Deployment of the microbial fuel cell latrine in Ghana for decentralized sanitation

Cynthia J. Castro, Joseph E. Goodwill, Brad Rogers, Mark Henderson
and Caitlyn S. Butler

ABSTRACT

A microbial fuel cell (MFC) latrine that treats human waste and produces compost and electricity was deployed in Agona Nyakrom, Ghana. After solid wastes were composted, the MFC treated organic matter and nitrogen from the remaining liquid stream. Organic matter was oxidized in the anode by anode-respiring bacteria that transfer electrons to an external circuit, producing electricity, which was observed to be 268 nW/m^2 after two years of operation. A separate nitrification stage transformed ammonium present in urine, to nitrate. Nitrate was reduced to nitrogen gas by cathode-oxidizing bacteria in the cathode completing nitrogen removal. The MFC latrine was constructed on-site using local labor and materials. Evidence of total nitrogen removal and power production was observed while the MFC latrine was in operation. Multiple user challenges and maintenance affected the performance, yielding low power output. The initial findings suggest that the viability of the system is directly correlated with its use. Incorporating the MFC latrine system into the user community's typical social practices is key to a successful deployment of the MFC latrine as a sanitation technology.

Key words | decentralized treatment, ecological sanitation, latrine, microbial fuel cell, sustainability

Cynthia J. Castro
Joseph E. Goodwill
University of Massachusetts Amherst,
Department of Civil and Environmental Engineering,
18 Marston Hall, 130 Natural Resources Way,
Amherst, MA 01003-9284,
USA

Brad Rogers
Mark Henderson
GlobalResolve,
Department of Engineering,
College of Innovation and Technology,
Arizona State University,
Polytechnic Campus,
Mesa, AZ 85212,
USA

Caitlyn S. Butler (corresponding author)
University of Massachusetts Amherst,
Department of Civil and Environmental Engineering,
16B Marston Hall, 130 Natural Resources Way,
Amherst, MA 01003-9284,
USA
E-mail: *cbutler@ecs.umass.edu*

INTRODUCTION

Less than half of the population in sub-Sahara Africa has access to improved sanitation facilities (World Health Organization/United Nations Children's Fund [WHO/UNICEF] 2013). There is limited access to sanitation facilities in urban environments in the developing world, and that access diminishes as we look towards rural environments. In Ghana, 33% of rural communities still practice open defecation and that value has been increasing over the past 20 years (WHO/UNICEF 2012). Despite relative economic stability, each year, 15,000 children under the age of five still die from diarrheal diseases due to lack of sanitation infrastructure.

While centralized facilities are viable in metropolitan hubs like Accra and Kumasi, many districts in the northern region live in extreme poverty. In the northern regions, 63% of the population lack adequate food and water (Debrah 2013). The most prevalent limitations in this area are food security, access to electricity, and access to clean sources of water and sanitation. For many women finding a private place to relieve themselves is particularly challenging so they wait until the evening. As a consequence, women have been bitten by poisonous snakes (Antwi 2013) or assaulted (Smith 2011). Communities may also be financially unable to make investments in sanitation facilities (Cairncross 2003). Low-cost, decentralized sanitation systems paired with community engagement is a successful way to expand sanitation coverage (Montgomery & Elimelech 2007) in Ghana.

Decentralized sanitation facilities often used in rural areas of developing countries include pit latrines, composting latrines, pour-flush latrines, and flush toilets (Mihelcic *et al.* 2009). Successful implementation of decentralized

doi: 10.2166/washdev.2014.020

systems is often linked with resources recovery from waste. Ecosan-style urine-diverting, dry-composting latrines provide a safe contained environment for excrement disposal and odor control, in addition to human waste compost, providing agricultural benefits as well as minimizing water pollution (Werner *et al.* 2003).

To generate additional resources from waste and eliminate the untreated effluent, our team has developed a microbial fuel cell (MFC) design to couple with composting latrines. MFCs produce electricity directly from the removal of organics and nitrogen in wastewater. Bench-scale MFCs have yielded over 1 kW/m^3 using acetate as a fuel source and diffused oxygen as the terminal electron acceptor in the cathode (Nevin *et al.* 2008). Previous research has shown that a two-chamber MFC can simultaneously remove reduced carbon in the anode and oxidized nitrogen in the cathode using a separate aerobic nitrification stage, sustaining 34.6 W/m^3 (Virdis *et al.* 2008). A membrane-less MFC for total nitrogen removal produced 19 W/m^3 (Butler 2009). These bench-scale MFCs used acetate as their electron donor in the anode, which is easily oxidized by anode-respiring bacteria (ARB).

