Volume 4 Number 1 March 2014
ISSN 2043-9083
Journal of
Water, Sanitation and
Hygiene for
Development

  Journal of Water, Sanitation and Hygiene for Development | 07.1 | 2017

Research Paper

Assessing ambient and internal environmental conditions of pit latrines in urban slums of Kampala, Uganda: effect on performance

Anne Nakagiri, Charles B. Niwagaba, Philip M. Nyenje, Robinah K. Kulabako, John B. Tumuhairwe and Frank Kansiime

ABSTRACT

There is increasing interest to improve the functionality and performance of pit latrines in low income urban areas. This study aimed at assessing the ambient and pit environmental conditions and their implications on the performance (smell and fly nuisance) of pit latrines. Forty-two pit latrines were investigated in urban slums of Kampala, Uganda, through field observation and measurements of ambient and pit environmental conditions. The implications were assessed using oxygen-reduction potential (ORP) and its association with smell/insect nuisances. The pit temperature (21 to 30.7 °C), pH (5.0–11.8) and ORP (−247 to 65.9 mV) were consistently, significantly different ($p < 0.001$) between the surface and 0.5 m depth of pit content. The conditions in most (95%) pit latrines were anoxic (ORP < + 50 mV), and mainly within the acid formation range (ORP −199 to −51 mV). Most smelling pit latrines and flies were within the acid formation ORP range, with a significant association (gamma, G = 0.797, $p = 0.014$) between ORP and smell in clean latrines only. The results suggest that ventilation of pit latrines within urban slums was not sufficient. Additionally, cleanliness, moisture reduction and waste stabilisation could address bad smells in pit latrines, ultimately improving their usage in urban slums.

Key words | ambient conditions, environmental conditions, oxygen-reduction potential, performance, pit latrine, urban slums

Anne Nakagiri (corresponding author)
Charles B. Niwagaba
Philip M. Nyenje
Robinah K. Kulabako
Department of Civil and Environmental Engineering, College of Engineering, Design, Art and Technology,
Makerere University,
Kampala, Uganda
E-mail: *anakagiri@gmail.com*

John B. Tumuhairwe
Department of Agricultural Production, College of Agricultural and Environmental Sciences,
Makerere University,
Kampala, Uganda

Frank Kansiime
Department of Environmental Management, College of Agricultural and Environmental Sciences,
Makerere University,
Kampala, Uganda

INTRODUCTION

The use of pit latrines in low income areas of developing countries is high (Strande 2014). In sub-Saharan Africa (SSA) alone, over half of the urban population uses some form of pit latrine for human excreta disposal (Nakagiri *et al.* 2016). However, there is concern about their ability to provide adequate, safe, hygienic and sustainable sanitation access, especially in low income, densely populated, unplanned urban areas (Jenkins *et al.* 2014). This is because most of them are usually full, overflowing, badly smelling, dirty and insect infested, which has led to user dissatisfaction and increased excreta-related health risks, like open defecation, and improper pit emptying techniques (Nakagiri *et al.* 2016).

To improve the usage of pit latrines, there is a need to address the shortfalls mentioned above. Currently, there is high interest in understanding the occurrences in the pits for their improvement and management. Studies have assessed the physico-chemical, biological and mechanical (thermal and rheological) properties of pit latrine content (faecal sludge) to give an indication of filling rates, and to understand and model degradation processes (Nwaneri *et al.* 2008; Brouckaert *et al.* 2013; Todman *et al.* 2015). Additionally, quantification and characterisation of the malodorous components of pit latrines have been carried out (Lin *et al.* 2013). Other investigations have focused on the efficiency of additives

doi: 10.2166/washdev.2017.085

(Taljaard *et al.* 2003; Buckley *et al.* 2008; Bakare *et al.* 2015), and developing pit emptying and faecal sludge treatment technologies (Radford & Sugden 2014; Zuma *et al.* 2015). However, little attention has been paid to understanding the ambient and pit environmental conditions of latrines being used in various contexts and how these affect their performance, in terms of filling, smell and insect nuisances. Moreover, studies have shown that pit latrine functioning and contents are variable, affected by design, usage, maintenance, geophysical and climatic factors (Ryan & Mara 1983; Bakare *et al.* 2012).

Documented information on the ambient (immediate surroundings) and pit environmental conditions could provide useful information for developing strategies to improve pit latrines. For example, ambient temperature, humidity, airflow patterns and air velocity are key factors to consider when determining ventilation and odour management in buildings (Aflaki *et al.* 2015) and are of special interest especially in ventilated improved pit (VIP) latrines (Ryan & Mara 1983). During decomposition of matter, the environmental conditions control ecological characteristics, microbial activity, biochemical conversions and volatilisation of gases. For instance, the nature of degradation of the pit contents can be depicted by environmental parameters like pH, dissolved oxygen (DO) and oxygen-reduction potential (ORP), which have for long been used in monitoring, control and management of processes in wastewater (Zipper *et al.* 1998; Lynggaard-Jensen 1999). Additionally, most malodorous gases are weak acids or bases, whose volatilisation is affected by the chemical composition, pH, airflow rate and temperature at the gas–slurry surface (Blanes-Vidal *et al.* 2012).

The aim of this study was to assess the ambient and internal environmental conditions of pit latrines that could influence their functionality (smell, insect nuisance and thus usage) in a typical low income urban setting. An assessment of the implications of the environmental conditions on the performance of pit latrines was also done.

