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Anaerobic digestion in Uganda: risks and opportunities for integration of waste management and agricultural systems

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Abstract

Much of the global population lacks access to basic public sanitation, energy and fertilizers. Micro-scale anaerobic digestion presents an opportunity for low-cost decentralized waste management that creates valuable co-products of renewable energy and organic fertilizer. However, field-based assessments of system performance and clearly articulated guidelines for digestate management and field application are needed. Feedstocks and effluent from seven digesters in Kampala, Uganda were monitored for standard wastewater and fertilizer metrics including indicator organisms (*Escherichia coli* and fecal coliform), chemical oxygen demand (COD), biological oxygen demand (BOD_5), total Kjeldahl nitrogen (TKN), total phosphorous (TP), heavy metals, pH, temperature and total solids (TS) over 2 yr. Results reveal that digester effluent does not meet standards for wastewater discharge or international safety standards for field application. Data indicate that digestate could be a suitable source of fertilizer (TKN = 1467 mg L^{-1}, TP = 214 mg L^{-1}) but poses issues for water quality if not managed properly (TS = 26,091 mg L^{-1}, COD = 3471 mg L^{-1} and BOD_5 = 246 mg L^{-1}). While effluent from the digester contained pathogen indicator organisms (fecal coliform = 8.13×10^5 CFU/100 ml, *E. coli* = 3.27×10^5 CFU/100 ml), they were lower than the influent concentrations, and lower than reported concentrations in drainage canals. All digestate samples contained little to no heavy metals suggesting effective source separation. Data suggest that micro-scale biogas systems have potential to improve waste handling and meet standards associated with fertilizer application with proper post-digestion treatment.

Introduction

In 2012, one in three people worldwide lacked access to basic sanitation (WHO, 2013). Densely populated urban informal settlements have a particular need for improved sanitation. Open defecation, flying toilets and unlined pit latrines used in these areas lead to the contamination of public water supplies and the spread of waterborne illnesses (Wright *et al.*, 2013). The lack of consistent municipal solid waste removal and insufficient grey-water management leads to flooding, nutrient loading of local watersheds and the proliferation of disease-transmitting insects and rodents (Carden *et al.*, 2007; Okot-Okumu and Nyenje, 2011). Urban areas are also home to manure producing livestock, which receives little to no management. Poor sanitation in these densely populated urban areas is strongly associated with an increased risk of waterborne illnesses and vector-borne disease (Bartram *et al.*, 2005).

Despite this critical need, improving waste management in rapidly growing unplanned urban settlements has proved elusive. In the past 25 yr, 15% of households worldwide acquired safer sources of drinking water, while only 8% of the population gained access to improved sanitation services (Isunju *et al.*, 2011; Szanto *et al.*, 2012; WHO, 2013). In Uganda fewer than 10% of Kampala's residents have access to the sewer system (Nyenje *et al.*, 2010; Letema *et al.*, 2012; Szanto *et al.*, 2012), and there is little capacity to manage solid or animal wastes. In the absence of centralized options, the vast majority of residents, particularly those in underserved areas of the city, pursue low-cost on-site waste management (Nyenje *et al.*, 2010; Letema *et al.*, 2012; Szanto *et al.*, 2012). As a result, over 90% of Kampala's wastewater is discharged directly into the Lake Victoria watershed with no treatment (Nyenje *et al.*, 2010).

Micro-scale anaerobic digestion (AD) has been identified as an on-site waste management solution (Brown, 2006; Katukiza *et al.*, 2012; Surendra *et al.*, 2013; Avery *et al.*, 2014). This technology relies on a simple design constructed with local materials. Because digesters accept many organic wastes, including fecal sludge, animal manure, food wastes and grey-water, these

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systems create an opportunity for an integrated waste management system that addresses the localized needs of each community. The valuable co-products of fertilizer and energy offer opportunities for micro-entrepreneurship that could incentivize construction and system maintenance (Murray *et al.*, 2011; Tumwesige *et al.*, 2014). Several urban settlements in Nairobi have successfully piloted innovative business models for integrated community toilets, cooking facilities and urban agriculture using digesters. In Uganda, the 2007 Renewable Energy Policy incentivized digester construction across the country, and an estimated 600 digesters have been installed within the past 10 yr (Okoboi and Barungi, 2012). Despite the rapid expansion of the biogas sector, a rigorous evaluation of effluent safety and the impact of these systems on public sanitation is missing from the literature (Katukiza *et al.*, 2012; Avery *et al.*, 2014).

Many centralized wastewater treatment systems utilize AD as part of their treatment processes, and the capacity of large-scale digesters to inactivate pathogens is well established (Olsen *et al.*, 1985; Olsen and Larsen, 1987; Kearney *et al.*, 1993; Larsen *et al.*, 1994; Plymforshell, 1995; Sahlstrom, 2003; Sahlstrom *et al.*, 2008; Slana *et al.*, 2011; Beneragama *et al.*, 2013). Digesters can also reduce biological oxygen demand (BOD_5) and chemical oxygen demand (COD) in wastewater by over 53 and 46%, respectively (Ichinari *et al.*, 2008; Al-Jamal and Mahmoud, 2009). Although the basic biochemical process of AD remains the same at any scale, there are notable differences between highly mechanized industrial systems and micro-scale digesters. Large-scale systems typically operate at higher mesophilic temperatures (30–35°C), which is associated with higher rates of pathogen removal (Sahlstrom, 2003). It is unclear whether micro-scale biogas systems, which fall within the lower range of mesophilic temperatures (20–25°C) and rely on ambient conditions for heating, can successfully remove pathogens. The few previous studies of pathogen reduction in micro-scale digesters in this lower temperature range have been limited to bench-top studies or controlled experimental sites and have not assessed performance of *in situ* systems (Yongabi *et al.*, 2009; Avery *et al.*, 2014)

This field-based study monitored the inputs (feedstock) and outputs (effluent) of seven micro-scale ADs under local management within a variety of institutional settings in the greater Kampala metropolitan region. Nutrients, pathogen indicators and other standard wastewater metrics were used to assess system performance and to develop recommended effluent management strategies.

