmotic process has antimicrobial activity that inhibits human pathogens, such as *Salmonella enterica serovar Typhimurium, Pseudomonas aeruginosa, Staphylococcus aureus, and E. coli*

[11,12]. This paves the way for commercialising the MFC technology for safe, off-grid sanitation [13,14].

The catholyte from urine-fed MFCs, which is rich in nitrogen and phosphate, could be used as liquid fertiliser to grow plants [15]; this concept has not been yet scaled up in an agricultural context. Also, MFCs have been developed for integration with hydroponics, but this is still early stage [16,17]. Therefore, in the present investigation, cylindrical ceramic MFCs were stacked in a plastic tray (MFC-tray) to generate electricity and liquid fertiliser directly from untreated sewage and synthetic urine.

2. Materials and methods

2.1. Fabrication of Stacked ceramic MFC-Trays.

Large ceramic cylinders of size 10 cm long, 4.2cm diameter, 0.3 cm thickness (Weston Mill Pottery, UK) that were used in earlier investigation [18] were cut into a height of 7 cm (open at one end). These ceramic cylinders create an actual working height of 5 cm (an extra 2 cm long is kept to make them suitable for fixing in Trays) when fixed in trays, which is half the working volume compared to earlier investigations [18]. These ceramic cylinders act as a membrane in MFC for ion exchange. A carbon veil (30 g m^{-2}) was used as the anode material, with a projected surface area of 945 cm^2. The carbon veil was folded and wrapped on the external surface of the ceramic cylinder wall [19]. Pieces of nickel-chromium wire were wrapped as rings to act as current collector and hold the carbon veil electrode in tight contact with the ceramic body.

The cathode material is fabricated using activated carbon (AC, Norit SX Ultra, Sigma Aldrich) blended with polytetrafluorethylene (PTFE, 60 wt% solution, Sigma Aldrich) in an 80%: 20% ratio [11]. The PTFE-activated carbon mixture was pasted over both surfaces of a stainless steel mesh (current collector) and was pressed using a hot iron, as previously described [11]. A piece of this cathode (surface area = 4 cm x 11 cm = 44 cm^2) was cut, stitched with nickel-chromium wire, and placed inside the cylindrical ceramic membrane. A cylindrical plastic tube was inserted in the cathode, pressed, and rolled to ensure a tight contact of the cathode to the inner surface of the cylinder, as previously described [11]. This air-breathing cathode material facilitates the oxygen reduction reaction, where activated carbon acts as the catalyst. The cathode-to-anode ratio was ~1:22, for achieving maximum power [18].

Two MFC trays were employed (Plastor, UK), with dimensions 36 cm (length), 27 cm (width), and 16 cm (height) (**Fig. 1**). A total of 40 small ceramic MFCs were prepared as described above and placed inside these two plastic trays, resulting in 20 MFCs per tray. A non-transparent acyclic sheet with 20 symmetrical holes (to match the outer diameter of the ceramic MFCs) was placed at a height of 6 cm from the bottom of the trays, resulting in a working volume of ca. 3L, as the anodic chamber (**Fig. 1**). The acyclic sheet acts as a lid covering the anodic chamber of the MFC tray, whilst the cathodic chamber of each MFC is still exposed to air (**Fig. 1**). The acyclic lid was painted black to avoid the growth of algae. Two separate holes were made on opposite walls in each tray, acting as the inlet and outlet to the anodic chamber. Both MFC trays were connected with plastic pipes, as shown in Fig. 1, for a continuous substrate feed.

2.2 Operation of MFC

The two MFC trays were stacked in a cascade manner, enabling feedstock (raw sewage/synthetic urine) to flow from the outlet of tray 1 to the inlet of tray 2 under gravity flow (**Fig. 1)**. Initially, synthetic urine was used as the substrate for these two modules, which was operated in fed-batch mode (keeping feedstock replenishment every 48 h) for 45 days. Then, raw sewage was collected from the nearest wastewater treatment plant (Millbrook Waterworks, Southampton) and supplied to the two trays in fed-batch mode for 30 days. Following this, sewage was fed to MFC tray-1 and MFC tray-2 continuously with a hydraulic retention time of 4 h. Under continuous mode, the substrate was fed into the first tray, overflowing once full, into the second tray-2. The outlet of MFC tray-2 was collected in a separate plastic bottle (collection chamber), and recycled to the feeding chamber (placed at the top) using a peristaltic pump (505U, WATSON-MARLOW, UK), as shown in **Fig. 1**. All 20 ceramic MFC units in each MFC tray were electrically connected in parallel as they shared the same anolyte.

