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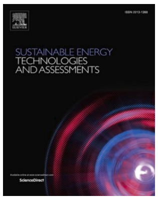

Original article

Microbial fuel cells in the house: A study on real household wastewater samples for treatment and power

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ABSTRACT

In line with the global movement towards sustainable buildings and dwellings, this work investigated the potential for integrating microbial fuel cell technology into future architecture. Various types of domestic greywater and wastewater from five different sources (bathroom, kitchen sink, dishwasher, laundry washing machine and urinal) were tested as feedstock in otherwise identical MFCs. In terms of power output, urine outperformed other feedstock types by producing a maximum power of 3.91 ± 0.27 mW (97.8 ± 6.8 W m^{-3}). The urine-fed MFCs showed a COD removal rate of 38.9 ± 1.1% and coulombic efficiency of 15.1 ± 3.4%. When urine was diluted with either bathwater or tap water, which represents a realistic scenario where flushing toilets are installed, results showed that MFC power output decreased with increasing dilutions. Interestingly, when commercial bleach was added in full concentration, although the level of instantaneous power dropped, performance recovered to the previous levels within 48 h after this was replaced with fresh urine. This suggests that the MFC systems are fairly robust and can be resistant to short-term domestic chemical exposure. These novel findings provide a stepping-stone to more sustainable future buildings and cities with fully integreated MFC technology.

Introduction

Traditionally buildings have been constructed to protect us from the elements, and intrusion from outsiders, predatory animals and insects. In modern architecture, the category of dangerous organisms has widened. Thanks to several pioneering scientists including Ignaz Semmelweis, Louis Pasteur, Robert Koch and Elie Metchnikoff [1,2], we now know that certain diseases can be transmitted via microorganisms such as viruses, bacteria and fungi. This discovery was one of the major breakthroughs in human history that has improved human health and life expectancy, significantly and could not have been more timely than now, when the whole world is still fighting against COVID. However, this has also contributed to the modern misconception about bacteria, whereby bacteria are often associated with the three D's: dirt, disease and death. Consequently, our living spaces have followed a path of moving away from microbes. Yet, the majority of bacteria are harmless, with many being actually beneficial [3]. In fact, our bodies are home to millions of beneficial bacteria [4–7]. This kind of negative perception, separating humans from their surroundings and looking at these as two separate entities, resulted in society largely overlooking the benefits arising from the positive interactions between them.

The "Living Architecture" project set out to address the question of what our future living spaces, and consequently societies, could be like and looked into how future homes and cities could be developed using a 'living technology' such as microbial fuel cells (MFCs). The transition towards more sustainable buildings and dwellings to reduce our negative impact on the environment has been rapidly moving forward [8,9]. For energy and ecological conservation, the sustainable architecture should take a holistic approach throughout the entire building process including design, material selection, procurement, construction and operation. Furthermore, harmonisation with the surroundings by establishing sustainable interactions cannot be overlooked. Living Architecture suggests that our future habits should harmonise with other living organisms, by directly incorporating living systems into building materials, technologies and methods, which can also be used for on-site wastewater treatment, energy generation and resource recovery [10].

Microbial fuel cells (MFC) is an emerging renewable technology, which exploits microbial metabolism to produce electricity. Unlike other 'classic' chemical fuel cells, this biological fuel cell can operate at ambient (15–30 °C) temperatures, with the exception of a few cases utilising extremophilic bacteria [11,12]. Another distinct difference of an MFC compared to chemical fuel cells, is its feedstock. Whereas most

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chemical fuel cells operate with refined, processed fuel such as hydrogen and methanol, mixed microbial communities in the electroactive biofilms in MFCs can utilise a wide range of substrates, from laboratory bacterial growth media to various solid/liquid organic wastes. When utilising organic waste as MFC feedstock, the waste becomes cleaner (treated) as a result of bacterial consumption of the organic fraction contained within. This dual-utility aspect, i.e. simultaneous energy generation and waste treatment, is one of the competitive advantages of the technology. With technological advancement, recently several successful pilot projects of large-scale systems (total reactor volume of over 90 L) have been reported [13–16].

As shown in a previous study investigating the feasibility of integration of the MFC technology and buildings [17], the paradigm shift for conventional building concepts from energy consumer to environmentally sustainable energy provider is very fascinating and definitely worth pursuing. However, this avenue of work has not been much explored yet. Ye *et al.* presented one example of potential domestic MFC systems, which is an MFC stack integrated into a kitchen sink drain pipe [18]. A stack of 5 MFCs produced a peak power of 45.74 ± 1.39 mW (25.9 W m^{-3}, normalised by the anodic volume) from synthetic wastewater and 11.58 ± 0.67 mW (6.5 W m^{-3}) from real wastewater. In that study, high temperature of wastewater (above 60 °C) was suggested as a potential risk for domestic MFC systems.

The present study was set to make further steps towards sustainable future cities and societies by exploring how MFCs can be integrated in building contexts and what needs to be considered. The work consists of three parts; (1) different types of real household greywater as well as human urine were tested as feedstock in MFCs in order to investigate where MFCs can be integrated within residential buildings in the future, (2) on the assumption that MFCs are operated with toilet flush (only urine at this stage), the effect of dilution rate on MFC power output was examined, (3) domestic cleaning products, which usually contain harsh/harmful chemicals for microorganisms, were tested in order to assess the resilience and limitations of MFC systems within the domestic environment. To the best of the Authors' knowledge, there are no previous studies looking into source separated real greywater or domestic cleaning products tested in MFCs. Therefore, findings from this work are expected to contribute towards building sustainable future homes.