Materials and methods

Study sites

Seven ADs in the greater Kampala area were monitored over a 2-yr period from April 2014–2016. During site visits, system operators were asked a series of standard questions about feeding regime, water use and general performance indicators. When possible, the study team validated questionnaire responses with direct observations of end-user behavior. All seven ADs are belowground, fixed-dome and continuous flow systems located at small institutions. Systems vary in size, age, retention time and feeding regime (Table 1). System owners all use the gas directly for cooking. Five of the systems in this study use a standard Center for Agricultural Mechanization and Rural Technology (CAMARTEC, Arusha, Tanzania) design with a single expansion chamber, and one system uses a modified CAMARTEC design with a series of three expansion chambers (Site 2, school, Table 1). Feedstocks are mixed in an aboveground chamber and then released via an inlet tube into a belowground primary digester dome. Expansion chamber(s) act as both an air-seal and overflow to extend the retention time of the system. Slurry then flows into a storage tank at the same rate as feedstock addition. Retention times commonly ranged from 20–30 days and was determined by the size and number of primary and expansion chambers as well as the feeding rate (Table 1). The only non-CAMARTEC digester in this study (Site 1, hospital) is designed as a series of rectangular underground storage tanks with floating gas collection drums. All systems are unheated and located belowground to retain heat and conserve space.

Temperature data

ThermoWorks® TRIX-8 Dataloggers LogTag LTI in waterproof instrument pouches were submerged 1–2 m in the expansion chambers of six digesters. The unusual design of the digester at Site 1 (hospital) made temperature sampling at this site impractical. The thermometers recorded temperature every hour. Data were downloaded every two weeks using a Thermoworks® LTI/USB Interface Cradle. Daily recorded surface temperature and precipitation data (Weather Station ID: 63705099999, Entebbe International Airport) were downloaded from the publicly available U.S. National Oceanic and Atmospheric Administration, National Climactic Data Center and Global Surface Summary of the Day. When available, temperature and precipitation recordings from weather stations in central Kampala and Makerere University were also included in the analysis; however, these weather stations had limited reporting dates.

Microbial analysis

Three replicates of inputs (feedstock) and outputs (effluent) were collected at each of the seven sites once per month from April 2014–December 2015. Fresh samples were held at 4°C for no longer than 2 h prior to microbial analysis to minimize decomposition. Standard indicator species (fecal coliform and *Escherichia coli*) were quantified using the IDEXX® Colilert Quanti-Tray 2000 system (IDEXX Laboratories Inc., Westbrook, ME), a defined substrate technology approved by the U.S. Environmental Protection Agency as an appropriate methodology under 40CFR Parts 136 & 503 for determining compliance with U.S. National Pollution Discharge Elimination System wastewater regulations. The National Water and Sewerage Corporation (NWSC) in Kampala also utilizes the IDEXX® system to assess compliance with National Effluent Discharge Standards. All analyses were conducted at the NWSC Laboratory in Kampala, Uganda.

Physiochemical analysis

A Hanna Instruments® HI 991001 Extended Range portable pH meter was used to measure effluent pH at the time of sample collection. Total Kjeldahl nitrogen (TKN) was determined by Kjeldahl digestion (4500-N_{org}) and extractable phosphorous (TP) by the Bray P1 method. Gravimetric methods were used to measure the concentration of total solids (TS) following drying overnight at 105°C. Commercially available Hach® high range (0–1500 mg L^{-1} COD) kits and a DR5000 spectrophotometer were used to assess COD. This method is EPA approved as

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appropriate for compliance monitoring under 40 CFR 136.3. The five-day BOD_5 was determined using the EPA-accepted Standard Method 5210B. One effluent sample from each of the seven systems was screened for heavy metals (chromium, cadmium, lead and zinc) at the beginning of the study using atomic absorption spectrophotometry.

Statistical analysis

All statistical analyses were performed using R version 3.2.1 (R-Core-Team, 2015). Normality assumptions were verified prior to parametric statistical analysis. *E coli*, fecal coliform and TP data revealed skewed residuals and were log-transformed as a correction. Confidence intervals (CI) as well as comparisons to discharge standards and reported wastewater metrics from the literature are based on Welch's two-tailed *t* test due to unequal variance between groups. Regulatory standards from 1999 Uganda National Effluent Discharge Standards (UNEDS) for release of wastes into water or on land and the 2006 World Health Organization (WHO) guidelines for the safe use of wastewater in agriculture were used for comparison. Daily temperature data revealed strong temporal autocorrelation and were thus aggregated into weekly averages prior to linear regression to meet assumptions of independence of the errors and residual homoscedasticity.

Results and discussion

Digester effluent physiochemical parameters

Micro-scale digester effluent far exceeded UNEDS for TKN, TP, TS, COD and BOD_5 (Table 2 and Fig. 1). Even the minimum values from each site often exceeded these standards, leaving no question that digester effluent does not meet requirements for direct discharge into public waterways. However, the effluent did meet UNEDS regulatory guidelines for pH, temperature and heavy metal discharge (Cd, Cr, Pb and Zn) (Table 2 and Fig. 1).