MATERIALS AND METHODS

Study area

This study was conducted in four slums of Kampala, the capital city of Uganda (Figure S1, available in the online version of this paper). The selection of the slums followed the criteria of having two types of terrains, low-lying with a high groundwater table (<1.5 m) and always flooding in the rainy seasons, and the other with a low ground-water table. Pit latrines in areas with low groundwater table were sunk in the ground and unlined. In contrast, in high water table areas, pit latrines were constructed fully lined and raised above the ground.

Data collection

In total, 42 simple pit and VIP latrines, located in both terrains were investigated: 15 in Bwaise II, 14 in Kibuye, 9 in Kamwokya and 4 in Nakulabye. Pit latrines selected were constructed out of brick superstructures and concrete slabs, and used by not more than four households per toilet stance. Pit latrines made of brick superstructures and concrete slabs are the most commonly used facilities within Kampala slums, which provide superior performance (reduced smells and insect nuisance) to other structures such as traditional latrines (Nakagiri *et al.* 2015) and are considered improved according to UNICEF and WHO (2008). Furthermore, latrines used by not more than four households (or about 20 individuals) per toilet stance ensure long-term hygienic and sustainable use (Günther *et al.* 2012).

Information collected in this study included the ambient conditions in the slums, general characteristics of the pit latrines and environmental conditions in the pit. Ambient conditions of temperature, wind speed and humidity in and around the pit latrines were measured using a pocket weather meter (Kestrel 4000, USA). The general characteristics of the pit latrines included the latrine dimensions, state and odour strength. Measurements of latrine stance dimensions (length, width, height) and depth of pit content from the drop hole were taken using a laser distance meter (Excelvan 60 m, USA). The latrine condition, clean or dirty, smelly or not, and presence of insects or not, were noted through observation, based on a scale used in an earlier study by Nakagiri *et al.* (2015). Details of the description of the different variables as used in this study are included in Table S1. Odour strength levels were taken from within the superstructure of the pit latrine with the door shut, using a handheld odour meter (Shinyei

OMX-ADM, Japan). To determine the environment in the pit, samples of the content were obtained at the surface (0 m), 0.5 m and 1 m depth below the surface of the content, using a fabricated multi-stage sludge sampler (Water For People, Uganda) (Figure S2, available in the online version of this paper). The pH, temperature, DO and ORP of the pit content were measured as soon as a given sample was obtained, using portable meters (Hanna HI991003, USA and Milwaukee MW600, USA). This study was carried out between September 2015 and December 2015. The information was collected during the day, between 9:00am and 3:00pm.

Data analysis

Data analysis in this study was done using SPSS version 21. The characteristics of the ambient and environmental conditions of the pit latrines investigated were presented using descriptive statistics and box and whisker plots. Significant variations in the environmental conditions around and within the pit latrine, and with respect to location, terrain and pit latrine type, were assessed using correlations, Student's t-tests and analysis of variance.

Implications of the environmental conditions in the pit on the performance of the latrines was done in two stages. First, variation of the ORP at different depths was presented categorically using horizontal bar charts. ORP was selected as it distinguishes well the biological processes, because it measures the net value of all oxidation-reduction reactions in an aqueous environment. Additionally, factors contributing to the electron activity, such as pH, temperature, biological activity and chemical constituents of the system are reflected by ORP (Peddie *et al.* 1990). The ORP categories (Table S2, available in the online version of this paper) were adopted from the literature and the redox tower, while chosen parameters were those known to impact on the performance of pit latrines (Gerardi 2008; Madigan *et al.* 2015). The ranges used in this study were: $\leq$200 mV (reduction of sulphur compound, acetate fermentation and methane formation); −199 to −51 mV (acid formation); −50 to +49 mV (nitrate/nitrite reduction); and $> +50$ mV (aerobic degradation). Second, an association between the environmental conditions (ORP) and smell (smelly, no smell)/insect (present, none) nuisance was assessed by cross-tabulation using Goodman and Kruskais' gamma (G). This was limited to only the surface of the pit content because that is where volatilisation of malodorous compounds into the gaseous state occurs for them to be smelt while flies are drawn to the matter at the pit surface.

RESULTS

General characteristics of pit latrines

The study involved 45% simple and 55% VIP latrines, with mean dimensions of 1,270 mm (length), 928 mm (width) and 1,871 mm (height) (Table S3, available in the online version of this paper). The pit latrines were within 911 (±526) mm of filling, with 74%, exhibiting a strong smell, 53% had few flies, 52% were dirty and had odour strength levels ranged from zero to 999 (odour meter limit), indicating inadequate performance (Table S4, available in the online version of this paper).

Ambient conditions around and inside the pit latrine structures

The temperatures around the pit latrine structures ranged from 23.3 to 34.3 °C while the relative humidity recorded was between 38.8 and 71.4% (Figure 1(a) and Table S5, available in the online version of this paper). The wind speed varied from 0 to 1.8 ms^{-1}. The range of ambient conditions inside the superstructures was 22.5–34.2 °C for temperature, 29.7–73.6% relative humidity and 0.0 to 0.6 ms^{-1} for wind speed. Analysis of variance revealed significant differences ($p \leq 0.001$) in the ambient conditions between the slums (Figure 1(b)) while none were found with respect to pit latrine type (simple or ventilated) and terrain. This implied that variations in ambient conditions are influenced by location. There was a strong significant correlation between the ambient conditions (temperature $r = 0.87$, $N = 42$, $p \leq 0.001$ and relative humidity $r = 0.74$, $N = 42$, $p \leq 0.001$) around and inside the pit latrine structures and none with respect to wind speed. The temperature and relative humidity within the pit latrine structures increased consistently with an increase in the same conditions outside. However, wind speed outside the superstructure did not directly influence the wind speed inside the superstructure.