This study is part of the Living Architecture project, which investigates the integration of innovative biotechnologies into the 'fabric' of buildings, to render these into self-sustainable habitats; further information can be found on the project website (https://livingarchitecture-h2020.eu).

Materials and methods

Microbial fuel cell design, inoculation and operation

For this study, a total of six cylindrical ceramic MFCs were built. Anode electrodes were made from plain carbon fibre veil (20 g m^{-2} carbon loading, PRF Composite Materials Poole, Dorset, UK) modified with activated carbon ink [19]. Each anode electrode had a macro surface area of 270 cm^2 (30 × 9 cm). This anode sheet was folded to fit inside a 9 cm-long ceramic cylinder (internal diameter 24 mm, thickness 2 mm) which was used both as a membrane and as an anode chamber. The ceramic cylinder was custom-made using a mixture of a plastic clay and 25 % chamotte (product no.: 366, Georg & Schneider, Siershahn, Germany) and fired at 960 °C for 20 min, at a rate of 150 °C h^{-1}. After placing the anode, the remaining displacement anolyte volume was 40 mL. Detailed information about the manufacturing process and properties of the ceramic are described in a previous study [20]. An open-to-air cathode made of hot-pressed activated carbon onto the plain carbon veil [17] (the same base material as the anode) was wrapped outside of the ceramic separator. The total macro surface area of the cathode was 64 cm^2 (8 × 8 cm). The schematic diagram of MFC design used in this study is shown in Fig. 1.

Anaerobic activated sewage sludge , collected from the local wastewater treatment plant (Wessex Water, Saltford, UK) was used to inoculate the MFCs, after being enriched with 1% tryptone and 0.5% yeast extract. Following the inoculation, MFCs were fed continuously (unless stated) with the subject feedstock at a flow rate of 0.35 L d^{-1} (hydraulic retention time: 2.74 h), using a multi-channel peristaltic pump (205U, Watson-Marlow Ltd., Falmouth, UK).

Throughout the work, variable external loads ranged between 50 and 100 Ω were connected to each MFC, which were determined based on polarisation runs that were carried out periodically. All MFCs were operated for 150 days. All tests were performed in triplicates in a temperature-controlled environment, at 22 ± 2 °C.

Feedstock: Household greywater and urine

Various types of real domestic greywater and wastewater from five different sources (bathroom, kitchen sink, dishwasher, washing machine and urinal) were tested as MFC feedstock. Greywater was collected from

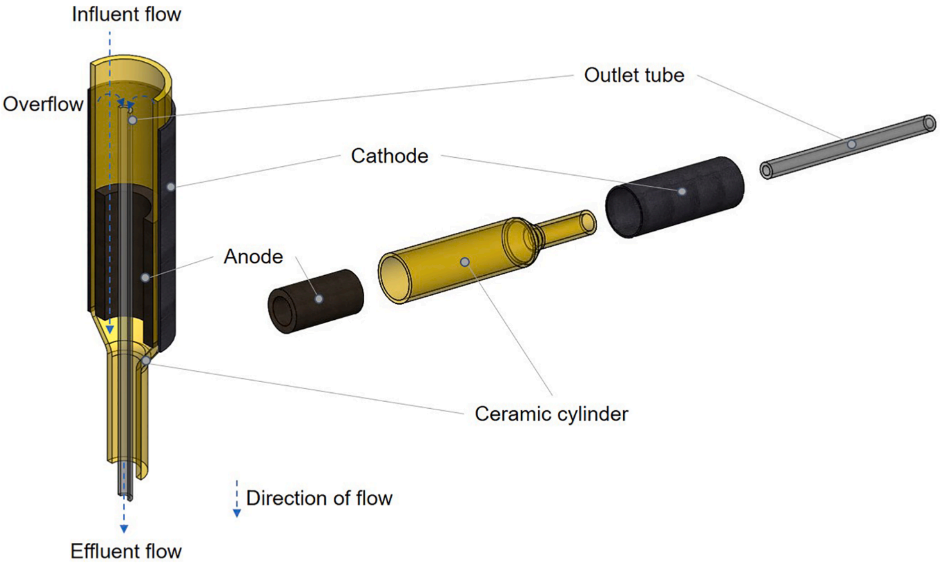

Fig. 1. Assembly diagram of an MFC reactor used in the study.

two households with no dietary restrictions. Neat human urine was donated from consenting adults, with no known health conditions and pooled before testing. Feedstocks were collected a day before the tests. Table 1 shows chemical properties of the tested feedstocks, which were measured on the days of testing.

Changes in pH, conductivity and COD between influent and effluent were measured with a 24-hour interval, which was sufficient to see stable power output levels from MFCs fed with the tested feedstocks.