The focus of current MFC research has been on increasing the power output of bench-scale systems that often requires expensive precious metal catalysts and proton exchange membranes to partition the anode and the cathode. Very little is known about the performance of large-scale MFC systems and their ability to directly treat human waste. Only a few MFCs greater than 10 L have been reported (Logan 2010) and, to the best of our knowledge, no large-scale MFC has used undiluted human waste directly.

A composting latrine and MFC combination (MFC latrine) treating human waste, composting solids and producing electricity is proposed. The MFC latrine eliminates expensive elements of bench-scale designs, reducing construction costs for developing areas. In the gravity-driven, step-feed MFC, the anode and the cathode are hydraulically partitioned, eliminating the need for a membrane. Low-cost, graphite granules serve as electrodes and microorganisms, not platinum-group catalysts. In addition, the microbial communities within this MFC are known to have low growth yield, generating little biomass and reducing maintenance requirements.

Our goal is to develop a technology that will provide a safe method for sanitation as well as providing two incentives for sanitation development in rural Ghana: compost and electricity. Communities deploying MFC latrines could sell compost or access to electricity to fund sustained operation and maintenance, motivating adoption of the technology. The MFC latrine may be advantageous and beneficial in areas where decentralized sanitation is developed through a sanitation-as-a-business model, which is an emerging approach used by aid-organizations (Breslin & Bramley 2010).

This paper will present a case study of the first MFC latrine deployed in Ghana. The primary goals of this project are to (1) demonstrate the first field-operated full scale MFC producing electricity, (2) evaluate the MFC latrine performance and (3) assess the local user interface with this new technology.

METHODS

Support

Our team made two trips to Ghana during this project in May 2012 and May 2013. Deployment of the MFC latrine was executed with significant local support. The Paramount Chief of the Agona Nyakrom region, Nana Bonsu, served as our primary adviser and assisted with site selection, material acquisition and hiring local labor. The Agona Nyakrom Secondary Technical School (NYASTEC) helped with identification of the optimal site on its campus and also operated and maintained the MFC latrine. Data collection was performed by Mary Kay and Charlie Jackson of Pure Home Water on a periodic basis.

Site selection

NYASTEC was selected as the general study site. NYASTEC and the surrounding area had an established need for additional sanitation facilities (Ghana News Agency 2011). Although the available sanitation facilities were limited, the MFC latrine played a supplemental role in the local sanitation capacity without being the primary source of sanitation. This dynamic was desirable for an experimental pilot system. As a technical high school, NYASTEC had a community (e.g., science teachers and students) who were more likely to be invested in the study. The MFC latrine could serve as a 'living laboratory', and enhanced educational opportunities in the school by exposing the students to the application of scientific principles.

NYASTEC is located in the Central region of Ghana, in the Agona West Municipal District at the village of Nyakrom, with an estimated population of 23,000. The climate in the area is tropical with typical daily high temperatures near 32 °C for the majority of the year. Rainfall varies considerably during the year, peaking in June where the average monthly rainfall is approximately 22 cm. To accommodate rainfall, slope stability and drainage measures were included in the site layout, and rain gutters were included in the roof system for the latrine.

Though the site sub-surface conditions were not quantified, it was clear that excavated soils were clay-like. This was advantageous to excavation due to the inherent stability in the clay soil. However, this also meant that infiltration rates were relatively slow. Therefore, the effluent from the MFC latrine was fed to an infiltration area filled with gravel. The infiltration area was located near the root system of a large tree and other vegetation to encourage water uptake.

The MFC latrine was located in a highly traveled, central location on campus, near several academic buildings. The anticipated user group was any student or faculty member that had the need for sanitation in that area of campus. The boarding school has 1,500 students whose ages ranged between 13 and 19 years. There were 550 female students. Additional sanitation facilities at the school include 36 flush toilets available in the dormitories, and 12 dry pit latrines (Garbrah 2013). The MFC latrine was next to a recently constructed facility, equipped with 12 flush toilets and sinks for hand washing. At the time of deployment, the facility was not connected to piped water or electricity and not in use. Students were observed to use a nearby unimproved pit latrine.