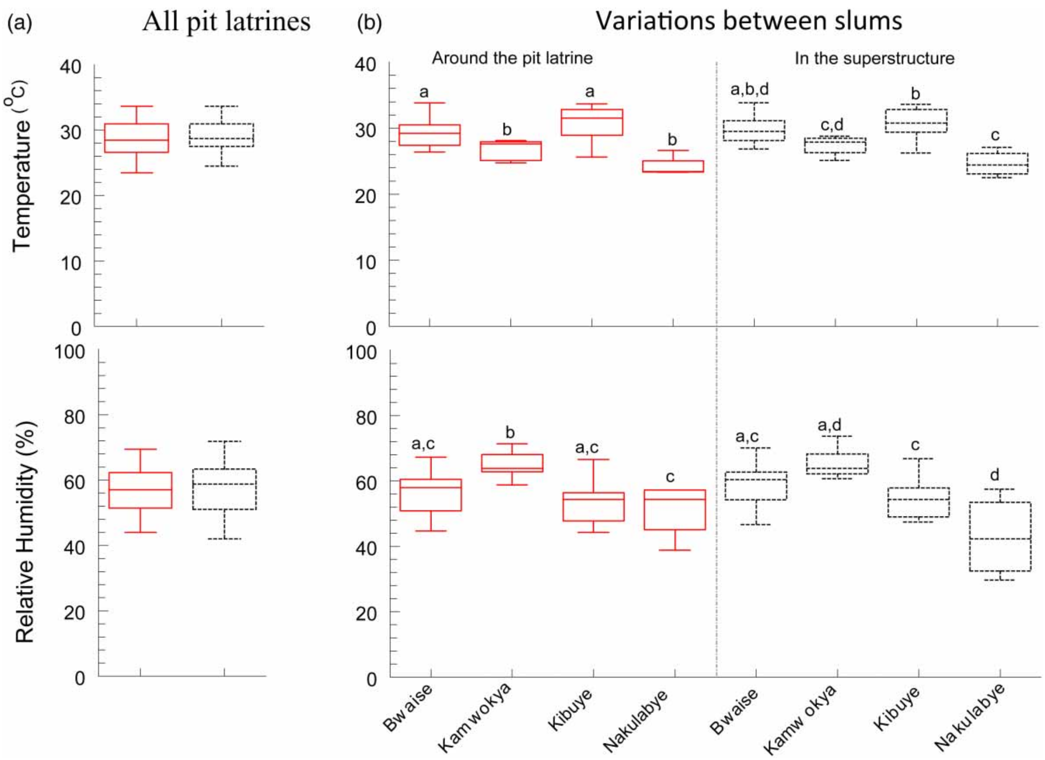

Figure 1 | Ambient conditions around and inside pit latrine structures. Box represents 50% of the data points, whisker represent minimum and maximum, line in box represents the median. Graphs with different letters (a–d) are significantly different from each other, $p < 0.05$.

The environmental conditions in the pit

The environmental conditions in the latrine pit are presented in Figure 2 and Table S6 (available in the online version of this paper). The temperature inside the pit ranged from 21 °C to 30.7 °C, with mean ± standard deviation values of 26.6 ± 2.3 °C (surface), 24.8 ± 1.1 °C (0.5 m) and 23.78 ± 0.5 °C (1 m) at the different depths. The pH of the pit content was between 5.0 and 11.8 while DO concentrations of 0 to 2.4 mg/L were recorded. The ORP ranged from −247 to 65.9 mV. Analysis of variance revealed significant differences in the environmental conditions with respect to slums and none with respect to pit latrine type and terrain. This implied that variations in pit environment could be influenced by only location and not the pit latrine type or the terrain.

There was a significantly strong correlation between the ambient temperature and that at the surface of the pit content ($r = 0.57$, $N = 42$, $p \leq 0.001$ around the superstructure vs. pit content and $r = 0.50$, $N = 42$, $p \leq 0.001$ in the superstructure vs. pit content). The temperature at the surface of the pit content in over half of the pit latrines was consistently lower than the ambient temperature. Further, significant t-statistics ($t(41) = 5.4$, $p < 0.001$ around the superstructure vs. pit content and $t(41) = 6.4$, $p < 0001$ in the superstructure vs. pit content) of the ambient conditions and the pit content imply that the variation is not due to chance.

Analysis for associations in the environmental conditions at different depths revealed significant Pearson's correlation coefficients (Table S7, available in the online version of this paper). The temperature and ORP dropped with increase in depth and this was consistent in a number of the pits. A consistently significant ($r = 0.84$, $N = 42$, $p \leq 0.001$) increase in pH was also noted between the content at the surface and at 0.5 m, and it decreased significantly at 1 m in most of the pits. In addition, a drop in DO was noted with increased depth. However, the drop was significant and consistent only between the content at the surface and that at 0.5 m. Between 0.5 m and 1 m depth, the results show an overall decrease in DO. However, the correlation was not significant, implying that the decrease was not consistent across the pit latrines.