Harsh domestic chemical exposure

For this line of work, two commonly used house-cleaning products, i.e. bleach and toilet cleaner (both products made in the UK, available from mainstream supermarkets; specific product information can be provided upon request) were chosen. The chemicals were diluted with tap water following the manufacturers' instructions for use. Solution conductivity and pH of the diluted cleaning products were 6.55 mS cm^{-1} and 11.73 for bleach and 0.77 mS cm^{-1} and 7.22 for toilet cleaner. For the test, the feedstock supply to two MFCs was stopped and simply switched to the test cleaning product at the same flow rate of 0.35 L day^{-1}. Exposure time for MFCs to the chemicals was 18 h and 7 h for bleach and toilet cleaner, respectively. During this period, there was no additional carbon source provided.

Polarisation test, data capture and calculation

For polarisation experiments, various external resistances ranged from 38 kΩ to 4 Ω were loaded every 5 min and the potential between the anode and cathode was recorded every 30 s. MFCs were left open circuit for at least 3 h before the test to reach stable open circuit voltages (OCVs). Power output of the MFCs was monitored in real time in volts (V) against time using a multi-channel Agilent 34972A DAQ unit (Agilent Technologies, California, USA) every 5 min. Power density is normalised by the anode liquid volume of 40 mL. Coulombic efficiency (CE) was calculated using the following equation [21];

$$CE_{cont} = \frac{MI}{FbQ\Delta COD}$$

where M is the molecular weight of oxygen (32), I is current generated under steady conditions, F is Faraday's constant, b is the number of electrons exchanged per mole of oxygen (4), Q is the volumetric influent flow rate, and ΔCOD is the difference in the influent and effluent COD.

Another MFC performance metric suggested by He [22,23], normalised energy recovery (NER) was also calculated. The NER can be expressed in two ways. The power is normalised either by the flow rate to the energy produced per volume treated (kWh m^{-3}), or by the flow rate and ΔCOD to reflect the energy produced per amount of COD degraded (kWh (kg COD) $^{-1}$). NER is calculated as follows;

$$NER = \frac{P}{Q}$$

$$NER = \frac{P}{Q\Delta COD}$$

where P is the power (W), Q and ΔCOD are the same as the above.

Water sample analysis

The pH and conductivity of the water samples were measured using a pH meter (pH 209, Hanna Instruments, UK) and conductivity meter (470 Cond Meter, Jenway, UK). For measuring chemical oxygen demand (COD), water samples were filtered through 0.45 μm pore size membranes (Millex, USA) and then immediately analysed according to the American Public Health Association (APHA) standard methods [24].

Results and discussion

Household wastewater for MFCs

Various organic and some inorganic substrates from many different sources have been tested as MFC feedstock. They range from simple low molecular weight substrates such as monosaccharides with added essential minerals and vitamins, to complex high molecular weight wastes such as municipal or industrial wastewater [25–30]. However, real household wastewater has not been studied much previously in MFCs from source-oriented point of view, especially within a building context.

Wastewater generated from residential buildings is divided into two categories; blackwater and greywater. Blackwater is from toilets and can contain faeces, urine, water (for flush toilets) and toilet paper. Greywater comes from all other sources in houses apart from toilets, such as kitchen sinks, baths and washing machines. These are of variable composition depending on number of occupants, age, lifestyle, activities and geographical region [31].

For a scenario where MFCs are integrated into residential buildings, MFC systems could be installed inside or bypassing sewage pipes thus receiving household wastewater directly from different sources. Therefore, real household greywater from different sources as well as human urine were tested in MFCs in the context of household integration.

Figure 2 presents maximum power output obtained from polarisation sweeps and COD reduction rates of MFCs when fed with different types of household wastewater (2nd batch wastewater shown in Table 1). The highest power level of 3.91 ± 0.27 mW (97.8 ± 6.8 W m^{-3}) was produced when urine was used, followed by 0.47 ± 0.12 mW (11.7 ± 2.9 W m^{-3}) from dishwasher effluent. Power curves and performance summary of MFCs fed with each feedstock are presented in Supplementary Materials (Fig. S1 and Table S1). Electrical energy produced per volume treated expressed in NER shows a similar pattern, whereby urine

Table 1
Characteristics of the tested household wastewater.

Household wastewater (per source)	1st batch			2nd batch		
	pH	Conductivity (mS cm^{-1})	COD (mg L^{-1})	pH	Conductivity (mS cm^{-1})	COD (mg L^{-1})
Kitchen sink	6.17	1.21	1,780	6.64	2.21	6,660
Dishwasher	7.22	3.27	2,640	6.98	3.49	3,020
Washing machine	7.25	0.72	180	7.59	0.92	975
Bathtub	7.44	0.72	466	7.81	0.71	810
Toilet (urine only)	9.40	33.8	5,410	9.22	30.0	6,530

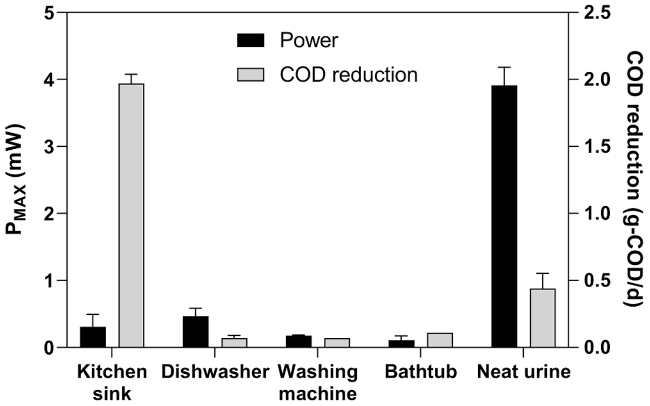

Fig. 2. Maximum power output and COD reduction with different types of household wastewater. Data presented are from MFC triplicates (n = 3).