2.3 Data Monitoring and Polarization of MFC Trays

Electrical output was continuously monitored using a Pico data logger connected to the computer. The polarisation study was carried out with variable resistance decade boxes, using a resistance range of 10000 Ω – 1 Ω, with a timestep (τ) of 30 minutes. The MFCs were left in open circuit voltage (OCV) for at least 2h for stabilisation before performing the polarisation study. Power was calculated by multiplying voltage and current. The polarisation curve of MFC was obtained by plotting the current (I) on the x-axis and voltage and power on two y-axes. The internal resistance of MFC was calculated from the I-V slope.

2.4 Electrochemical analysis of catholyte

Catholyte electrochemical analysis was carried out as previously described [20]. The *in-situ* synthesised catholyte was collected using a sterile syringe. Electrical conductivity and pH were measured using a pH conductivity meter (HI5522, Hanna, UK). Ion chromatography (IC 930 Compact IC Flex, Metrohm, UK) was used to determine the concentration of cations and anions in the catholyte samples, as well as in sewage and synthetic urine. The COD analysis of different samples was carried out by following the standard closed reflux method, APHA. All wastewater samples and catholytes were filter-sterilised using 0.45 μm filters (Millex, USA) before their analysis.

2.5 Antimicrobial activity of catholyte

Antimicrobial analysis of catholyte was carried out using the agar well diffusion method [21,22]. Nutrient agar plates were prepared in the laminar airflow chamber, and 0.1 ml of sewage (as a mixed microbial source) was spread over them. The catholyte from the MFC tray was collected in a sterilised test tube, and 0.01 ml of catholyte was applied against the sewage-mixed microbial inoculum. All the agar plates were incubated at 37°C for 24 h. The inhibition zone in the agar plates was determined after 24 h of their incubation.

3. Result and discussion

3.1 Electrical performance of MFC Trays

Initially, the MFC trays were fed synthetic urine, and their electrical output was monitored. The electrical performance of synthetic urine-fed MFC achieved a maximum OCV of 638 mV and 558 mV in MFC tray-1 and MFC tray-2, respectively **(Fig. 2).** Similarly, the voltage across 100 Ω resistor, was 375 mV and 345 mV for MFC tray-1 and MFC tray-2, respectively. A polarisation study was conducted separately after 30 days of operation, considering the biofilm maturation and their internal resistance values were determined. Based on this polarisation run, the external resistor values were changed to match their internal resistance values to maximise the power performances. Based on the initial polarisation study, the internal resistance values were calculated to be 50 Ω and 10 Ω. However, after 45 days of operation, internal resistance was determined to be 5.6 Ω and 6.4 Ω for MFC tray-1 and MFC tray-2, respectively **(Fig. 3)**. MFC tray-1 has achieved a maximum absolute power of 16.47 mW (48.50 mA), whereas tray 2 showed 14.97 mW (54.72 mA) **(Fig. 3)**. Subsequently, both trays were operated under 4.7 Ω, which is close to the internal resistance values obtained during the polarisation run **(Fig. 3)**.

The voltage across 4.7 Ω was 320 mV (current of 68 mA) and 298 (current of 63.4 mA) over 60 days of operation. Furthermore, MFC tray-1 and MFC tray-2 produced 21.78 mW and 18.89

mW of power, respectively. Theoretically, each single MFC unit of both trays has produced an average power of 1.02 mW. It is important to note that each large MFC cylinder (10 cm) was cut into half with a working size of 5 cm and still produced equivalent levels of power compared to those recorded with the power of 1.2 mW using these same cylinders in their full size [18].