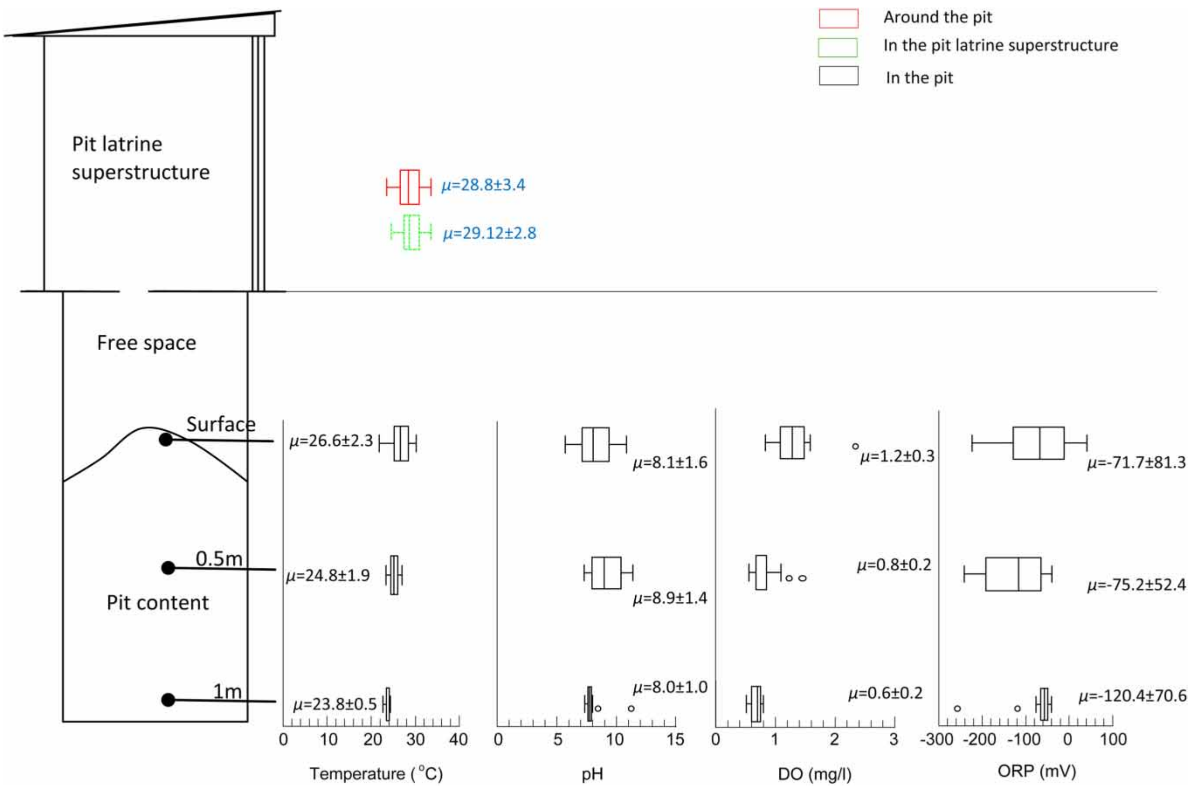

Figure 2 | Environmental conditions in the pit. Box represents 50% of the data points, whiskers represent minimum and maximum values, lines in the box represent the median. μ is the mean $\pm$ standard deviation.

The paired t-statistics values (Table S7, available in the online version of this paper) were significant ($p \leq 0.001$) for all the pit environmental conditions at the surface and at 0.5 m. This implied that the average changes in the values of each parameter was not by chance, and could thus be explained. Thereafter, between 0.5 m and 1 m the noted change was due to chance variation.

Implications of the pit environmental condition on the performance of pit latrines

Categorical variations of ORP in the pit

Environmental conditions in pit latrines have an implication on the nature of biological reactions, which in turn, affects their performance. To depict the biological reactions in pit latrines, ORP values have been presented categorically (Figure 3). It was noted that 95% of the pit latrines were anoxic (ORP values less than +50 mV). Aerobic conditions (ORP values greater than +50 mV) were noted at the surface of the pit content of only 5% of the pit latrines.

The ORP levels for samples taken from the surface of the pit content (Figure 3(a)) in the majority of the latrines (48%) were within the acid formation range (ORP values −199 mV to −51 mV), while 43% of the pit latrines were within the nitrite/nitrate reduction level (ORP values of −50 mV to +50 mV). Reduction of sulphur compounds (ORP < −200 mV), methane formation (ORP < −240 mV) and acetate fermentation (ORP < −280 mV) conditions were found in only 7% of the pit latrines. At increased depth below the pit surface (Figure 3(b) and 3(c)), acid formation (−199 mV to −51 mV) was common in the majority of the pit latrines. In addition, at 0.5 m, there was a decrease in the number of pit latrines in the nitrite/nitrate reduction range (−50 mV to +50 mV) to only 17% and an increase in those in the sulphur, acetate reduction and methane formation range to 17.1%.