produced the highest of 0.1992 ± 0.0330 kWh m^{-3} followed by dishwasher effluent (0.0195 ± 0.0041 kWh m^{-3}) and kitchen sink greywater (0.0185 ± 0.0031 kWh m^{-3}). During the same period, the external resistance value for urine fed MFCs was 50 Ω, and 100 Ω for both dishwater and kitchen sink greywater fed MFCs. The organic content of the feedstock, measured in COD, did not directly correspond to power output, since dishwasher greywater (COD of 3,020 mg L^{-1}) was the 3rd highest after the kitchen sink greywater (6,660 mg L^{-1}) and urine (6,530 mg L^{-1}). This demonstrates that the carbon content of these types of feedstock is not directly bio-available for anodic bacterial utilisation. The kitchen sink greywater showed the highest COD removal efficiency of 84.6 ± 3.0 % (COD removal capacity: 1.97 ± 0.07 g d^{-1}), but the lowest coulombic efficiency of 0.6 ± 0.2 %. On the other hand, urine-fed MFCs which reduced COD by 38.9 ± 1.1 % (COD removal capacity: 0.44 ± 0.11 g d^{-1}), showed higher coulombic efficiency of 15.1 ± 3.4 %. Similarly, urine produced the largest energy per amount of COD degraded (0.1655 ± 0.0270 kWh (kg COD)$^{-1}$) whereas kitchen sink effluent produced the lowest energy of 0.0025 ± 0.0013 kWh (kg COD)$^{-1}$. This could mean that the majority of organic matter in the greywater originating from the kitchen sink, was consumed by organisms other than anodophiles. Kitchen sink greywater could contain dish washing detergents, oil, fats, food residue, raw meat washing, fruit and vegetable peels, tea or coffee, traces of food preservatives, amongst other substances [31]. Therefore, it was assumed that the higher COD of the kitchen sink greywater perhaps contained a higher concentration of complex organic matter for anodophiles to utilise, compared to the dishwasher greywater. Although only individual MFC units were used for this study, the final MFC systems in residential buildings are most likely to be scaled up through stacking and cascading [32,33]. In that case, MFC cascades could be sequentially treating these complex substrates, which would add high value to the treatment and electricity generation processes in a household environment [34].

Although it was not visible, precipitation of large and heavy organic particles inside MFCs might be another reason for high COD reduction of kitchen sink greywater. This could lead to clogging of MFC systems in the long term. Therefore, pre-treatment stages such as screening or settling will be needed when MFC systems receive kitchen wastewater.

Another parameter of MFC substrate affecting the power output is salinity. As Lefebvre *et al.* reported, higher salinity (up to 20 g L^{-1}) of MFC feedstock benefits power generation due to higher conductivity of the solution [35]. Solution conductivity of neat human urine used in this study measured the highest value of 30 mS cm^{-1}, which could be one of the reasons explaining why urine is a favourable feedstock for the MFC power generation. This high solution conductivity is beneficial for ion transport by reducing the electrolyte ohmic losses. This could explain the higher power output from dishwasher greywater despite the lower organic content (3,020 mg L^{-1} COD) in comparison to kitchen sink greywater (6,660 mg L^{-1} COD). In this case, dishwasher salt added for example to dishwasher units could enhance the MFC power output (measured solution conductivity of dishwasher greywater: 3.49 mS cm^{-1}, compared to 2.21 mS cm^{-1} of kitchen sink greywater).

Overall, among the real household wastewater types tested, neat urine yielded the highest power. In addition to the high solution conductivity, its higher pH compared to other types of wastewater is considered beneficial for the anode oxidation kinetics.

It should be noted that the tested domestic wastewater was generated as a result of normal daily life and each feedstock varied significantly in terms of composition and concentration as shown in Table 1. This considerable variance inevitably resulted in large differences in levels of power output between batches. Also generation of household greywater or human urine in building contexts are usually intermittent and the amount changes throughout the day. For a stable and consistent level of electricity output, therefore, within a domestic context, where MFCs are fully integrated, pooling or mixing with other greywater types prior to feeding into MFC systems can be considered. Efficient energy storage technologies for intermittent use, will also be needed and this is where future efforts should be focussing to avoid using batteries. In order to maintain the performance of the anodic biofilms under an irregular feeding condition, management of power and electrochemically active bacterial cells with the help of electronics and artificial intelligence [36,37] is already showing promise.

Diluted urine for MFCs

Since urine is the most favourable feedstock among residential building wastewater streams in terms of MFC power generation, the next set of tests was carried out based on a scenario where an MFC system receives wastewater from a toilet. Although toilet wastewater can contain excrement and other solid waste such as toilet paper, due to practical reasons, only urine was tested in this study. Thus, this section deals with toilet wastewater containing urine and flush water only, not typical blackwater that includes faeces, urine, water and toilet paper.

Figure 3 shows power output of urine-fed MFCs in relation to dilution of the feedstock dilution. When urine was diluted with either bathtub water or tap water before being fed to MFCs, MFC power output decreased with increasing dilutions. The highest power output of 2.80 ± 0.31 mW (70.0 ± 11.0 W m^{-3}) was produced from undiluted human urine. When urine was diluted by a factor of two, power decreased by 29–34% (2.00 ± 0.18 mW and 1.83 ± 0.17 mW for tap water and bathtub greywater as diluent respectively). Overall, there was no significant difference observed between the two diluents, tap water and bathtub greywater.