Likewise, levels of TKN, TP, TS, COD and BOD_5 in digester effluent exceeded reported levels found in treated wastewater from the UNWSC Naalya Sub-Station over the same time period, supporting conventional wisdom that AD should not be considered an equivalent substitute for traditional centralized wastewater treatment facilities (Table 2 and Fig. 1). The values of these five physiochemical parameters also exceeded reported metrics from drainage canals within densely populated informal settlements of Mulago, Kamwokya, Natete, Nakivubo and Bwaise III (Table 2 and Fig. 1). For example, reported values of TP sampled from local drainage canals ranged from 1.6 to 13 mg L^{-1}, whereas the digestate concentrations reported in this study averaged 214 mg L^{-1} (Kanyiginya *et al.*, 2010; Nyenje *et al.*, 2014; Fuhrimann *et al.*, 2015; Katukiza *et al.*, 2015). This study reports digestate physiochemical characteristics prior to discharge, whereas published values of water quality from drainage canals estimate storm water diluted discharges. The concentration of nutrients and solids in digestate nearly always exceeded concentrations found in drainage canals; however, they were equivalent to concentrations commonly found in fecal sludge from latrines (Nyenje *et al.*, 2010) (Table 2 and Fig. 1). These data strongly suggest that digesters, like latrines, pose a significant risk of point-source pollution during precipitation events that cause system overflow (Nyenje *et al.*, 2013; Wright *et al.*, 2013).

In contrast to TKN, TP, TS, COD and BOD_5, the temperature and pH of the digester effluent fell well within UNEDS regulatory guidelines and did not differ significantly from other reported discharges into public waterways in Kampala (Table 2 and Fig. 1). Digester effluent had non-detectable (<0.01 mg L^{-1}) levels of cadmium (Cd), chromium (Cr) and lead (Pb), and very low levels of zinc (Zn) (0.5 mg L^{-1}), although each of the seven digesters monitored in this study was only tested for heavy metals once (Table 2). Reported heavy metal contamination in open drainage canals far exceeded the concentration of heavy metals found in digester effluent. Lead concentrations reported in the Nakivubo channel ranged from 0.5–2.2 mg L^{-1}, levels that pose a risk to both the environment and public health (Fuhrimann *et al.*, 2015). Because anoxic conditions tend to favor the solubility, and thus mobility, of heavy metals, if heavy metals were present in the feedstocks of ADs, detectable levels of heavy metals would likely be present in the effluent. These results suggest that digester system owners have engaged in effective source separation, resulting in little to no heavy-metal contamination of the feedstocks by batteries, personal care products, cleaning products or industrial wastes. Alternatively, the physical location of digesters within residential areas and the raised input lines may have protected the systems from contaminated runoff. Leaded petrol and chemical discharges frequently cause heavy metal contamination in areas near major roads. None of the sites in this study were immediately adjacent to such places.

Direct discharge of digester effluent into Kampala's waterways does not mitigate the environmental, economic and public health threats facing the Lake Victoria watershed and its surrounding community. Digestate management plans must be integrated into AD systems for digester installation to improve nutrient management. Prior to digester installation, the sites surveyed in this study utilized unimproved pit latrines and either applied raw animal manure to local gardens or deposited the manure directly into drainage canals. After construction, only one system permitted effluent to overflow directly into a drainage canal. The remaining systems either transported effluent to a centralized wastewater treatment facility or made productive use of the slurry as a fertilizer, a clear improvement in nutrient management (Table 1).

Digester effluent microbial parameters

The mean concentration of indicator organisms in digester effluent exceeded UNEDS for fecal coliform (<5.0×10^3 CFU/100 ml) as well as WHO guidelines for *E. coli* (<1.0×10^3 CFU/100 ml). The average concentrations of fecal coliform (8.13×10^5 CFU/100 ml) and *E. coli* (3.27×10^5 CFU/100 ml) surpassed these regulatory standards by several orders of magnitude, indicating that digester effluent does not meet current regulatory standards for direct discharge (Fig. 2 and Table 2). Digesters varied considerably in their ability to reduce fecal coliform and *E. coli* concentrations (Fig. 2 and Table 3). The system at Site 2 (school) consistently outperformed the other six digesters, with a mean concentration of 1.13×10^5 CFU fecal coliform per 100 ml of effluent, and a nearly 4-log reduction in *E. coli* concentrations (Tables 3 and 4, Fig. 2). In contrast, the system at Site 1 (hospital) had no detectable impact on microbial community composition and final discharge concentrations of fecal coliform averaged 2.02×10^6 CFU per 100 ml of effluent. The concentration of *E. coli* in the feedstocks from Site 1 did not differ significantly

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Table 1. Operational and design parameters of seven digesters sampled from April 2014–2016

Site	Description	Year installed	Size (m^3)	Retention time (days)	Feedstock	Slurry use
1	Hospital (350 beds)	2001	50	14	Flush toilets, medical waste	Discharged onto property for landscape irrigation
2	Government primary school (800 students)	2010	16	120	Latrine waste	Transported to central sewage treatment facility
3	Community primary school (700 students)	2014	12	30	25% latrine waste, 75% cow manure	Applied on-site to school garden
4	Research site (1 resident)	2013	30	30	5% latrine waste, 95% cow manure	Applied on-site to maize fields
5	Orphanage (30 children)	2009	8	30	Cow manure	Direct discharge to drainage canal
6	Social center (10 residents)	2010	8	30	Cow manure	Applied on site to garden
7	Private student hostel (500 residents)	2012	30	40	Cow manure	Transported to commercial farm

from the effluent, making the processed waste indistinguishable from raw wastes (Table 3 and Fig. 2).