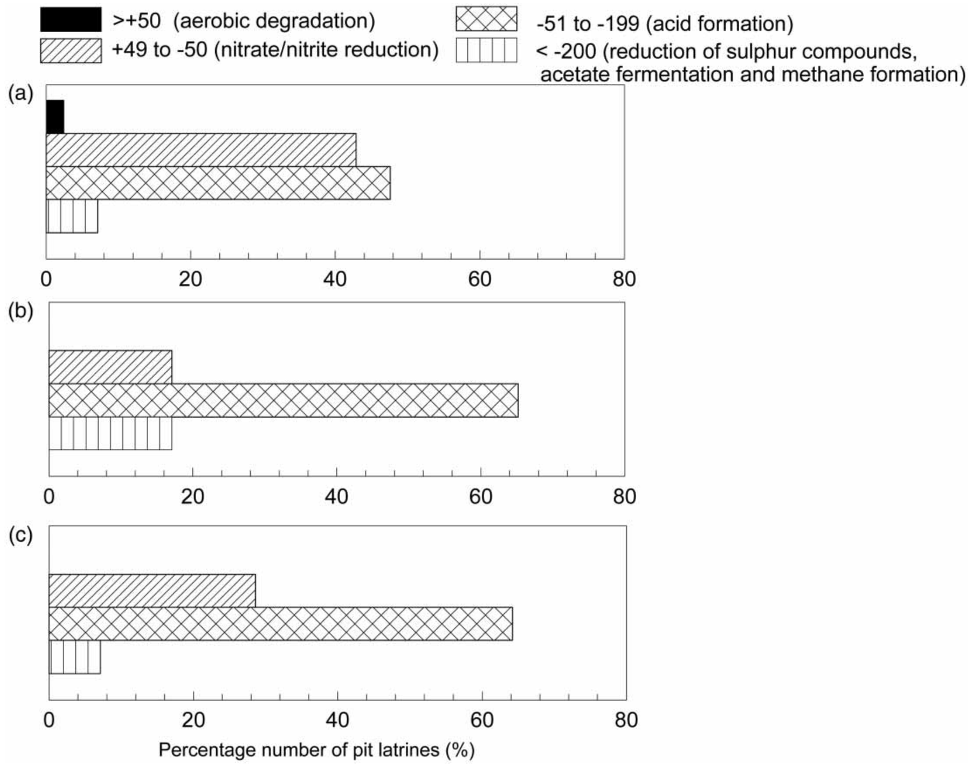

Figure 3 | Pit latrine ORP ranges at different depths of the pit content: (a) surface of the pit content, (b) 0.5 m below the surface and (c) 1 m below the surface of the pit content.

Relating ORP categories to smell and flies in pit latrines

Cross-tabulation of ORP with smell and fly nuisance (Tables 1 and 2) revealed that the most smelling pit latrines (N = 17) and flies (N = 10) were found within the ORP ranges of −199 mV to −50 mV followed by −50 mV to +50 mV (N = 12 smell and N = 8 flies). However, gamma analysis for association showed no significant correlations between ORP and smell (G = 0.483, p = 0.115) or fly nuisance (G = 0.081, p = 0.767). Results from cross-tabulation analysis of only clean pit latrines (Tables 1 and 2) showed that smell and flies were also found mainly within the ORP ranges of −199 mV to −50 mV (N = 9; smell and N = 5; flies). The clean pit latrine with ORP range less than −200 mV was also smelling and had flies (Table 2).

Gamma analysis for associations within clean pit latrines showed a strong positive correlation between ORP and smell, which was statistically significant (G = 0.797, p = 0.014). However, while there was a moderate correlation between ORP and fly nuisance, it was not

Table 1 | Cross-tabulation of ORP ranges with smell

	All pit latrines			Clean pit latrines			Dirty pit latrines		
	No smell	**Smell**	**Total**	**No smell**	**Smell**	**Total**	**No smell**	**Smell**	**Total**
>+ 50	0	1	1	0	0	0	0	1	1
+49 to −50	6	12	18	5	2	7	1	10	11
−51 to −199	3	17	20	3	9	12	0	8	8
≤200	0	3	3	0	1	1	0	2	2
Total	9	33	42	8	12	20	1	21	22

Table 2 | Cross-tabulation of ORP ranges with Fly nuisance

	All pit latrines			Clean pit latrines			Dirty pit latrines		
	No flies	Flies	Total	No flies	Flies	Total	No flies	Flies	Total
>+50	0	1	1	0	0	0	0	1	1
+49 to −50	10	8	18	5	2	7	5	6	11
−51 to −199	10	10	20	7	5	12	3	5	8
≤200	1	2	3	0	1	1	1	1	2
Total	21	21	42	12	8	20	9	13	22

statistically significant (G = 0.451, $p = 0.277$). The results indicate that as ORP at the surface of the pit content decreases, there is likely to be smell and flies in pit latrines. However, the relationship is only statistically significant for smell among clean pit latrines. There were no significant correlations for ORP and smell (G = 0.818, $p = 0.306$) or fly nuisance (G = 0.70, $p = 0.849$) among the dirty latrines.

DISCUSSION

The study aimed at assessing the ambient and environmental conditions of pit latrines and their implication on the performance of pit latrines. General assessment of level of pit content, cleanliness, smell and flies showed that while some pit latrines are considered improved, they do not provide hygienically safe access as sanitation facilities. Moreover, studies have shown that full, dirty, smelling latrines that have flies are related to user dissatisfaction and are often abandoned for open defecation (Tumwebaze *et al.* 2012; Kwiringira *et al.* 2014), posing a risk to public health. These findings are consistent with previous studies in urban slums (Kwiringira *et al.* 2014; Nakagiri *et al.* 2015; Okurut *et al.* 2015).

The ambient temperature (range 23.3 to 34.3 °C) and relative humidity (29.7–73.6%) around the pit latrine superstructure is typical of that of tropical climates (18–35 °C) (Pidwirny 2006). However, the results of the study showed low wind speeds (0.56 ± 0.46 m/s) and, in some cases, there was no wind movement (0 m/s). Studies in Botswana and Zimbabwe found wind speeds of 2 m/s and above (Ryan & Mara 1983). The low ambient wind speeds in this study could be attributed to obstruction from the surrounding buildings as pit latrines in urban slums are placed close to the houses due to overcrowding. While ventilation pipes are meant to increase air flow in the latrines, the results from the study showed no air movements within the superstructures. This is because, while the ventilation pipes of the VIP latrines are well above the highest point of the latrine roof, they did not exceed the roofs of the nearby residential buildings. Air movement in VIPs is also constrained by inappropriate vent pipe sizing and location of openings (Nakagiri *et al.* 2015).