The current EU guidelines recommend the maximum full flush volume of 6 L per flush, and 3 L per flush for water-saving toilets [38]. Given that the typical amount of urine excrement is between 300 and 500 mL for adults [39,40], normally urine would be diluted with flushing water by 6–20 times. Based on the results shown here, the dilution of urine will reduce the MFC power output by 80–95 % (dilution ratio from 5 to 15-fold). This can decrease further since the dilution rate can be even greater for lower excrement volumes or for less efficient water use toilets. Therefore, unless a change of the current water-flushing toilet systems is effected, it is expected that power generation from toilets of residential buildings would be significantly lower compared to the case of using neat urine directly.

In many developed countries with modern sewage systems, water-flushing toilets are the most common type and is considered as a desired sanitary system [41]. For most cases, toilet flushing water quality isequivalent to tap water, which requires vast amounts of energy to produce. In the UK, flushing toilets accounts for 22% of household water consumption, which is equivalent to 740 billion litres per year nationally [42]. This conventional “flush-and-discharge” model not only wastes clean water, but also increases the difficulties of the sewage treatment. A typical secondary sewage treatment plant consumes about

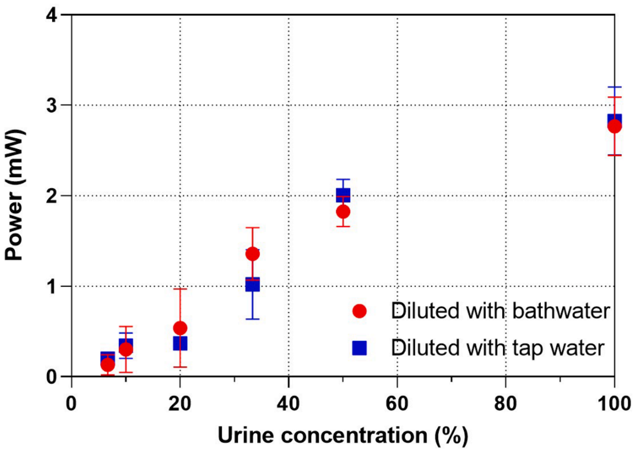

Fig. 3. Power output change with diluted urine as a feedstock (n = 3).

0.6 kWh m^{-3} for treating wastewater [43]. Furthermore, the energy required for conveyance is several times more than that for treatment [44]. Consequently, with increasing awareness of inefficiency of the current water-flushing toilet systems in terms of energy and resource use, there is ongoing effort towards alternative sanitation model, e.g. ecological sanitation (Eco-San). This alternative approach is based on sustainable ecosystem principles and the closure of material flow cycles [45,46]. These include waterless toilets, vacuum toilets and urine diversion. Within the initiative, especially urine has drawn a great deal of attention as a resource due to its high nutrient content and relatively low risk for handling. As the results show here, urine has another great potential as fuel for electricity generation using MFCs, and higher power output can be achieved with less dilution. Therefore, urine diversion systems with no water or much less water requirements to create a concentrated stream is definitely worth pursuing. Additionally, the remaining household greywater streams, which are relatively clean, can be used for toilet flushing after minimum treatment.

Resilience of MFC biofilms to household cleaning products

A key aspect to be considered for integration of the MFC technology into residential buildings is resilience of MFC biofilms, since a number of anti-bacterial cleaning products are being used on a daily basis. A case study carried out in Copenhagen, Denmark revealed that greywater is commonly overloaded with various household chemical products (e.g. 40 g per person in a week) containing high concentrations of surfactants and xenobiotic organic compounds [47]. When these domestic cleaning products enter MFC systems installed in buildings, this might bring a detrimental effect on the system performance. In order to investigate this aspect, two off-the-shelf consumer-cleaning products (bleach and toilet cleaner) were directly added to the MFCs, and the response was monitored.

As shown in Fig. 4, the level of instantaneous power dropped, but only in some cases. For bleach, after 18 h of exposure, power output levels of both MFCs dropped from 3.11 mW and 2.23 mW to 1.72 mW and 1.50 mW respectively, which are 44.7 % and 33.4 % reduction. The decline of power output was consistent during the chemical exposure. When the supply of bleach stopped and urine restarted, the MFCs responded quickly. The power performance of both MFCs recovered to the same levels within 48 h after fresh urine was supplied. In the case of the toilet cleaner, after 7 h of exposure, there was no visible power decline for either MFC. And power output remained at the same levels when urine was resupplied. These results demonstrate that MFC systems can be resilient to domestic cleaning products, which is in agreement with biofilm theory and microbiology literature that reports biofilms being much more resistant to perturbation compared to planktonic communities [48–52].