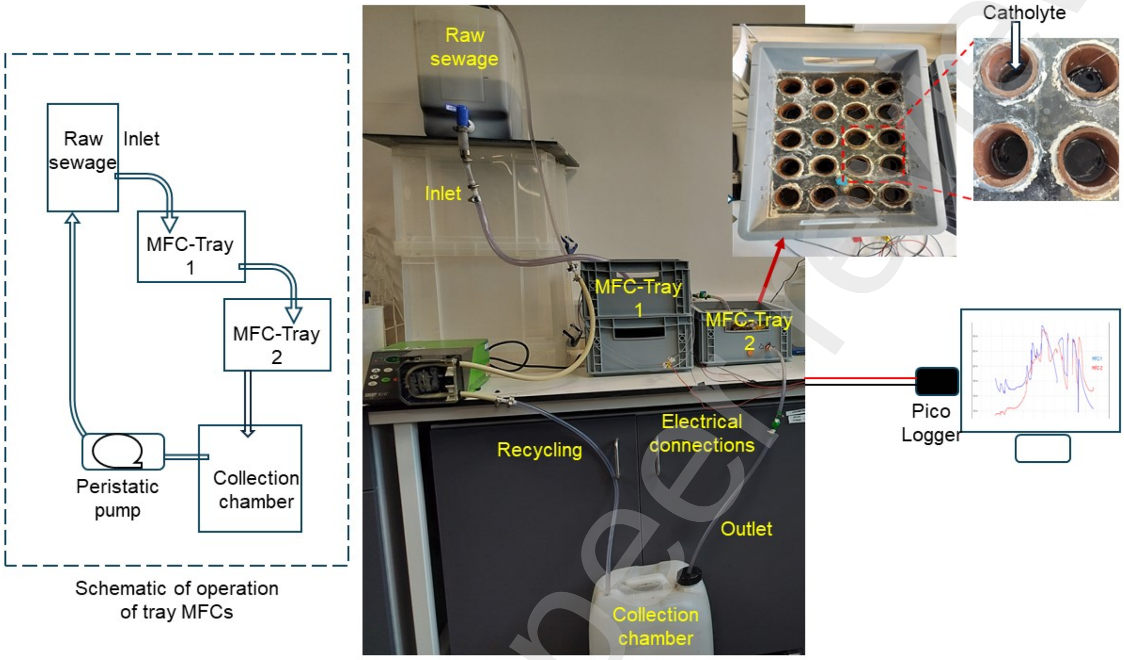

Fig. 1: Operation of MFC Trays. Raw sewage is fed to MFC tray-1 through gravity, followed by tray-2. The outlet from tray-2 is recycled through the peristaltic pump.

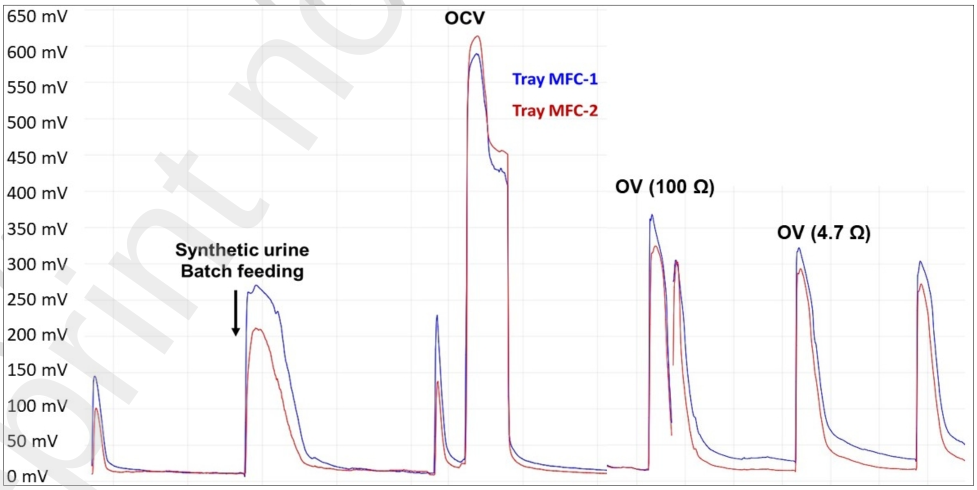

Fig.2 Voltage output, against 4.7 Ω resistance, of MFC trays fed with synthetic urine and raw sewage.

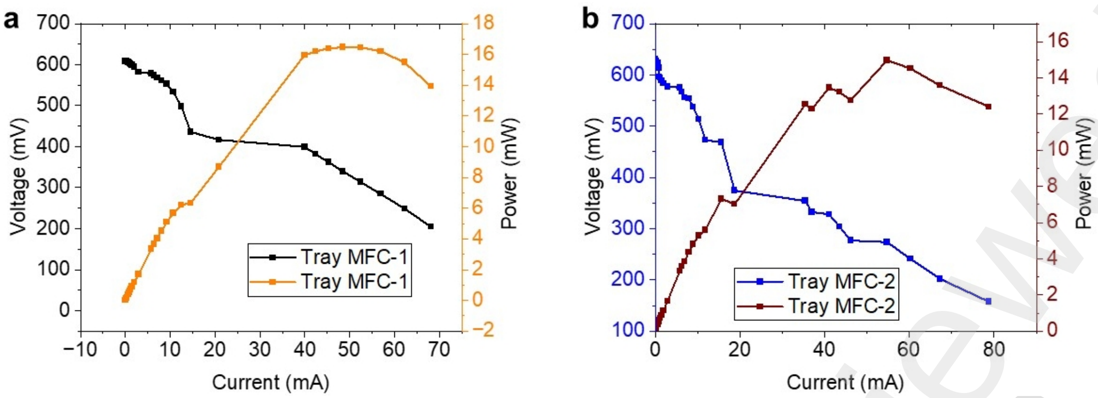

Fig. 3: Polarisation study of continuous sewage feeding MFC trays (**a**) MFC tray-1 and (**b**) MFC tray-2.