The environmental conditions of the contents from the pits in this study (temperature, 21 °C to 30.7 °C; pH, 5.0 to 11.8 and DO, 0 mg/L to 2.4 mg/L) varied significantly with location and not according to pit latrine type nor terrain. This could be because classification of simple and VIP latrines is determined by the presence of a vent pipe on the superstructure and not the nature of the pit. However, variations based on slums could arise from the differences in characteristic between slums. Previous studies have reported temperature of 24.2 °C to 26.2 °C and DO 0.9 mg/L–1.72 mg/L (Kimuli *et al.* 2016) and temperature of 25.5 °C to 33 °C and pH 5.2–8.2 (Irish *et al.* 2013). Other studies found pH ranges of 7.31–9.01 (Wood 2013), 6.4–6.9 (Appiah-Effah & Nyark 2014) and from 5.3 to 7.5 (Rose *et al.* 2015). The rise in pH within the pits in this study may be attributed to accumulation of ammonium ions from urea in the pit latrines.

There was a significant difference in the environmental conditions between the surface and that at 0.5 m depth of the pit content and not thereafter, which could be attributed to the different stages of faecal matter degradation and associated physical state, chemical and biological processes in the pit. This observation is in agreement with previous studies (Buckley *et al.* 2008; Bakare 2014) which showed that degradation of matter occurred from the surface down to some section of the pit.

The ORP values have for long been used to depict different cellular activities of organic matter degradation (Koch & Oldham 1985; Ndegwa *et al.* 2007). Even with the occurrence of DO in the pit content, ORP ranges show that the main form of degradation in the majority (95%) of the pit latrines was anaerobic. This is contrary to Nwaneri *et al.*'s (2008) assertion that rapid degradation of matter under aerobic conditions occurs at the surface of the pit content until the material is covered. The difference in findings could be attributed to high moisture content (about 80%) (Kimuli *et al.* 2016) and low air circulation indicated by the low wind speed observed in the pit latrines in this study. Among the causes of high moisture content are included, cleaning the latrines before/after use, by every user, and directing the wash water into the pit and, in some cases, use of the facility as a bathroom (Nakagiri *et al.* 2015). In addition, the pit latrines are without urine diversion, thus human excreta (faeces and urine) is collected in the same pit.

Anaerobic degradation of organic matter is normally considered a two-stage process involving acid formation (hydrolysis) and waste stabilisation, where microorganisms exploit any oxidation-reduction reaction resulting in formation of recalcitrant stable compounds (McCarty 1964; Rittmann & McCarty 2001). From the results of this study, hydrolysis may not be a limiting stage in anaerobic degradation, as the majority of the latrines were in the acid formation (−199 mV to −51 mV) range. This is further supported by the pH range (5.0 to 11.8) of the pit contents in this study and volatile organic compounds reported in other studies (Lin *et al.* 2013). Material stabilisation, as noted in this study, could have been dominated by denitrification, while optimal ORP ranges for reduction of sulphur compounds (ORP < −200 mV), methane formation (ORP < −240) and acetate fermentation (ORP < −280 mV) were not attained in most of the pit latrines. Inhibition for stabilisation (through methanogenesis) within the pits could have resulted from the high pH ranges as the optimal pH range for methanogenic bacteria is 6.5 to 7.5 (Parkin & Owen 1986).

Smell in clean pit latrines in this study was in the acid formation range (−199 mV to −50 mV) and ORP range less than −200 mV. These finding are in agreement with Lin *et al.* (2013) who characterised a range of volatile compounds in faecal sludge from pit latrines. Further, the study showed that with a decrease in ORP in clean latrines, smell was more likely to be evident. However, flies were not significantly associated with an increase in ORP, possibly because of their phototropic nature. In addition, the dirty nature of the pit latrine could have contributed to lack of association between ORP and smell in those latrines.

IMPLICATIONS AND CONCLUSION

The findings of this study suggested that improvements to the functioning of pit latrines in urban slums should consider the ambient and internal environmental conditions and their location. The results showed that natural ventilation of pit latrines by introducing a vent pipe was not effective because of overcrowding in urban slums. This implied that improving ventilation in pit latrines in slum settings may necessitate introduction of mechanical devices to increase air flow in the structures.

Further, the results showed a relationship between the environmental conditions in the pit (represented by ORP) and the performance (smell and fly nuisance). However, the association was statistically significant for only smell in clean pit latrines. This implied that changes in the biological processes in the pit could only affect the smell of the latrine and be effective when they were kept clean.

As noted, significant anaerobic degradation activity existed within the top 0.5 m of the pit content. Reducing the moisture content, by introducing ways of limiting the amount of liquid that gets into the pit, could improve the aerobic nature and processes of the pit content (realised by an increase in ORP), resulting in a reduction in smell. This could be attained by use of urine diversion inserts in the drop holes of existing latrines. In addition, behaviour change could be attained though sensitisation to ensure that latrines are cleaned once a day, by mopping or directing the wash water into a separate soakaway, and are not used as bathrooms. Attaining material stabilisation by use of microorganisms and/or enzymes operating within the noted environmental conditions could be sufficient. This could effect the conversion of intermittent compounds, most malodorous by nature to more stable compounds. Finally, besides pit latrine cleanliness, interventions to fly nuisance could look at entomological studies into the types of flies and their behaviour.