Digester design and operational parameters exert a strong influence on system performance. One of the best-characterized predictors of pathogen kill in anaerobic digesters is operational temperature. Temperatures exceeding 70°C result in complete removal of the six most common *E. coli* serotypes within 10 s, exposure to temperatures of 55°C require only one hour for complete kill, and temperatures below 35°C have no impact on concentrations even after 20 days of continuous exposure (Smith *et al*., 2005). Studies of *Salmonella typhi, Streptococcus faecalis* and *Vibrio cholerae* have revealed similar results, with temperatures in the thermophilic range (exceeding 55°C) promoting rapid and complete pathogen removal, temperatures near 35°C resulting in significant pathogen removal within 10 days, and lower ambient temperatures necessitating a minimum 20–30 days until 90% of effluent samples tested negative for pathogens (Olsen and Larsen, 1987; Kunte *et al*., 2000; Masse *et al*., 2011; Beneragama *et al*., 2013). The results of pathogen reduction studies among hardier spore forming parasites, such as *Cryptosporidium* spp. and *Giardia* spp., reveal mixed results, suggesting that AD is ineffective at removing such pathogens, except under thermophilic conditions (Chauret *et al*., 1999).

All the digesters monitored in this study operated within the lower range of mesophilic temperatures (25–26°C), far below the temperature conditions required for effective pathogen removal (Table 3). Ambient temperatures in Kampala were directly related to digester temperature, suggesting that digesters respond to changes in ambient temperature. Some digesters were more sensitive to ambient temperatures than others, likely due to variation in digester depth and insulation. If the sunny, equatorial climactic conditions of Kampala were insufficient to push digester temperatures within the range required for effective pathogen kill, it seems unlikely that micro-scale digesters elsewhere will offer significant pathogen reductions. Solar-powered heating elements could increase the temperature of these digesters, but such interventions are either cost-prohibitive or not currently available.

A more realistic recommendation to increase pathogen kill of micro-scale digesters may be to incentivize the construction of systems with extended retention times. In this study, the system with the greatest reduction in indicator organisms had the longest retention time (Site 2, 120 days), whereas the digester that did not significantly reduce fecal coliform or *E. coli* concentrations had the shortest retention time (Site 1, 14 days) (Table 4). The majority of pathogen reduction studies of anaerobic digesters examined batch systems, where hydraulic retention time is tightly controlled. These studies clearly reveal that longer retention times are more likely to result in greater pathogen kill. However, in continuous flow systems like the digesters reported in this study, retention times are more fluid and vary in response to changes in feeding regime. When a system designed with a 30-day retention time experiences high rates of loading (over-feeding conditions), undigested wastes may pass through the system in several days. Although many of the digesters observed in this study had relatively stable feeding regimes over the course of the sampling period, at least two systems (Sites 3 and 4) experienced extreme changes in feeding consistency. The study team directly observed evidence of both over-feeding (e.g., foul odors, fly-covered effluent) and under-feeding (dry or crusted effluent). Even consistently maintained digesters experienced occasional disruptions in feeding patterns as a result of school holidays or national elections. System-owners also self-reported seasonal changes in water use, suggesting that digesters received more dilute feedstocks during the rainy season. The operational variability observed in this study is a strong reminder that the guidelines for pathogen reduction generated by experimental studies of well-controlled, bench-top anaerobic digesters should be applied to the field with caution. While a 30-day retention time may be biologically sufficient to ensure pathogen removal at ambient temperatures in controlled laboratory settings, digesters with longer retention times (120 days) could help buffer the impacts of operational variability in the field.

Effluent discharge and land application regulatory environment

Agricultural application of the effluent could prevent a significant fraction of nutrients from leaching into the Lake Victoria watershed, while simultaneously offering local farmers an affordable and locally produced fertilizer. Uganda has one of the highest rates of soil depletion and one of the lowest rates of fertilizer

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Table 2. Microbiological and physiochemical properties of anaerobic digester effluent

Parameter	*n*	Mean	Min	Max	95% CI	Regulatory standard	Reported local discharges
Fecal coliform (CFU/100 ml)	131	8.13×10^{5}	8.20×10^{2}	8.58×10^{7}	5.49×10^{5}–1.20×10^{6}[a]	5×10^{3}[b]	2.3×10^{3}–2.9×10^{3}[b, c] 2.5×10^{7}[d] (TC) 2.7×10^{6}–6.9×10^{6}[e] (TTC) 1×10^{5}[b,f]
E. coli (CFU/100 ml)	122	3.27×10^{5}	4.83×10^{2}	5.42×10^{7}	2.03×10^{5}–5.27×10^{5}[a]	1×10^{3}[b]	4.0×10^{6}[d] 2.3×10^{5}–6.6×10^{5}[e]
COD (mg L^{-1})	43	3471	7	60,300	1680–7,174[a]	100[b]	52–62[b,c] 4450[d] 211–304[b,e] 30,000[f]
BOD_5 (mg L^{-1})	43	246	19	1830	155–388[a]	50[b]	21–25[b,c] 95[b,d] 83–100[b,e] 5500[f]
TP (mg L^{-1})	112	214	10	1340	175–260[a]	10[b]	4.2–5.3[b,c] 1.6[b,d] 9.7–13.3[b,e] 5.2[b,g] 450[f]
TKN (mg L^{-1})	104	1467	50	3620	1295–1638	10[b]	3.6–5.7[b,c] 11.0[b,d] 19.6–22.8[b,e] (NH_3-N) 32.4[b,g] (NH_3-N) 3400[f]
TS (mg L^{-1})	135	26,091	385	111,866	21,564–30,619	100[b]	47–61[b,c] 1210[b,d] 141–257[b,e] 30,000[f]
pH	112	7.5	5.1	8.8	7.4–7.6	6–8	8.0–8.3[c] 7.1–7.3[e] 7.7[g]
Cr (mg L^{-1})	7	<0.01	<0.01	<0.01	NA	1	0.01–0.10[e]
Cd (mg L^{-1})	7	<0.01	<0.01	<0.01	NA	0.1	0.07–0.22[e]
Pb (mg L^{-1})	7	<0.01	<0.01	<0.01	NA	0.1	0.56–2.26[e]
Zn (mg L^{-1})	7	0.5	0.02	1.29	0.09–0.91	5	0.10–2.00[e]
Temp. (°C)	1588	25.2	19.9	31.1	25.2–25.3	20–35	25.9–26.7[c] 26.1–26.8[e] 24.2[b,g]