Basis for design

The MFC latrine design was based on a urine-diverting, composting latrine (Breslin 2002; Morgan 2007). The latrine superstructure was constructed of concrete block and mortar following previous design methods (Mihelcic 2009). The MFC latrine has the addition of the MFC components (Figure 1). The design diverts male urine that enters a urinal to the nitrification chamber. Female urine and all solids enter the composting chamber where solids are composted aerobically. The remaining liquid is transported by gravity to the MFC. Electrical current is generated by the biological transformation of organics and nitrogen in the waste stream. The MFC was designed for minimal material use and simple construction techniques to account for limited resources in the study area. All materials for the MFC latrine were acquired locally, with the exception of granular graphite.

MFC set-up

The MFC consists of three chambers: the anode chamber, the cathode chamber, and the nitrification chamber. ARB oxidize dissolved organic matter in liquid effluent from the composting chamber and transfer electrons to the anode (Figure 1). Simultaneously, ammonium (NH_4^+) from urine in the nitrification chamber is oxidized to nitrate (NO_3^-) by nitrifying bacteria. Effluent streams from both the anode and nitrification chamber enter the cathode, where nitrate is reduced to nitrogen gas by cathode-oxidizing bacteria. The anode and the cathode are anoxic and below grade, while the nitrification chamber is aerobic and on grade.

A 208 L (55 Gal) drum was used for the nitrification chamber. The tank was laid on its side and screened vents were added to the top of the drum to allow air to enter, creating an aerobic environment for nitrification. The liquid volume in the chamber was approximately 25% of the total volume to increase the surface area of the liquid-air interface and promote oxygen transfer.

Graphite granules between 2–10 mm in diameter served as the anode and cathode material and filled approximately 66% of both the anode and cathode chambers. The chambers were approximately 40 cm in diameter and 63.5 cm in length, and 30 cm separated the anode from the cathode, with 90 cm separating their corresponding electrodes. There was no physical partition between the chambers (e.g., no membrane), however, they were