In conclusion, this research highlighted the inadequacy in performance (smell and flies) and ventilation of pit latrines in urban slums. Addressing cleanliness, modifying the environment in the pit to reduce the moisture content through urine diversion or behaviour change, could improve the performance of pit latrines. Additionally, attaining material stabilisation and entomological studies could provide additional options for reducing smell and fly nuisance. Thus, the findings provide important information for practitioners, researchers and bio-additive manufacturers looking at improving the performance of pit latrines within urban slums.

ACKNOWLEDGEMENTS

This research was carried out as part of the project entitled 'Stimulating Local Innovation on Sanitation for the Urban Poor in SSA and South-East Asia', which is funded by the Bill & Melinda Gates Foundation, United States through UNESCO-IHE in partnership with Makerere University. The grant number is OPP1029019. The authors are grateful for the assistance provided by Dr. Joel R. Kinobe, Mr. Swaib Semiyaga and Mr. Alfred Ahumuza in field data collection. Mr. Swaib Semiyaga is acknowledged for proof reading and checking the English language in this paper.

REFERENCES

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z. & Baharum, M. R. 2015 A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings* **101**, 153–162.

Appiah-Effah, E. & Nyark, K. B. 2014 Characterization of public toilet sludge from peri-urban and rural areas of Ashanti region of Ghana. *Journal of Applied Sciences in Environmental Sanitation* **9** (3), 175–184.

Bakare, B. F. 2014 *Scientific and Management Support for Ventilated Improved Pit Latrines (VIP) Sludge Content*. PhD Thesis, School of Chemical Engineering, University of KwaZulu Natal (UKZN), Durban, South Africa.

Bakare, B., Foxon, K., Brouckaert, C. & Buckley, C. 2012 Variation in VIP latrine sludge contents. *Water SA* **38** (4), 479–486.

Bakare, B., Brouckaert, C., Foxon, K. & Buckley, C. 2015 An investigation of the effect of pit latrine additives on VIP latrine sludge content under laboratory and field trials. *Water SA* **41** (4), 509–514.

Blanes-Vidal, V., Guàrdia, M., Dai, X.-R. & Nadimi, E. 2012 Emissions of NH_3, CO_2 and H_2S during swine wastewater management: characterization of transient emissions after air-liquid interface disturbances. *Atmospheric Environment* **54**, 408–418.

Brouckaert, C., Foxon, K. & Wood, K. 2013 Modelling the filling rate of pit latrines. *Water SA* **39** (4), 555–562.

Buckley, C. A., Foxon, K. M., Brouckaert, C. J., Rodda, N., Nwaneri, C. F., Balboni, E., Couderc, A. & Magagna, D. 2008 *Scientific Support for the Design and Operation of Ventilated Improved pit Latrines (VIPS) and the Efficacy of pit Latrine Additives.* Water Research Commission, South Africa.

Gerardi, M. 2008 *ORP Management in Wastewater as an Indicator of Process Efficiency*. Application Note. Environmental YSI, Yellow Springs, OH. Available at: www.ysi.com/File%20Library/Documents/Application%20Notes/A567-ORP-Management-in-Wastewater-as-an-Indicator-of-Process-Efficiency.pdf (accessed 10 January 2016).

Günther, I., Niwagaba, C. B., Lüthi, C., Horst, A., Mosler, H.-J. & Tumwebaze, I. K. 2012 *When is Shared Sanitation Improved Sanitation? The Correlation Between Number of Users and Toilet Hygiene*. MPRA Paper No. 45830. Available at: http://mpra.ub.uni-muenchen.de/45830/.

Irish, S., Aiemjoy, K., Torondel, B., Abdelahi, F. & Ensink, J. H. J. 2013 Characteristics of latrines in central Tanzania and their relation to fly catches. *PLoS ONE* **8** (7), e67951. doi:10.1371/journal.pone.0067951.

Jenkins, M., Cumming, O., Scott, B. & Cairncross, S. 2014 Beyond 'improved' towards 'safe and sustainable' urban sanitation: assessing the design, management and functionality of sanitation in poor communities of Dar es Salaam, Tanzania. *Journal of Water, Sanitation and Hygiene for Development* **4** (1), 131–141.

Kimuli, D., Zziwa, A., Banadda, N., Kabenge, I., Kiggundu, N., Kambugu, R., Wanyama, J., Tumutegyereize, P. & Kigozi, J. 2016 Quantification of physico-chemical characteristics and modeling faecal sludge nutrients from Kampala city slum pit latrines. *International Journal of Research in Engineering & Advanced Technology (IJREAT)* **3** (6), 129–141.

Koch, F. & Oldham, W. 1985 Oxidation-reduction potential – a tool for monitoring, control and optimization of biological nutrient removal systems. *Water Science and Technology* **17** (11–12), 259–281.

Kwiringira, J., Atekyereza, P., Niwagaba, C. & Günther, I. 2014 Descending the sanitation ladder in urban Uganda: evidence from Kampala Slums. *BMC Public Health* **14** (1), 624.

Lin, J., Aoll, J., Niclass, Y., Velazco, M. I., Wünsche, L., Pika, J. & Starkenmann, C. 2013 Qualitative and quantitative analysis of volatile constituents from latrines. *Environmental Science & Technology* **47** (14), 7876–7882.