95% CI based on Welch's two-tailed *t* test; TC, total coliforms; TTC, thermotolerant coliforms; NH_3-N, ammonia.
[a]Indicates CI based on log-transformed data to meet normality assumptions.
[b]Concentrations reported in this study exceeded these values (one-sample, two-tailed Welch's *t* test) $P < 0.0001$.
[c]UNWSC Naalya substation wastewater discharge (95% CI). Samples collected Apr 2014–2016 ($n = 66$).
[d]Nsooba drainage canal, Bwaise III, Kampala (means). Samples collected 2010–2012 ($n = 27$) (Katukiza *et al.*, 2015).
[e]Nakivubo drainage canal, Kampala (95% CI). Samples collected Oct–Dec 2013 ($n = 112$) (Fuhrimann *et al.*, 2015).
[f]Direct measurements of fecal sludge from latrines in informal settlements around Kampala (means). Samples collected 2007–2008 (*n* unknown).
[g]Drainage canal, Bwaise III, Kampala (means). Samples collected 2010–2012 (*n* unknown) (Nyenje, 2014).

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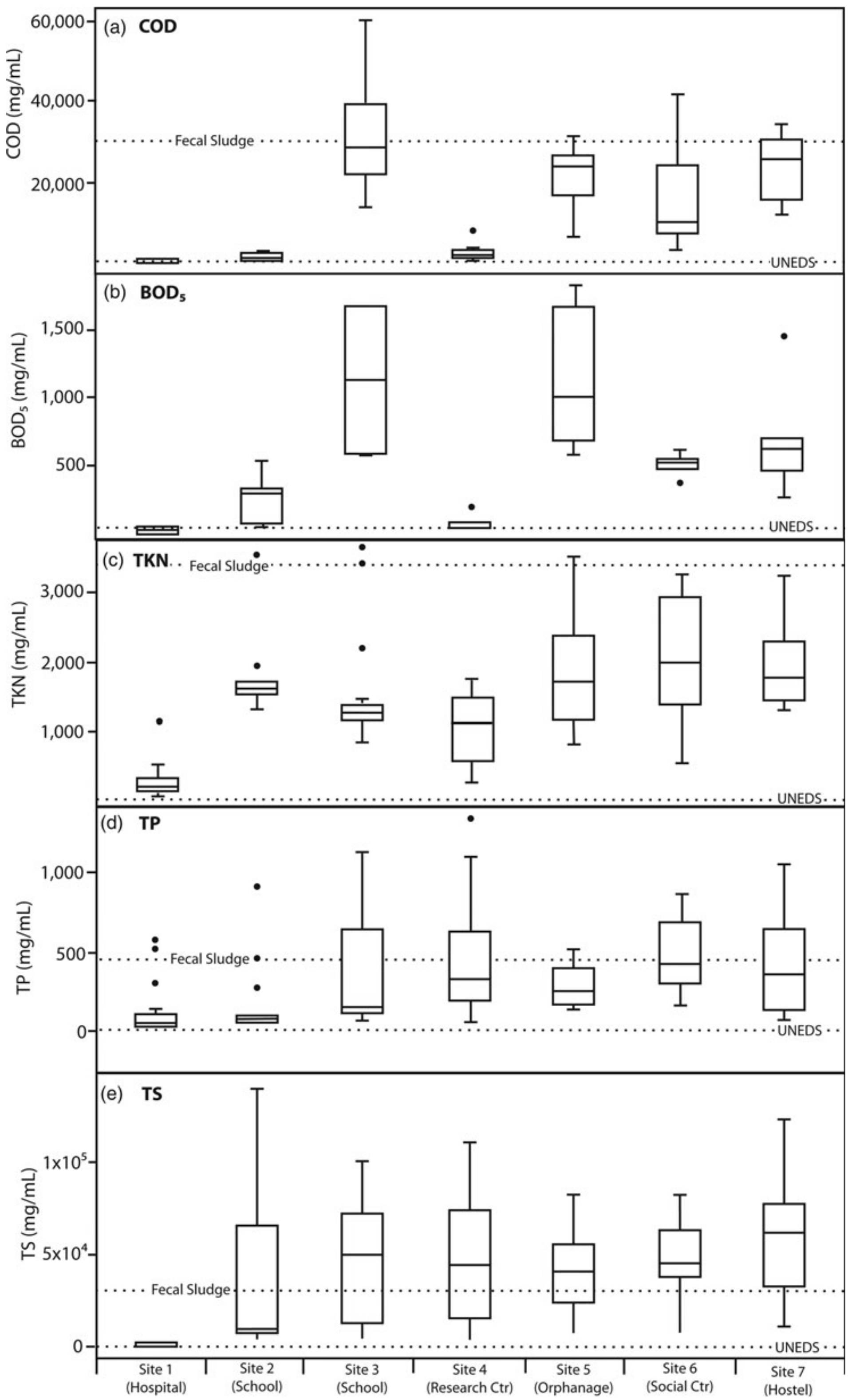