Sewage was then fed to MFC tray-1 overflowing into MFC tray -2, with 300 mV and 265 mV recorded across 4.7Ω, respectively **(Fig. 4)**. Maximum power output values were 19.1 mW (63.82 mA) and 14.9 (56.38 mA) for sewage-fed MFC tray-1 and MFC tray-2, respectively. Therefore, each MFC unit in both trays achieved a power of up to 0.85 mW when sewage was the source of substrate electroactive biofilms in MFCs. It is important to mention that large ceramic membrane MFCs (height 7 cm) have been employed in this study, which are essential to get more catholyte in the cathodic chamber. Despite the half-height and the fact that higher normalised power has been generated compared to full-height experiments [18], these MFCs (height = 10 cm) underperformed compared to smaller diameter, same 7cm height ceramic MFCs (2.9 times less power) [18]. Therefore, smaller MFCs would have achieved higher power and catholyte production from sewage [23], and this will be pursued in our future scale-up studies.

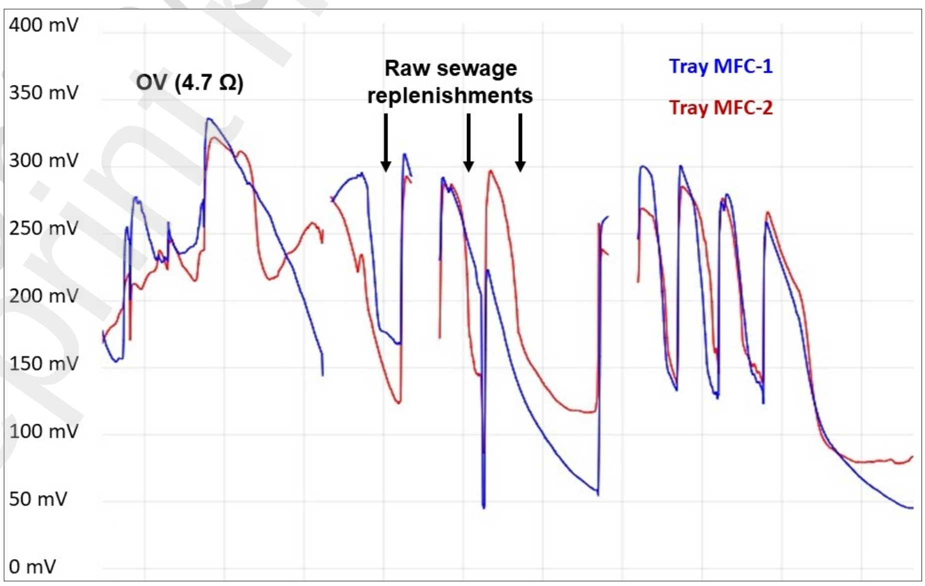

Fig.4 Voltage under 4.7 Ω resistance of MFC trays fed with synthetic urine and raw sewage.

In addition, raw sewage had a very low COD value, 372 ± 12 mg/L, at the inlet in MFC Tray-1 and 68 mg/L at the outlet of tray-2. However, synthetic urine has a COD value of ~ 3000 mg/L. Therefore, it can be concluded that the lower electrical performance in the case of sewage-fed MFCs compared to synthetic urine-fed MFCs was possibly due to lower COD values in the sewage. These results offer a new perspective for using wastewater with higher COD values, e.g., swine wastewater, distillery, and brewery wastewater, to achieve a higher electrical performance in MFC Trays[24].

3.2 Catholyte analysis

The catholyte is produced in the cathodic charmers **(Fig. 1)**. This observation is similar to earlier experiments where urine-fed ceramic MFC has been demonstrated with catholyte production through electro-osmotic mechanisms [7]. Ions present in the anolyte are dragged toward the cathodic chamber, through the ceramic membrane, due to the electro-osmotic effect when MFCs are operated in a closed-circuit mode [7]. The rate of catholyte production in each MFC tray was observed to be 1.2L from 2.5L of sewage during 48h. The nature of the catholyte is colorless, as shown in **Fig. 5** and odorless.