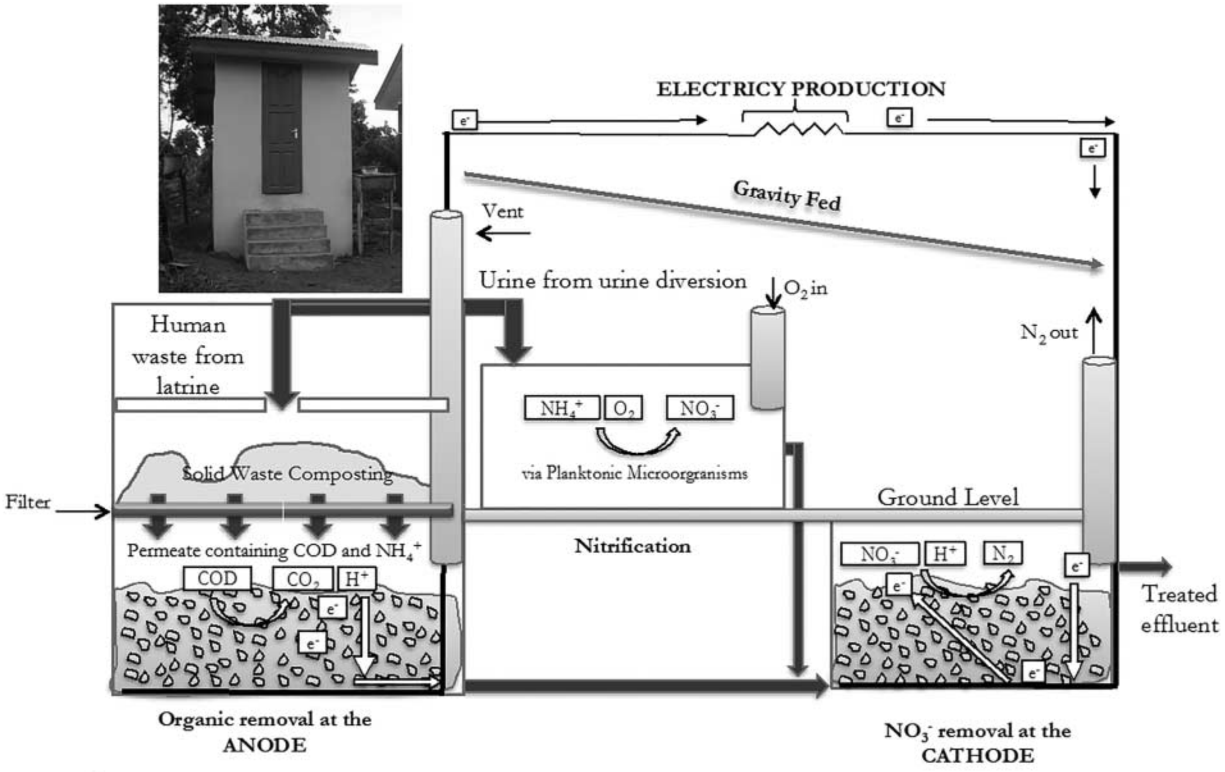

Figure 1 | Design of the MFC latrine in Agona Nyakrom, Ghana.

hydraulically separated by gravity driven flow. The estimated available liquid volume for the anode and cathode chambers was 40 L and the estimated accessible electrode surface area was 25.2 m^2. Graphite granules acted as a surface for biofilm formation. Graphite rods connected the granules to external circuitry to allow for electron transfer between the anode and cathode. Both the anode and cathode were inoculated with water from a nearby well. In addition, a small amount of dog food was added to the electrode chamber as a source of nutrients to promote bacterial growth during start up.

A circuit was constructed to deliver electrical power from the MFC to power a light emitting diode (LED). The circuit contained a 1.2 V AA rechargeable battery, a two-position switch and a 2.7 kΩ resistor. The resistor and rechargeable battery managed the fluctuations in power produced from the MFC. The battery was charged during daylight hours and powered the light located inside the latrine during darkness. The flow of electricity between the MFC, battery and LED was controlled with the switch.

MFC operation and data collection

Pure Home Water, LLC visited the site monthly for the first 6 months of operation. Conductivity, pH, ammonium, and nitrate data was collected in the anode, cathode and nitrification chambers, using a Vernier LabQuest 2 and Vernier probes (Beaverton, OR). Voltage, resistance and current were monitored across the anode and cathode with a multimeter. Each parameter was measured across the actual anode and cathode electrodes while attached to the lighting system in the off position. Power is reported normalized to the estimated graphite granule surface area in the anode chamber (P/A), were $P = VI$, and P represents the power, V is the voltage, I is the current, and A is the reported surface area. The surface area is a projected value based on a distribution of granule geometry and was not directly measured. Additionally, the liquid volume in the electrode chamber was variable so the entire electrode surface was not always accessible. For these reasons, reported values should be interpreted with caution, as they may not directly represent the power produced per surface area.

Education and maintenance plan

Education and maintenance activities included a seminar to faculty and students explaining MFC latrine fundamentals and maintenance requirements. Copies of the presentation were shared with the science teachers for reference. We appointed several science teachers and students to take on the responsibility of replacing toilet paper, woodchips, and charcoal ash. A construction and maintenance manual was also provided to the school headmaster.

RESULTS AND DISCUSSION

Deployment of the MFC latrine

In May 2012, the first MFC latrine was deployed at NYASTEC. Construction of the system took two and a half weeks by a team of local masons and carpenters. The system was put to immediate use after completion. After 1 year, the first composting chamber was closed and the second opened.

MFC latrine performance

Power production was low to begin with, at 0.18 µW (6.6 nW/m^2) (Figure 2). Initial power, 0.17–0.18 µW was consistent with our 1:1 scale, lab-based pilot study power density, which averaged 0.21 ± 0.54 µW (Castro 2014). This power production was sufficient to power an LED light unit that we deployed in our system in Ghana.

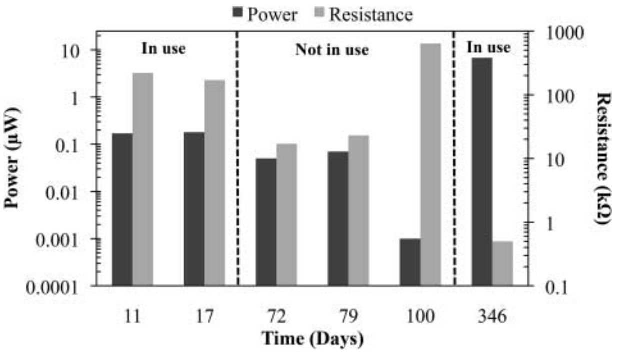

Figure 2 | Power (black bars) produced by the MFC latrine and the measured internal resistance (gray bars).