Conclusions

In this study, possibilities of the MFC technology integration into residential buildings were explored. Household greywater and wastewater vary between batches in terms of composition and concentration, which leads to variance in the MFC performance. For a stable and consistent level of electricity output, pooling of different waste streams prior to supplying to MFC systems can be an option to consider. This can also be achieved through power management including energy storage, and sustainable bacterial cell management with other technologies such as electronics, material science and artificial intelligence. Although MFC systems provide a good alternative for on-site waste treatment, which normally requires external energy input, power generation from MFC systems alone might not be sufficient for meeting the total energy demand of a whole building. Therefore smart approaches are needed such as integrating different renewable energy generation technologies in a smart/micro grid manner to deliver constant power output on-demand, whilst normalising for variance in input; this canalso lead to further synergies [53,54].

Some waste streams such as bathwater or washing machine effluent that have low organic content, thus low MFC power output, could be used for toilet flushing which would be mixed with the favorable MFC substrate, urine, although dilution of urine reduces the level of electricity generation. Lastly, MFC systems in a domestic context seem robust enough with short-term exposure to some of the harsh chemicals. These novel findings provide a stepping-stone to more sustainable future buildings and cities with the MFC technology fully integrated.

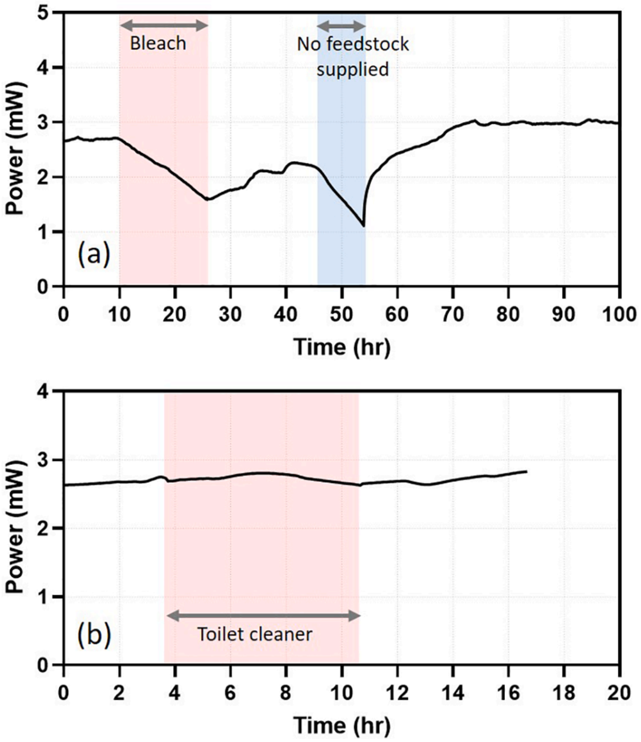

Fig. 4. MFC behaviour during and after experiencing harsh domestic chemicals; bleach (a) and toilet cleaner (b). The sections in pink indicate the period of MFC exposure to the subjected cleaning products, the area in blue shows when there was no feedstock supply. Data points are average values of 2 MFCs.

CRediT authorship contribution statement

Jiseon You: Investigation, Writing – original draft, Project administration. **John Greenman:** Writing - review & editing, Funding acquisition. **Ioannis A. Ieropoulos:** Conceptualization, Writing - review & editing, Funding acquisition.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2021.101618.

References

[1] Faintuch J, Faintuch S. Microbiome and metabolome in diagnosis, therapy, and other strategic applications. Academic Press; 2019.

[2] Blevins SM, Bronze MS. Robert Koch and the “golden age” of bacteriology. Int J Infect Dis 2010;14(9):e744–51. https://doi.org/10.1016/j.ijid.2009.12.003.

[3] Zhou Q, Li K, Jun X, Bo L. Role and functions of beneficial microorganisms in sustainable aquaculture. Bioresour Technol 2009;100(16):3780–6. https://doi.org/10.1016/j.biortech.2008.12.037.

[4] Cogen AL, Nizet V, Gallo RL. Skin microbiota: a source of disease or defence? Br J Dermatol 2008;158:442–55. https://doi.org/10.1111/j.1365-2133.2008.08437.x.

[5] Relman DA. Microbiology: learning about who we are. Nature 2012;486(7402):194–5. https://doi.org/10.1038/486194a.

[6] Rowland I, Gibson G, Heinken A, Scott K, Swann J, Thiele I, et al. Gut microbiota functions: metabolism of nutrients and other food components. Eur J Nutr 2018;57(1):1–24. https://doi.org/10.1007/s00394-017-1445-8.

[7] Collins SL, Patterson AD. The gut microbiome: an orchestrator of xenobiotic metabolism. Acta Pharm Sin B 2020;10(1):19–32. https://doi.org/10.1016/j.apsb.2019.12.001.

[8] Omer MAB, Noguchi T. A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs). Sustain Cities Soc 2020;52:101869. https://doi.org/10.1016/j.scs.2019.101869.

[9] Munaro MR, Tavares SF, Bragança L. Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment. J Clean Prod 2020;260:121134. https://doi.org/10.1016/j.jclepro.2020.121134.

[10] LIAR Consortium. Living Architecture – transform our habitats from inert spaces into programmable sites. Living Archit Webpage 2016. https://livingarchitecture-h2020.eu/ (accessed September 10, 2019).

[11] Larrosa-Guerrero A, Scott K, Head IM, Mateo F, Ginesta A, Godinez C. Effect of temperature on the performance of microbial fuel cells. Fuel 2010;89(12):3985–94. https://doi.org/10.1016/j.fuel.2010.06.025.