Fig. 1. Digester effluent physiochemical parameters including (a) COD, (b) BOD_5, (c) TKN (d) TP and (e) TS, at seven digesters in the greater Kampala area monitored from 2014–2016. Boxplot reveals the median and interquartile range. Upper and lower whiskers capture all points within 1.5 × IQR. Outliers indicated as individual points (Tukey method). The UNEDS indicate discharge standards. Fecal sludge indicates reported values in fecal sludge from latrines in Kampala.

usage in the world (Namazzi, 2008). Modest rates of fertilizer application (60 kg N, 45 kg P_2O_5 and 30 kg K_2O per hectare) can increase yields by 270% when compared to no-fertilizer regimes common among small-holders in Uganda (Namazzi, 2008). All of Uganda's inorganic fertilizers are imported from Kenya, and Ugandan agricultural producers suffer from both chronic shortages of fertilizer and rapidly increasing prices (Omamo, 2003).

Fecal coliform and *E. coli* concentrations of digester effluent exceed World Health Organization (WHO) guidelines for unrestricted agricultural field application of excreta-based biosolids ($<1 \times 10^3$ CFU *E. coli* g^{-1}) (Table 4). These results indicate that

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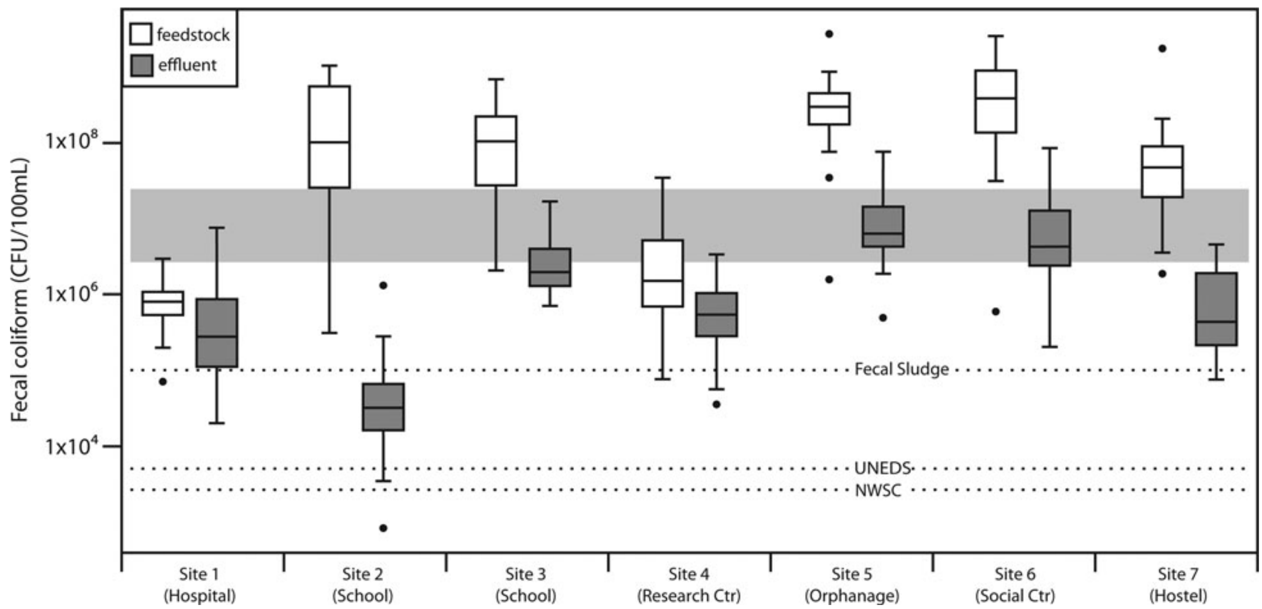

Fig. 2. Feedstock (white) and effluent (dark grey) fecal coliform concentrations at seven anaerobic digesters in the greater Kampala area monitored from 2014–2016. Standard box and whisker plot visualize the median, IQR and outliers (Tukey method). The UNEDS regulatory guidelines (5×10^3 CFU/100 ml), reported values in fecal sludge from latrines in Kampala (1×10^5 CFU/100 ml) and mean discharge concentration from NWSC Naalya substation waste water treatment plant (2.6×10^3) are indicated. Grey shading represents previously reported ranges of concentrations found in open drainage canals around Kampala (2.7×10^6–2.5×10^7 CFU/100 ml). *E. coli* concentrations revealed similar trends (not shown).

digestate poses a risk to human health and should not be field applied. Although the use of human excreta on food crops is not without risk, such a simplistic interpretation misinterprets the complexities of the policy environment, does not engage with the intent behind the existing regulatory standard and ignores the reality of current exposure risks in Uganda (Dumontet *et al.*, 1999).

Common enteric pathogens persist in manures, composts, soils and plants, posing a potential risk to farmers and consumers alike. The utilization of digestate in agriculture poses similar risks (Avery *et al.*, 2012). Designing a robust quantitative microbial risk assessment (QMRA) to directly link the concentrations of pathogens or indicator organisms in fertilizers to health outcomes presents a formidable challenge, as gathering data in Uganda is extremely difficult. Actual risk is very site specific due to variability in pathogen prevalence and virulence, the vulnerability of human populations (immune status, age, nutritional status, etc.), microclimatic conditions (humidity, temperature, storage conditions, etc.) and behavioral risks (use of personal protective equipment, timing of application, other local farming practices, etc.) (Avery *et al.*, 2012).