Shortly after start-up, NYASTEC recessed for the summer break. Due to lack of use, power decreased to 1 nW (0.04 nW/m^2), demonstrating that power production was correlated with use (Figure 2). During the follow-up trip in May 2013, power increased to 6.75 µW (268 nW/m^2). After one year of operation, total resistance decreased to 0.5 kΩ, designating a more efficient biofilm formation around the electrodes. Power production was low due to high ohmic losses associated with large granular-graphite electrodes and the complex waste compared to synthetic wastes often used in lab studies. On-going studies are exploring MFC configurations that will yield improved power outputs.

There was evidence of nitrogen transformation in the MFC latrine. Rates of nitrification and denitrification were not calculated due to inconsistency of latrine use and infrequency of data collection. In the nitrification chamber, a decrease in ammonium concentrations from the initial 7.1 g NH_4 as N/L indicated the occurrence of nitrification (Figure 3(c)). Due to incomplete nitrification, ammonium accumulation was observed in the cathode (Figure 3(b)). Low ammonium concentrations and high nitrate concentrations in the anode over time suggest nitrification is occurring in the anode, likely due to oxygen intrusion from the headspace of the incompletely filled chamber or possible nitrification in the aerobic composting chamber (Figure 3(a)). There was evidence of denitrification in the cathode when school was in session indicated by low nitrate concentrations during that time period, averaging at 308 ± 152 mg NO_3-N/L. During school recess, nitrogen species accumulated in the nitrification and cathode chambers. The pH levels at the beginning of the study began near 5.0 and increased to 7.0 in both the anode and cathode over the first 6 months and were near 7 on the return trip in May 2013.

Since we were not able to measure all of the microbial metabolites in the field, we observed the transformation of a synthetic urine media, consisting of primarily urea and ammonium, in our lab-based pilot MFC. The influent averaged 8560 ± 110 mg N/L of total nitrogen. Total nitrogen removal of 68.4 ± 2.81% was observed in the combination

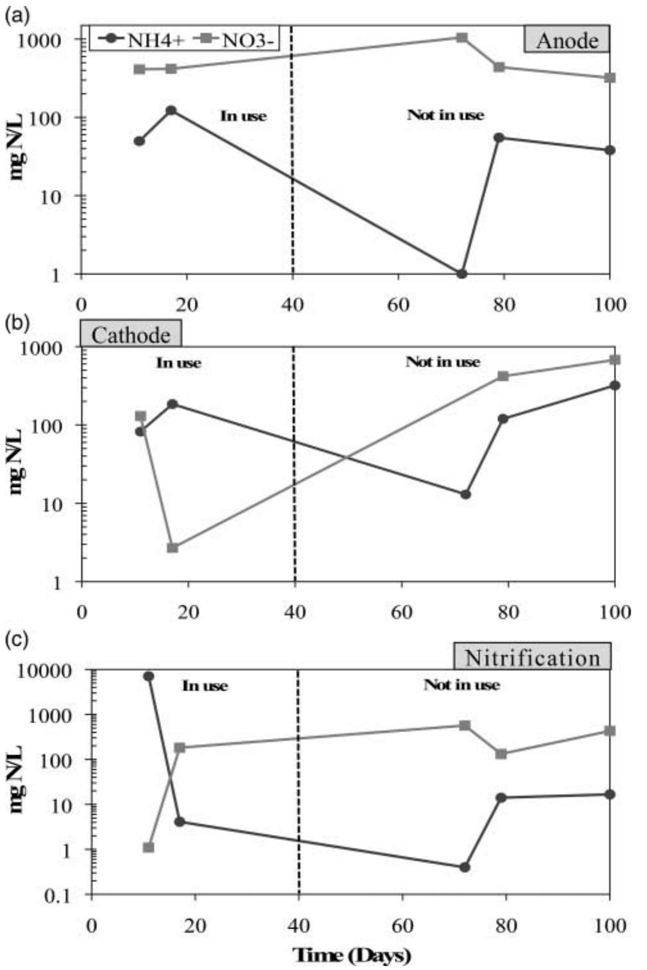

Figure 3 | Ammonium and nitrate concentrations in the anode (a), cathode (b), and nitrification chamber (c).