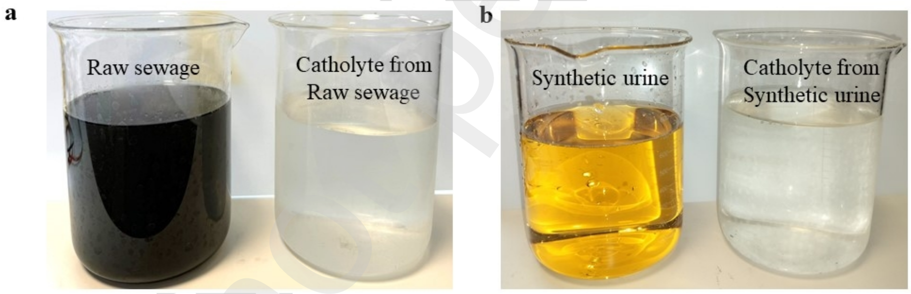

Fig.5 Catholyte from MFC trays. (a) Catholyte recovered from raw sewage (MFC tray 2); (b) Catholyte recovered from synthetic (MFC tray 2).

Table 1: Cations present in the catholyte samples

Sample	Color	pH	Electrical conductivity ($mS\ cm^{-1}$)	COD (mg/L)
Raw Sewage	Dark grey/ Black	7.5	1.89	372 ± 12
Anolyte-sewage fed MFC Tray	Dark grey/ Black	7.2	2.60	--

Catholyte-sewage fed MFC Tray	colorless	10.3	5. 69	--
Synthetic urine	Pale yellow	7. 06	3.68	3000 ± 6
Anolyte-synthetic urine fed MFC	Pale yellow	6.9	4.85	--
Catholyte-synthetic urine fed MFC	Colorless	11.1	14.43	--

The catholyte was analysed to understand its chemical composition and the presence of different cations and anions. The catholyte of the raw sewage-fed MFC has a pH of around 10.3 **(Table 1)**, which is corroborated with previous experiments, where caustic content was observed in the catholyte of ceramic MFC that facilitated increased power [10]. The concentrations of total nitrogen, phosphate, and potassium (N, P, and K) are essential components for plant growth. The catholyte of sewage and synthetic urine-fed MFCs showed significant amounts of phosphate, potassium, and total nitrogen concentrations. Notably, in the case of sewage-fed MFCs, the concentration of NO_3^-, PO_4^{-2}, and K^+ was observed to be 25 ± 1 [mg/kg], 9 ± 3[mg/kg], and 95 ± 14 [mg/kg], respectively. However, the concentration of NO_3^-, PO_4^{-2}, and K^+ was observed to be <0.3 [mg/kg], <0.3 [mg/kg], and 18 ± 15 [mg/kg], respectively, in raw sewage **(Table 2** and **Table 3)**. This suggested that the electro-osmotic dragging causes accumulation of ions in the cathodic chamber over time and is the result of active transfer over a continuous feed of low concentration feedstock, whilst accumulating in the cathode half-cell, over 48 hours [10]. For open circuit conditions, diffusion may occur under normal osmotic pressure, as previously reported [10].

3.3 Antimicrobial test

Furthermore, the antimicrobial activity of the catholyte was investigated using agar well diffusion-based culturing methods, where the catholyte was applied in the middle of the microbial agar plate to check their inhibition properties against anolyte (mixed microbial source from sewage). The inhibition zone was determined based on the diameter of the zone of inhibition. It was observed that the catholyte produced in both sewage-fed and synthetic urine-FEC MFCs had inhibitory effects, against the mixed microbial population **(Fig. 6)**. The zones of inhibition were observed to have an average diameter of 9.2 mm, 8.5 mm, and 8.3 mm in triplicate agar plates, exposed to antimicrobial dosing, from both sewage and synthetic-urine fed MFC tray catholyte. This is due to the accumulation of highly concentrated anions and cations present in the catholyte, such as Na^+ (1759 ± 3 mg/kg) and Cl^- (618.5 ± 0.3 mg/kg), Ca^{2+} **(**95 ± 14 mg/kg), SO_4^{2-} **(**101 ± 1 mg/kg), make it highly saline **(Table 2** and **Table 3)**. In addition, the catholyte pH of both sewage-fed MFCs and synthetic urine-FEC MFCs was nearly 10.3 and 9.6, respectively. These properties inhibit most native microbial species from growing, as they are not usually halophilic or alkaliphilic. The antimicrobial properties of the catholyte samples collected in this study are due to the simultaneous effect of high salinity and pH, as reported in previous investigations [10,15,26]. In previous studies, catholyte diluted with water up to 1:10 could still inhibit human pathogens, i.e., *Salmonella typhimurium* (5 log-fold reductions in 4 min), and kept inhibiting pathogen growth for 10 days signifying its long-term inhibition effect on pathogens [8]. Similarly, catholyte from human urine-fed ceramic MFCs (10 mm height) reached a pH of 11.0 on day 42 of operation and inhibited *E. coli* [11].