The *WHO guidelines for the safe use of wastewater, excreta and greywater* provides a detailed review of QMRA approaches to guide development of local standards. The document suggests that policies should be based on contextualized estimates of health outcomes associated with the use of wastewater or human excreta on agricultural crops and should support practices that do not increase mortality or morbidity in the population beyond the tolerable risk of 1×10^{-6} disability adjusted life years (DALY) (WHO, 2006). These guidelines outline quantitative standards and protocols likely to reduce risk below this threshold. Specifically, (1) the concentration of *E. coli* in dried excreta should be less than 1×10^3 CFU g^{-1} TS and (2) there should be a minimum of 30 days between biosolid application and harvest. A sewage treatment method is likely to meet the *E. coli* standard when a 6-log reduction in fecal coliform is achieved. The log reductions of fecal coliform observed in this study (0.2–3.8) and the corresponding concentrations of *E. coli* (4.28×10^4–6.03×10^6 CFU g^{-1} solids) do not meet this threshold (Table 3). However, the guidelines also note that in communities facing food, freshwater and resource constraints, more relaxed standards may be necessary to promote cost-effective nutrition and water conservation. These are precisely the conditions facing densely populated informal settlements in Kampala. Ultimately, policymakers must consider whether the use of digestate in agriculture poses a significant additional risk to human health when compared to current practices.

Current risk profiles of Uganda's farmers vary considerably. Farmers switching from conventional chemical fertilizers to digestate, or those transitioning from no-fertilizer regimes to digestate application would likely face an increased risk of pathogen exposure, even with additional digestate post-processing and strict adherence to application guidelines. Education and enforcement of such guidelines would require extensive education and outreach, an ongoing challenge in Uganda's agricultural sector. Digestate likely represents a safer alternative for farmers who are currently using raw sewage for irrigation or fertilization, a common practice in Kampala's urban gardens. For example, produce from urban gardens around Kampala was found to have high levels of heavy metal contamination (Nabulo *et al.*, 2010). This study found comparatively low or non-detectible levels of heavy metal contamination in digestate. Six of the seven digesters sampled had significantly higher concentrations of indicator organisms in the feedstocks than the system effluent, demonstrating that digester effluent is less risky than raw fecal sludge (Table 3 and Fig. 2).

In addition, the concentrations of fecal coliform and *E. coli* in digestate were comparable to, and in many cases significantly less

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Table 3. 95% CI of fecal coliform and *E. coli* concentrations in digester feedstocks and effluent

Site	Fecal coliform (CFU/100 ml)		*E. coli* (CFU/100 ml)	
	Feedstock	Effluent	Feedstock	Effluent
1 (hospital)	4.56×10^5–1.15×10^6	1.45×10^5–8.69×10^5	1.71×10^5–4.86×10^5	7.78×10^4–2.84×10^5
2 (school)*	3.01×10^7–2.26×10^8	1.67×10^4–6.63×10^4	2.84×10^7–1.77×10^8	5.64×10^3–2.70×10^4
3 (school)*	3.32×10^7–1.81×10^8	1.51×10^6–3.88×10^6	1.93×10^7–1.19×10^8	1.15×10^6–2.83×10^6
4 (research site)**	7.97×10^5–4.03×10^6	2.61×10^5–1.01×10^6	1.34×10^5–1.17×10^6	6.49×10^3–7.79×10^4
5 (orphanage)*	1.15×10^8–4.69×10^8	4.45×10^6–1.35×10^7	8.43×10^7–3.40×10^8	2.58×10^6–9.4×10^6
6 (social ctr)**	1.14×10^8–7.22×10^8	2.78×10^6–1.38×10^7	7.16×10^7–4.69×10^8	5.98×10^5–6.06×10^6
7 (hostel)*	1.85×10^7–9.22×10^7	2.94×10^5–1.04×10^6	1.09×10^7–6.18×10^7	1.29×10^5–6.62×10^5

*$P < 0.00001$, **$P < 0.002$; concentration of feedstocks (inputs) significantly exceeded concentrations of effluent (outputs) for both indicator organisms as determined by a Welch's two-tailed *t* test.

Table 4. Mean effluent concentrations of fecal coliform and *E. coli* with corresponding log reductions, retention times and digester temperatures

Site	Fecal coliform		*E. coli*		Retention time (days)	Digester temp. (°C)
	Mean (CFU g^{-1})	Log reduction	Mean (CFU g^{-1})	Log reduction		
Site 1 (hospital)	3.45×10^7[a]	−0.30	4.69×10^6	0.19	14	NA[b]
Site 2 (school)	1.58×10^5[a]	3.43	4.28×10^4	3.83	120	26.4
Site 3 (school)	2.58×10^6[a]	1.68	1.69×10^6	1.69	30	24.9
Site 4 (research site)	4.42×10^5[a]	0.68	3.54×10^4	1.26	30	24.3
Site 5 (orphanage)[c]	8.10×10^6	1.48	6.03×10^6	1.47	30	24.3
Site 6 (social ctr)[c]	4.20×10^6	1.58	1.96×10^6	1.71	30	25.9
Site 7 (hostel)[c]	2.99×10^5	2.15	1.56×10^5	2.05	40	25.6

[a]Concentrations of fecal coliform exceed WHO standards for land application of human excreta.
[b]Digester design prevented temperature monitoring.
[c]These systems utilize only cow manure and are not subject to WHO guidelines for land application.