[12] Patil SA, Harnisch F, Kapadnis B, Schröder U. Electroactive mixed culture biofilms in microbial bioelectrochemical systems: The role of temperature for biofilm formation and performance. Biosens Bioelectron 2010;26(2):803–8. https://doi.org/10.1016/j.bios.2010.06.019.

[13] Ge Z, He Z. Long-term performance of a 200 liter modularized microbial fuel cell system treating municipal wastewater: treatment, energy, and cost. Environ Sci Water Res Technol 2016;2(2):274–81. https://doi.org/10.1039/C6EW00020G.

[14] Liang P, Duan R, Jiang Y, Zhang X, Qiu Y, Huang X. One-year operation of 1000-L modularized microbial fuel cell for municipal wastewater treatment. Water Res 2018;141:1–8. https://doi.org/10.1016/j.watres.2018.04.066.

[15] Walter XA, Merino-Jiménez I, Greenman J, Ieropoulos I. PEE POWER® urinal II – Urinal scale-up with microbial fuel cell scale-down for improved lighting. J Power Sources 2018;392:150–8. https://doi.org/10.1016/J.JPOWSOUR.2018.02.047.

[16] Goto Y, Yoshida N. Scaling up microbial fuel cells for treating swine wastewater. Water 2019;11:1803. https://doi.org/10.3390/w11091803.

[17] You J, Rimbu GA, Wallis L, Greenman J, Ieropoulos I. Living architecture: toward energy generating buildings powered by microbial fuel cells. Front Energy Res 2019;7:94. https://doi.org/10.3389/fenrg.2019.00094.

[18] Ye D, Deng B, Li J, Zou W, Ke C, Yuan Z, et al. Electricity production of a microbial fuel cell stack integrated into a sink drain pipe. Res Chem Intermed 2016;42(11):7689–700. https://doi.org/10.1007/s11164-016-2654-0.

[19] Gajda I, You J, Santoro C, Greenman J, Ieropoulos IA. A new method for urine electrofiltration and long term power enhancement using surface modified anodes with activated carbon in ceramic microbial fuel cells. Electrochim Acta 2020:136388. doi:10.1016/j.electacta.2020.136388.

[20] You J, Wallis L, Radisavljevic N, Pasternak G, Sglavo VM, Hanczyc MM, et al. A comprehensive study of custom-made ceramic separators for microbial fuel cells: towards “living” bricks. Energies 2019;12(21):4071. https://doi.org/10.3390/en12214071.

[21] Logan BE, Hamelers B, Rozendal R, Schröder U, Keller J, Freguia S, et al. Microbial fuel cells: methodology and technology. Environ Sci Technol 2006;40:5181–92. https://doi.org/10.1021/es0605016.

[22] He Z. Microbial fuel cells: now let us talk about energy. Environ Sci Technol 2013;47(1):332–3. https://doi.org/10.1021/es304937e.

[23] He Z. Development of microbial fuel cells needs to go beyond “power density”. ACS Energy Lett 2017;2(3):700–2. https://doi.org/10.1021/acsenergylett.7b00041.

[24] Association APH. Standard methods for the examination of water and wastewater. 20th ed. Washington, DC: American Public Health Association; 1998.

[25] Liu H, Cheng S, Logan BE. Production of electricity from acetate or butyrate using a single-chamber microbial fuel cell. Environ Sci Technol 2005;39(2):658–62.

[26] Jung S, Regan JM. Comparison of anode bacterial communities and performance in microbial fuel cells with different electron donors. Appl Microbiol Biotechnol 2007;77(2):393–402. https://doi.org/10.1007/s00253-007-1162-y.

[27] You J, Walter XA, Greenman J, Melhuish C, Ieropoulos I. Stability and reliability of anodic biofilms under different feedstock conditions: towards microbial fuel cell sensors. Sens Bio-Sensing Res 2015;6:43–50. https://doi.org/10.1016/j.sbsr.2015.11.007.

[28] Pandey P, Shinde VN, Deopurkar RL, Kale SP, Patil SA, Pant D. Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. Appl Energy 2016;168:706–23. https://doi.org/10.1016/j.apenergy.2016.01.056.

[29] Zhang G, Zhao Q, Jiao Y, Wang K, Lee D-J, Ren N. Biocathode microbial fuel cell for efficient electricity recovery from dairy manure. Biosens Bioelectron 2012;31(1):537–43. https://doi.org/10.1016/j.bios.2011.11.036.

[30] Heidrich ES, Dolfing J, Wade MJ, Sloan WT, Quince C, Curtis TP. Temperature, inocula and substrate: contrasting electroactive consortia, diversity and performance in microbial fuel cells. Bioelectrochemistry 2018;119:43–50. https://doi.org/10.1016/j.bioelechem.2017.07.006.

[31] Shaikh IN, Ahammed MM. Quantity and quality characteristics of greywater: a review. J Environ Manage 2020;261:110266. https://doi.org/10.1016/j.jenvman.2020.110266.

[32] Walter XA, Forbes S, Greenman J, Ieropoulos IA. From single MFC to cascade configuration: the relationship between size, hydraulic retention time and power density. Sustain Energy Technol Assessments 2016;14:74–9. https://doi.org/10.1016/j.seta.2016.01.006.

[33] Abdallah M, Feroz S, Alani S, Sayed ET, Shanableh A. Continuous and scalable applications of microbial fuel cells: a critical review. Rev Environ Sci Biotechnol 2019;18(3):543–78. https://doi.org/10.1007/s11157-019-09508-x.