It was previously shown that the catholyte from urine fed-MFC had antimicrobial properties against a wide range of human pathogens, i.e., *Salmonella typhimurium*, *Salmonella enterica*, *E. Coli*, and *Hepatitis B virus* [8,26–28]. In general, gram-positive bacteria are more sensitive to salt than gram-negative bacteria as they have a thicker peptidoglycan cell wall that is more permeable to ions, including salt, making them more susceptible to its effects. However, earlier investigation on catholyte shows antimicrobial properties against both gram-positive (*Staphylococcus aureus*) and gram-negative (*Salmonella enteritidis* serovar Typhimurium (S. Typhimurium) and *Pseudomonas aeruginosa*) bacterial species [12]. Also, in previous studies, it was noted that the catholyte from human urine-fed MFCs was highly effective against human pathogens even during a prolonged 10-day incubation period, and the inhibitory effect on the bacteria was reversible [8,26]. Therefore, the antimicrobial effect of the catholyte from sewage-fed MFC can be utilised to combat plant pathogens and protect plants in hydroponic and soil-based farming, which will form part of our future research in this area. A preview of our ongoing microbial-hydroponic is shown in **Fig. S1** and **Supplementary data S1**, establishing that the catholyte is suitable for growing basil plants in hydroponic.

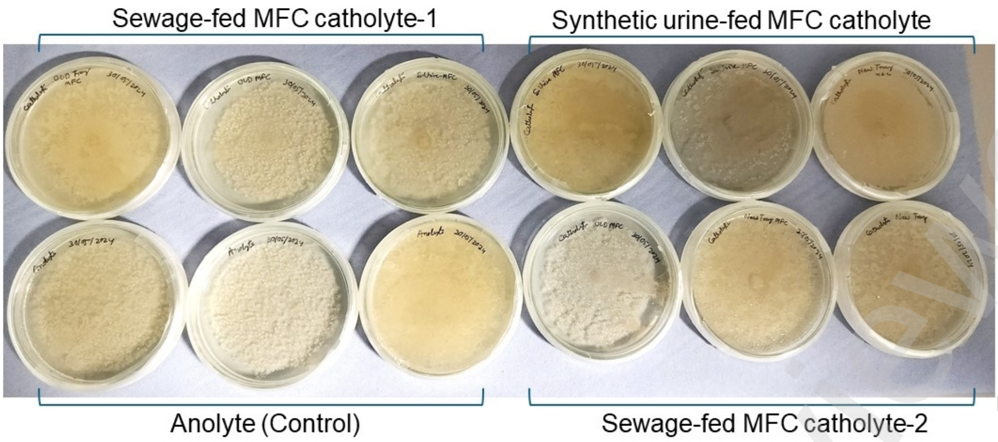

Fig.6. Antimicrobial activity test of catholyte from MFC trays. Catholyte-1 (from tray-1) and catholyte-2 (from tray-2) were applied to anolyte (as mixed microbial sources) of the same MFC in triplicate nutrient agar plates. The inhibition zones were measured after 24h of incubation period.

Table 2: Cation present in the catholyte samples

Sample	**Na^+ [mg/kg]**	**NH_4^+ [mg/kg]**	**K^+ [mg/kg]**	**Ca^{+2} [mg/kg]**	**Mg^{+2} [mg/kg]**
Raw Sewage	314 ± 3	<0.5	18 ± 15	85 ± 4	28 ± 12
Catholyte sewage-fed MFC	1759 ± 3	<0.5	95 ± 14	23 ± 4	<0.2
Synthetic urine	684 ± 2	<0.5	400 ± 13	117 ± 4	<0.2
Catholyte synthetic urine-fed MFC	2827 ± 3	<0.5	395 ± 14	39 ± 4	16 ± 11