Lynggaard-Jensen, A. 1999 Trends in monitoring of waste water systems. *Talanta* **50** (4), 707–716.

Madigan, M. T., Martinko, J. M., Bender, K. S., Buckley, D. H. & Stahl, D. 2015 *Brock Biology of Microorganisms*. Pearson Education Limited, Harlow, UK.

McCarty, P. L. 1964 Anaerobic waste treatment fundamentals. *Public Works* **95** (9), 107–112.

Nakagiri, A., Kulabako, R. N., Nyenje, P. M., Tumuhairwe, J. B., Niwagaba, C. B. & Kansiime, F. 2015 Performance of pit latrines in urban poor areas: a case of Kampala, Uganda. *Habitat International* **49**, 529–537.

Nakagiri, A., Niwagaba, C. B., Nyenje, P. M., Kulabako, R. N., Tumuhairwe, J. B. & Kansiime, F. 2016 Are pit latrines in urban areas of Sub-Saharan Africa performing? A review of usage, filling, insects and odour nuisances. *BMC Public Health* **16** (1), 1–16.

Ndegwa, P. M., Wang, L. & Vaddella, V. K. 2007 Potential strategies for process control and monitoring of stabilization of dairy wastewaters in batch aerobic treatment systems. *Process Biochemistry* **42** (9), 1272–1278.

Nwaneri, C. F., Foxon, K. M., Bakare, B. F. & Buckley, C. A. 2008 Biological degradation processes within a pit latrine. In *WISA Biennial Conference & Exhibition*, 18–22 May, Water Institute of Southern Africa (WISA), Sun City, South Africa.

Okurut, K., Kulabako, R., Abbott, P., Adogo, J., Chenoweth, J., Pedley, S., Tsinda, A. & Charles, K. 2015 Access to improved sanitation facilities in low-income informal settlements of East African cities. *Journal of Water Sanitation and Hygiene for Development* **5** (1), 89–99.

Parkin, G. F. & Owen, W. F. 1986 Fundamentals of anaerobic digestion of wastewater sludges. *Journal of Environmental Engineering* **112** (5), 867–920.

Peddie, C. C., Mavinic, D. S. & Jenkins, C. J. 1990 Use of ORP for monitoring and control of aerobic sludge digestion. *Journal of Environmental Engineering* **116** (3), 461–471.

Pidwirny, M. 2006 Climate classification and climatic regions of the world. In *Fundamentals of Physical Geography* (J. F. Petersen, D. Sack & R. E. Gabler, eds)., 2nd edn. Cengage Learning, Okanagan, Canada. Available at: http://www.physicalgeography.net/fundamentals/7v.html (accessed 22 March 2016).

Radford, J. & Sugden, S. 2014 Measurement of faecal sludge in-situ shear strength and density. *Water SA* **40** (1), 183–188.

Rittmann, B. E. & McCarty, P. L. 2001 *Environmental Biotechnology: Principles and Applications*. McGraw-Hill, New York, USA.

Rose, C., Parker, A., Jefferson, B. & Cartmell, E. 2015 The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Critical Reviews in Environmental Science and Technology* **45** (17), 1827–1879.

Ryan, B. A. & Mara, D. D. 1983 *Ventilated Improved Pit Latrines: Vent Pipe Design Guidelines*. Washington DTWB, Washington, DC, USA.

Strande, L. 2014 The global situation. In *Faecal Sludge Management: Systems Approach for Implementation and Operation* (L. Strande, M. Ronteltap & D. Brdjanovic, eds.), IWA Publishing, London, UK.

Taljaard, L., Venter, A., Gorton, D. & South Africa Water Research Commission 2003 *An Evaluation of Different Commercial Microbial or Microbially-derived Products for the Treatment of Organic Waste in Pit Latrines*. Water Research Commission, Gezina, South Africa.

Todman, L. C., van Eekert, M. H., Templeton, M. R., Hardy, M., Gibson, W. T., Torondel, B., Abdelahi, F. & Ensink, J. H. 2015 Modelling the fill rate of pit latrines in Ifakara, Tanzania. *Journal of Water, Sanitation and Hygiene for Development* **5** (1), 100–106.

Tumwebaze, K. I., Orach, G. C., Niwagaba, C., Luthi, C. & Mosler, H. 2012 Sanitation facilities in Kampala slums, Uganda: users' satisfaction and determinant factors. *International Journal of Environmental Health Research* **1** (1), 1–14.

UNICEF and WHO 2008 *Progress on Drinking Water and Sanitation. Special Focus on Sanitation*. WHO/UNICEF Joint Monitoring Program for Water Supply and Sanitation. Available at: http://www.who.int/water_sanitation_health/monitoring/jmp2008/en/index.html (accessed 5 August 2012).

Wood, K. 2013 *Transformation of Faecal Sludge in VIPs: Modelling Fill Rate With an Unsteady-State Mass Balance*. MScEng Thesis, University of KwaZulu-Natal.

Zipper, T., Fleischmann, N. & Haberl, R. 1998 Development of a new system for control and optimization of small wastewater treatment plants using oxidation-reduction potential (ORP). *Water Science and Technology* **38** (3), 307–314.

Zuma, L., Velkushanova, K. & Buckley, C. 2015 Chemical and thermal properties of VIP latrine sludge. *Water SA* **41** (4), 534–540.

First received 17 May 2016; accepted in revised form 26 October 2016. Available online 2 January 2017