than, the concentrations of indicator organisms already present in drainage canals around Kampala (Table 2 and Fig. 2) (Nyenje *et al.*, 2013; Fuhrimann *et al.*, 2014; Fuhrimann *et al.*, 2015). The discharge of untreated fecal sludge into open waterways is a persistent danger to public health in Kampala. Local residents in Kampala's largest informal settlement, Bwaise, report constructing latrines as close to drainage canals as possible to make it easier to empty raw sewage directly into open waterways (Kulabako *et al.*, 2010). A QMRA of this area suggests that poor sanitation is directly responsible for an annual disease burden of 0.68 DALY per person per year, exceeding the WHO standard of tolerable risk, 1×10^{-6} DALY per year, by several orders of magnitude (Katukiza *et al.*, 2014). Informal settlements in Kampala have one of the highest rates of cholera in the country, where outbreaks occur during the rainy season and are highly correlated with poor sanitation and wastewater discharge (Bwire *et al.*, 2013). In this context, using digestate as a fertilizer rather than discharging effluent into waterways offers a clear public health benefit.

Finally, it remains unclear whether the regulatory standards apply to all digesters in this study. The standards referenced herein are largely concerned with safe discharge or land application of human excreta, not animal manures. Three of the digesters in this study rely exclusively upon cow manure as feedstock (Table 1). Among the four digesters that utilize human excreta, two systems add enough cow manure to ensure that latrine wastes account for less than 50% of their total feedstocks. Globally, the regulatory framework for animal manure disposal remains unclear. Common enteric pathogens such as helminthes, *Ascaris* spp., *Giardia duodenalis* and *Cryptosporidium* spp. are zoonotic and known to infect livestock worldwide, although most transmission is likely person-to-person. However, even countries with strict regulatory frameworks, such as the U.S., frequently develop manure application standards based upon nutrient discharges rather than disease risk.

In Uganda, there is no restriction on land application of manure-based bio-solids, and even the legality of human excreta and wastewater utilization remains unclear (Mutagmaba, 2006). The UNEDS were designed to govern industrial discharges into public surface waters. In the absence of national guidelines, the Kampala City Council introduced municipal regulations under the *2007 Urban Agriculture and Solid Waste Management Ordinance* that restricted the use of untreated human wastes on food crops. However, these ordinances do not define what constitutes treated and untreated waste, nor do they articulate application protocols or quantitative monitoring standards (NETWAS, 2011). The ambiguity of local, national and international guidelines makes it difficult to determine which, if any, of the biogas systems in this study should be subject to restrictions on land application of digestate.

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Cost-effective strategies for reducing risks of land application

Additional post-digestion processing can further reduce the risks associated with land application of digestate on crops grown for human consumption. Simply storing the digestate (even at temperatures below 20°C) decreases pathogen levels over three months. Likewise, increasing the time between digestate application and harvest by 90 to 265 days (depending upon the crop and the degree of manure contact) is another way to reduce disease risk (Alegbeleye *et al.*, 2018). However, this approach may not mitigate the risks posed by some pathogens, such as *Listeria*, that can survive longer than six months in extreme environments (Nicholson *et al.*, 2005). Composting digestate can further reduce pathogen concentrations. However, composting, like digestion, requires monitoring of temperature and holding times to achieve pathogen inactivation, and, attention is required to avoid risks of pathogen regrowth (Alegbeleye *et al.*, 2018).

Solid–liquid separation systems generally separate the pathogens into the liquid fraction, as microbes tend to minimize attachment to solids when there is a high concentration of bioavailable organic matter in the substrate (Burch *et al.*, 2018). Simple solid–liquid separation systems also simplify and improve nutrient management in densely populated informal settlements. Transporting light-weight dried solids to cropland for land application is safer and more cost-effective than hauling and applying high moisture digestate. Recirculating the remaining liquid digestate fraction offers the potential for improved pathogen reduction and vastly reduces the freshwater demands of these systems, a critical improvement in communities where freshwater resources are limited.

To ensure that micro-scale AD supports urban sanitation and food security, rather than posing additional risk to vulnerable ecosystems and human communities, researchers and policymakers should (1) support the development of affordable post-digestion processes that enable greater pathogen kill (such as heating systems, UV-exposure or effluent desiccation), (2) incentivize the construction of systems with longer retention times (>120 days) and/or multiple expansion chambers to improve pathogen kill, (3) require both a clearly articulated slurry management plan and installation of secure storage tanks that are sized to contain effluent throughout the rainy season for all new construction and (4) provide training to farmers to educate them on digestate application, including guidelines for early growing season treatments and discouraging use on belowground crops.

Conclusion

Effluent from micro-scale ADs in Kampala, Uganda does not meet national or international regulatory standards for direct discharge. Phosphorous and nitrogen concentrations in digester effluent exceed reported values in drainage canals, and direct discharge would likely exacerbate eutrophication of Lake Victoria, but could provide a valuable fertilizer. To avoid contributing to environmental degradation, digester effluent should be land-applied as fertilizer or transported for additional treatment in centralized sanitation facilities. Although the concentrations of fecal coliform and *E. coli* in digestate exceeds WHO guidelines for land application, use of digester effluent in agricultural applications may reduce the exposure risk of consumers depending upon previous agricultural practices, but digestate represents a safer alternative to raw wastes. It may be financially prohibitive to increase digester operational temperatures to levels that would increase pathogen inactivation; however, construction of digesters with longer retention times may reduce pathogen survival. Post-digestion processing also has the potential to increase pathogen inactivation reducing risks for agricultural applications. The results of this study suggest that AD should not be considered equivalent to centralized wastewater treatment facilities, but may be considered a cost-effective option for distributed waste management that offers modest improvements in existing public sanitation while supporting urban agriculture.

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