[34] Ledezma P, Greenman J, Ieropoulos I. MFC-cascade stacks maximise COD reduction and avoid voltage reversal under adverse conditions. Bioresour Technol 2013;134:158–65. https://doi.org/10.1016/j.biortech.2013.01.119.

[35] Lefebvre O, Tan Z, Kharkwal S, Ng HY. Effect of increasing anodic NaCl concentration on microbial fuel cell performance. Bioresour Technol 2012;112:336–40. https://doi.org/10.1016/j.biortech.2012.02.048.

[36] Kim T, Yeo J, Yang Y, Kang S, Paek Y, Kwon JK, et al. Boosting voltage without electrochemical degradation using energy-harvesting circuits and power management system-coupled multiple microbial fuel cells. J Power Sources 2019;410-411:171–8. https://doi.org/10.1016/j.jpowsour.2018.11.010.

[37] Jha SK, Bilalovic J, Jha A, Patel N, Zhang H. Renewable energy: present research and future scope of Artificial Intelligence. Renew Sustain Energy Rev 2017;77:297–317. https://doi.org/10.1016/j.rser.2017.04.018.

[38] Genty A, Kowalska M, Wolf O, Institute for Prospective Technological Studies. Development of EU ecolabel and GPP criteria for flushing toilets and urinals - Technical report. Publications Office of the European Union; 2013. doi:10.2791/52507.

[39] Walker-Smith J, Murch S. Diseases of the small intestine in childhood. 4th ed. CRC Press; 1999.

[40] Boron WF, Boulpaep EL. Medical Physiology E-Book. 3rd ed. Elsevier Health Sciences; 2016.

[41] Quitzau M-B. Water-flushing toilets: systemic development and path-dependent characteristics and their bearing on technological alternatives. Technol Soc 2007;29(3):351–60. https://doi.org/10.1016/j.techsoc.2007.04.005.

[42] Energy Saving Trust. At home with water. London: 2013.

[43] McCarty PL, Bae J, Kim J. Domestic wastewater treatment as a net energy producer-can this be achieved? Environ Sci Technol 2011;45(17):7100–6. https://doi.org/10.1021/es2014264.

[44] Englehardt JD, Wu T, Tchobanoglous G. Urban net-zero water treatment and mineralization: Experiments, modeling and design. Water Res 2013;47(13):4680–91. https://doi.org/10.1016/j.watres.2013.05.026.

[45] Langergraber G, Muellegger E. Ecological sanitation - A way to solve global sanitation problems? Environ Int 2005;31(3):433–44. https://doi.org/10.1016/j.envint.2004.08.006.

[46] Hu M, Fan B, Wang H, Qu B, Zhu S. Constructing the ecological sanitation: a review on technology and methods. J Clean Prod 2016;125:1–21. https://doi.org/10.1016/j.jclepro.2016.03.012.

[47] Eriksson E, Auffarth K, Eilersen AM, Henze M, Ledin A. Household chemicals and personal care products as sources for xenobiotic organic compounds in grey wastewater. Water SA 2003;29:135–46. https://doi.org/10.4314/wsa.v29i2.4848.

[48] Kubota H, Senda S, Tokuda H, Uchiyama H, Nomura N. Stress resistance of biofilm and planktonic Lactobacillus plantarum subsp. plantarum JCM 1149. Food Microbiol 2009;26(6):592–7. https://doi.org/10.1016/j.fm.2009.04.001.

[49] Vetas D, Dimitropoulou E, Mitropoulou G, Kourkoutas Y, Giaouris E. Disinfection efficiencies of sage and spearmint essential oils against planktonic and biofilm Staphylococcus aureus cells in comparison with sodium hypochlorite. Int J Food Microbiol 2017;257:19–25. https://doi.org/10.1016/j.ijfoodmicro.2017.06.003.

[50] Barker LK, Giska JR, Radniecki TS, Semprini L. Effects of short- and long-term exposure of silver nanoparticles and silver ions to Nitrosomonas europaea biofilms and planktonic cells. Chemosphere 2018;206:606–14. https://doi.org/10.1016/j.chemosphere.2018.05.017.

[51] Gloag ES, Fabbri S, Wozniak DJ, Stoodley P. Biofilm mechanics: implications in infection and survival. Biofilm 2020;2:100017. https://doi.org/10.1016/j.bioflm.2019.100017.

[52] Patil S, Harnisch F, Schröder U. Toxicity response of electroactive microbial biofilms–a decisive feature for potential biosensor and power source applications. ChemPhysChem 2010;11(13):2834–7. https://doi.org/10.1002/cphc.201000218.

[53] Kwan TH, Katsushi F, Shen Y, Yin S, Zhang Y, Kase K, et al. Comprehensive review of integrating fuel cells to other energy systems for enhanced performance and enabling polygeneration. Renew Sustain Energy Rev 2020;128:109897. https://doi.org/10.1016/j.rser.2020.109897.

[54] Khalil Muhammad Ibrahim, Jhanjhi NZ, Humayun Mamoona, Sivanesan SivaKumar, Masud Mehedi, Shamim Hossain M. Hybrid smart grid with

sustainable energy efficient resources for smart cities. Sustain Energy Technol Assessments 2021;46:101211.