of nitrification and cathode chambers. Ammonium, nitrate, and nitrite concentrations were observed in the effluent of the cathode due to insufficient activity in the nitrification chamber, as well as insufficient and incomplete denitrification in the cathode. Precipitates along the nitrification chamber and within the tubing were observed and suggest precipitation of struvite due to urea hydrolysis (Castro 2014).

Organics and solids were indirectly monitored as turbidity. Low fluid levels and small graphite particles in suspension impacted results. Additionally, after 6 months of operation, the charging unit on the data logger failed and our partners were unable to collect additional data. Furthermore, user interface challenges began to interfere with the system performance.

On-going lab-based studies are exploring ways to maximize the conversion of waste organics and nitrogen species to electrical energy, by understanding the breakdown of complex organic matter in the anode compartment. Power production is directly related to the complexity of the substrate in the anode (Pant *et al.* 2010). **Q1** With various organic substrates, microbial communities become diverse. During anaerobic degradation of organics, methanogenic bacteria grow and likely outcompete ARB for organic substrates, reducing power production (Zhang *et al.* 2012). Additionally, the presence of nitrate in the anode suggests there is also competition between ARB and heterotrophic denitrifiers for substrates. The diversion of substrates to methanogenesis and denitrification reduces the amount of energy that can be recovered from the wastes. On-going studies are currently exploring anode competition.

Only a few large-scale, field-tested MFCs have been demonstrated with limited success. A pilot-scale MFC consisting of 12 vertical tubular reactors, with a combined liquid volume of 1,000 L was constructed in Yatala, Queensland, Australia to treat a dilute brewery wastewater. It yielded low chemical oxygen demand removal in the anode and caused biofouling in the air-cathode due to oxidation of organics in the cathode influent (Logan 2010). Although air-cathodes have also been shown to produce higher power densities when coupled with membrane-less MFC reactors (Liu & Logan 2004), they become impractical for use in reactors that treat complex material wastewaters because of oxygen diffusion to the anode and biofilm accumulation on the cathodes due to incomplete removal of organics in the anode. Cusick *et al.* (2011) constructed a continuous flow pilot-scale microbial electrolysis cell (MEC) of 910 L (liquid volume) to produce hydrogen gas from treating winery wastewater in Oakville, CA. After an intensive start-up period that explored pH and temperature effects on power, it produced a maximum current density of 7.4 A/m^3 and evolved 0.19 ± 0.04 L/L/day of hydrogen. However, MECs require external power input, making these systems impractical for developing countries where power sources are already limited. The MFC latrine installed in Ghana does not require external power sources of any kind, and therefore represents a more sustainable approach to generating electrical power from human waste in developing areas.

Use and maintenance

There were several challenges that affected the performance of the MFC latrine. One challenge was the improper disposal of waste paper. Our educational efforts failed in communicating that it was desirable to put waste paper into the toilet, which is contrary to the local convention of putting waste paper in a trash bin. We expected the absence of a trash receptacle, combined with our educational efforts, would encourage users to put the waste paper into the toilet. Instead, waste paper was placed in the ash and woodchip bucket and urinal. Failure to add ash and woodchips prevented sludge stabilization in the composting chamber and thus, decreased the carbon-to-nitrogen ratio of the sludge, potentially reducing compost quality. Further research is needed to understand the effect of these actions on MFC performance. Considerable woodchips and ash were added to the composting chamber in May of 2013 before the chamber was closed and the second one opened.

The second consequence of improper waste paper disposal is preventing access to the urinal. When the wood and ash chip bucket was full of waste paper, the urinal was subsequently used as a waste receptacle, preventing the diversion of male urine to the nitrification chamber. When the urinal is not in use, nitrification does not occur and the nitrate reduction cannot occur in the cathode, reducing power production in the MFC.

Likewise, replacement of toilet paper, ash and woodchips did not occur regularly over the year. During the follow-up trip, corrective actions were taken to improve the user interactions with the MFC latrine. A separate waste paper container was placed inside the latrine alongside a container for woodchips. Basic instructions for urinal use and waste paper disposal were also provided inside the latrine.