Table 3: Anions present in the catholyte samples

Sample	**F^- [mg/kg]**	**Cl^- [mg/kg]**	**NO_2^- [mg/kg]**	**NO_3^- [mg/kg]**	**PO_4^{-2} [mg/kg]**	**SO_4^{-2} [mg/kg]**
Raw sewage	<0.08	480.5 ± 0.3	<0.8	<0.3	<0.3	77 ± 1
Catholyte sewage-fed MFC	<0.08	618.5 ± 0.3	<0.8	25 ± 1	9 ± 3	101 ± 1
Synthetic urine	53 ± 0.5	36.9 ± 0.3	<0.8	9.1 ± 0.9	189 ± 2	102 ± 1
Catholyte synthetic urine-fed MFC	2.5 ± 0.5	50.7 ± 0.3	<0.8	<0.3	11 ± 3	4201 ± 1

All results are reported in mg/kg. The limit of detection (LODs) values is reported as ("<" values) for different ions.

Notably, in the context of wastewater treatment efficiency, ~ 48 % of treated water (in the form of neat catholyte) was recovered from untreated sewage within 48 h using ceramic MFC trays (total surface area of 20 ceramic modules ~ 0.042 m^2), which might increase with optimum design. Therefore, the performance of the Tray MFC was quite decent compared to earlier investigations using ceramic membrane technology under high-pressure driven mechanisms for wastewater treatment, with a rate of treated water recovery of 6-30 L/m^2 h [25]. Ceramic membrane-based technology with different pore sizes is becoming popular in developed countries like the USA, UK, Japan, and Singapore for removing suspended particles, viruses, and bacteria from wastewater [25]. Therefore, the production of catholyte in a ceramic MFC through an electroosmotic-driven mechanism demonstrated in this study could be a suitable option for wastewater treatment along with nutrient recovery without the need for disinfection or electricity consumption.

4. Conclusion

In this investigation, ceramic MFCs were scaled up to produce electricity and liquid fertiliser from sewage. Maximum power was 19.1 mW and 14.9 for sewage-fed MFC tray-1 and MFC tray-2, respectively. Therefore, each MFC unit in both trays achieved a power of ca. 0.85 mW when sewage was used. This power output can also be optimised using smaller MFCs with optimum design to achieve a minimum power of 1.0 mW from small MFC units, which is our main objective. The catholyte obtained in the ceramic MFCs was rich in nitrogen, phosphate, and potassium along with other ions, including sodium and sulphate. Also, the catholyte has antimicrobial properties due to its high salinity and high pH (~10.3). Furthermore, as part of a preliminary study in this line of experiments, the catholyte was also used in hydroponics along with Sonneveld's plant nutrient solution (1:1) and successfully grew basil plants (*Ocimum Basilicum*). Therefore, future research could be focused on stacking multiple ceramic MFC trays that can power the LEDs and pumps used in hydroponics, whilst using the catholyte as liquid fertiliser, enabling the development of self-powered hydroponic systems. Therefore, the integrated MFC-hydroponic system could facilitate nutrient and energy recovery from sewage, offering a promising solution for simultaneously sewage management, remote electricity production and urban farming.

CRediT authorship contribution statement

Dibyojjyoty Nath: wrote the draft, designed and performed the MFC tray experiments, and analyzed the data. **Yannis Ieropoulos:** conceived the idea of miniaturization, designed, supervised the experiments, project administration, funding acquisition. All the authors played active roles in analysing the results and finalising the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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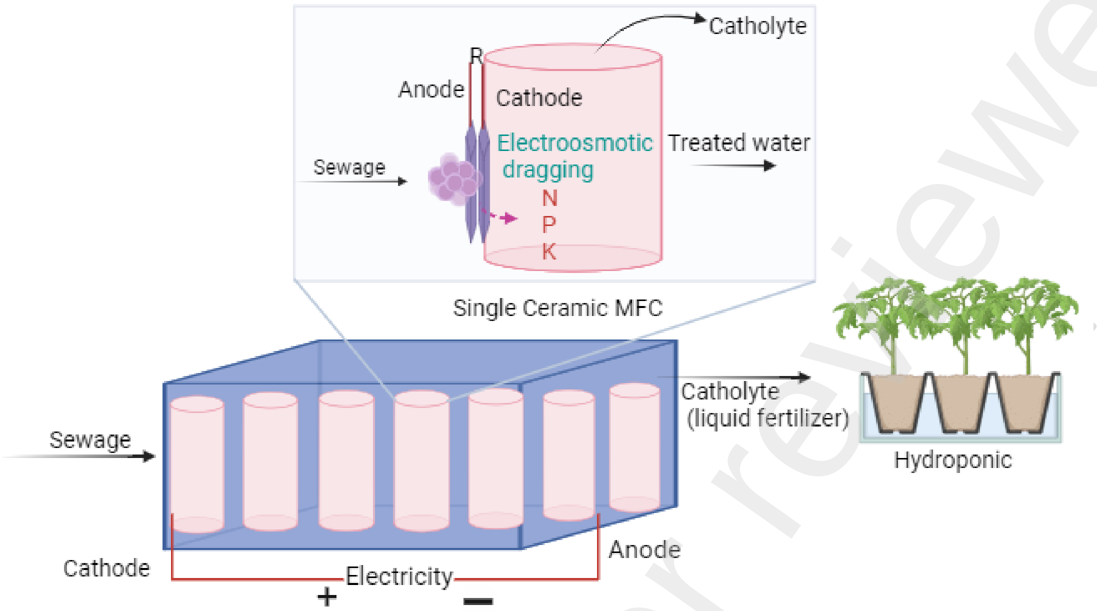
Graphical Abstract:



Supplementary data:

Supplementary data S1:

Sewage-fed catholyte (50%) from MFC trays, along with Sonneveld's plant nutrient solution (50%), is the mixed together and also used in hydroponics for growing basil plants, i.e., *Ocimum Basilicum* **(Fig. S1)**. The basil plants were grown well in hydroponics, and this is the first investigation that shows the utilisation of nutrient-rich catholyte synthesised from sewage for application in hydroponics. The percentages of sewage-fed catholyte used in hydroponics also needs to be optimised to obtain better plant growth. Besides that, high salt concentrations and Na^+ and SO_4^{-2} ions might be toxic to some plants. However, the high salt concentration in sewage-fed catholyte is diluted when mixed with Sonneveld's plant nutrient solution (50%) and used in hydroponics, reducing the negative effect on plant growth. Plants grown in hydroponics, including tomatoes, basil, broccoli, cabbage, and spinach, are mostly salt-tolerant; salt up to a certain concentration (4 to 8% NaCl) in saline soils enhances crop productivity by promoting rhizobacteria such as *Arthrocnemum*, *Pseudomonas, Bacillus*, *Enterobacter*, *Agrobacterium*, *Streptomyces*, *Klebsiella*, and *Ochromobacter* [29]. Therefore, the integration of MFCs and hydroponics could be a cutting-edge circular platform, promoting urban agriculture, effectively merging C, N, and P metabolism in plants with microbial metabolism.

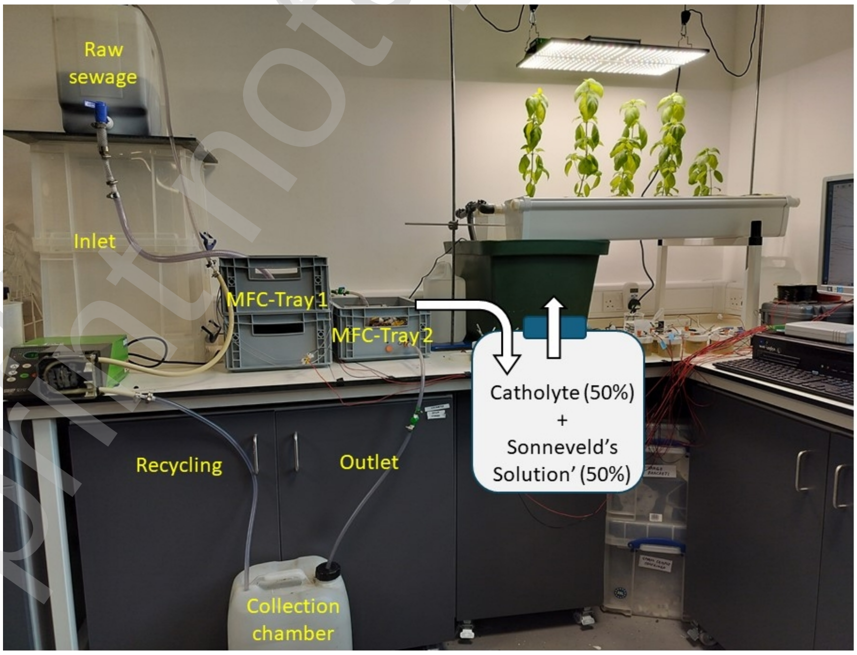


Fig. S1 Catholyte from MFC trays fed with raw sewage and Sonneveld's plant nutrient solution (50%) are mixed and used in hydroponics to grow Basil plants (*Ocimum Basilicum*). All the electrical appliances shown in this picture, including the LEDs, peristaltic pumps, aerators, etc., are powered by mains electricity. This experiment is in progress.