Interviews conducted in January 2014 revealed that 23% of the students surveyed use the MFC latrine on a daily basis (Knutson, in review). This is attributed to the hygienic state of the interior of the latrine. This confirmed what we learned from our interview of the headmaster and teachers in 2013 (Garbrah 2013). A cleaner facility can promote more frequent use and consequently provide the organics and nutrients required for the MFC to improve performance.

It was not possible to verify that the LED system was illuminated during the course of this study, due to the previously described issues and the periodic nature of subsequent visits to the MFC latrine. Results indicate that more than enough electricity was produced by the MFC system at times to charge the LED electrical circuit and illuminate the LED. It is also possible that exposure to the elements damaged the LED circuit.

Construction costs for the experimental pilot MFC latrine

Material and labor costs for the MFC latrine were $1,000 and $1,200, respectively. The graphite granules were an additional $1,700, including shipping and custom fees. Since this is a pilot project, there was redundancy in labor and materials. Several amenities were added to the latrine to complement the surrounding buildings: solid wood door with lock, rain gutters, footings to prevent soil erosion, and toilet seat covers. It is expected that if the MFC were to be reproduced as a retrofitting system for existing latrines and if the electrode material could be sourced locally, the costs would reduce to $100. Biochar, a charcoal produced by the carbonization of biomass and typically used as a soil additive (Lehmann 2007), is being investigated as a potential electrode **Q2** alternative. Preliminary studies have shown that biochar can sustain an average maximum power of 338 mW/m^3 (unpublished data) in bench-scale MFCs.

MFC latrine as an improved sanitation solution

The MFC latrine is a potentially viable solution for sanitation in Ghana and other developing countries. Composting latrines, by definition, produce compost, and have been leveraged as part of sanitation development programs (Breslin & Bramley 2010). However, they do not produce electricity like the MFC latrine. It is anticipated the MFC latrine could be deployed in a similar sanitation development program but with the electricity providing income opportunities. Also, it is possible that simple monitoring equipment could be powered from the MFC and thereby, provide valuable information to sanitation entrepreneurs.

CONCLUSIONS

1. A MFC latrine was constructed in Nyakrom, Ghana. All materials were procured locally, with the exception of granular graphite and the LED electrical circuit, with local labor. The total cost of the MFC latrine system was $3,900. The experimental nature of the system and import fees of the electrode material contributed significantly to the cost. It is estimated that the cost to add an MFC component to a previously constructed latrine system would be 95% less; assuming a suitable, local alternative for imported granular graphite was available.
2. Power production was directly correlated with latrine use. While school was in session, power production from the full-scale MFC was consistent with pilot study results. Power production was generally low due to high ohmic losses and the complex nature of the waste.
3. Multiple user challenges negatively affected the performance of the MFC, including the improper disposal of waste paper, failure to stabilize waste solids in the composting chamber by adding ash and woodchips, and inconsistent use of the urine diversion system. Educational programing was partially successful in overcoming these challenges. Sustainable use of the latrine ultimately requires establishing good user habits and adapting the technology to the user community's typical social practices.
4. The MFC latrine succeeded as a proof of concept demonstration that a continuous flow, two-chamber MFC with a separate nitrification stage can use human waste to produce electricity. The MFC latrine has advantages over other improved sanitation technologies because the MFC latrine produces electricity in addition to compost, all without the need for additional electrical inputs or waste collection and transportation.

ACKNOWLEDGEMENTS

This work was supported by The Bill & Melinda Gates Foundation (Grand Challenges Explorations Rounds 7) and the National Science Foundation (Grant No. S121000000211). The authors also gratefully acknowledge the support of the community of Agona Nyakrom, and the students, faculty and staff of the Nyakrom Secondary Technical High School (NYASTEC).

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First received 11 February 2014; accepted in revised form 10 July 2014. Available online 18 August 2014

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Manuscript: WASHDEV-D-14-00020

Q1	Please confirm the change of citation from Pant (2009) to Pant et al. (2010) as per the reference list.
Q2	Please confirm the correct spelling of Lehmann (2007) as per the reference list.
Q3	Esrey & Habicht (1986) is not cited in the text. Please cite else delete from the list.
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