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Manga, M, Evans, BE orcid.org/0000-0001-9815-3141, Camargo-Valero, MA orcid.org/0000-0003-2962-1698 et al. (1 more author) (2016) Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management. Water Science and Technology, 74 (12). pp. 2795-2806. ISSN 0273-1223

https://doi.org/10.2166/wst.2016.451

Effect of filter media thickness on the performance of sand drying beds used for faecal sludge management

M. Manga[1,3*], B. E. Evans[1], M. A. Camargo-Valero[1,2], N. J. Horan[4]

[1]Institute for Public Health and Environmental Engineering (iPHEE), School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK

[2]Departamento de Ingeniería Química, Universidad Nacional de Colombia, Campus La Nubia, Manizales, Colombia

[3]Department of Construction Economics and Management, College of Engineering, Design, Art and Technology (CEDAT), Makerere University, P.O. Box 7062, Kampala, Uganda.

[4]AquaEnviro Ltd., Appleton Court, Calder Park, Wakefield WF2 7AR, UK

[*]*Corresponding email: cn10m3m@leeds.ac.uk / musamanga@cedat.mak.ac.ug*

Abstract

The effect of sand filter media thickness on the performance of faecal sludge (FS) drying beds was determined in terms of dewatering time, contaminant load removal efficiency, solids generation rate, nutrient content and helminth eggs viability in the dried sludge. A mixture of VIP-latrine sludge and septage in the ratio 1:2 was dewatered using three pilot-scale sludge drying beds with sand media thicknesses of 150mm (A), 250mm (B) and 350mm (C). Five dewatering cycles were conducted and monitored for each drying bed. Although filter A (150mm) had the shortest average dewatering time of 3.65 days followed by filters B (250mm) and C (350mm) with 3.83 and 4.02 days respectively, there was no significant difference ($p>0.05$) attributable to filter media thickness configurations. However, there was a significant difference for the percolate contaminant loads in the removal and recovery efficiency of suspended solids, total solids, total volatile solids, nitrogen species, total phosphorus, COD, DCOD and BOD, with the highest removal efficiency for each parameter achieved by the filter C (350mm). There were also significant differences in the nutrient content (NPK) and helminth eggs viability of the solids generated by the tested filters. Filtering media configurations similar to filter C (350mm) have the greatest potential for optimising nutrient recovery from FS.

Keywords: dewatering; dewatered solids; faecal sludge; filtering media thickness; Helminth eggs; percolate;

Introduction

Globally, faecal sludge (FS) management is a growing challenge especially in urban Africa, and this is due to rapid urbanisation, population growth and poor FS treatment facilities. These have contributed to an increase in the volume of FS generated and accumulated within urban areas. Currently, it is estimated that over 2.7 billion people globally rely on on-site sanitation facilities for their sanitation needs, and this population is anticipated to increase to 5 billion by 2030 (Strande, 2014). Of which, In Sub-Saharan Africa, about 65-100% of the urban residents are served by on-site sanitation technologies other than sewer systems. These systems generate significant volumes of highly concentrated FS material without the benefit of the dilution that is provided by water-borne sewered sanitation infrastructure (Montangero and Strauss 2004).

Despite the progress made in the past decades to deliver improved sanitation in urban Africa, sanitation service delivery in the form of infrastructure development for FS treatment facilities has not been harmonised with the needs of the increasing population. Therefore, sustainable FS treatment technologies are largely still lacking in these areas. Consequently, FS is collected directly from on-site sanitation installations without any treatment and subsequently used in agriculture and aquaculture or indiscriminately disposed of into the environment (e.g., natural wetlands and drainage channels), leading to severe environmental and public health risks. Given that FS from on-site sanitation facilities is characterised by nutrient and pollutant concentrations that are 10-100 times stronger than domestic wastewater (Strauss *et al.* 1997), its indiscriminate disposal into water bodies leads to serious public health risks in addition to oxygen depletion in aquatic systems. Yet, FS contains valuable organic matter and plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K), which can be recovered for safe reuse in agriculture. However, FS contains pathogens that need to be inactivated if it is to be reused in agriculture so as to minimise the public health risks. In urban Africa where helminthic infections are rampant, helminth eggs especially *Ascaris* eggs have been suggested as the best hygienic indicator since they are more resistant to die-off than all other excreted pathogens (Feachem *et al.* 1983).

Various methods for low-cost FS treatment have been described, of which unplanted sludge drying beds followed by co-composting of biosolids are considered to be amongst the most feasible options (Cofie *et al.* 2009). Unplanted sludge drying beds have proven to be a technically feasible FS treatment technology with the recovery of nutrient and biosolids for agriculture reuse. However, the current design and operational criteria has been associated with some limitations such as: generation of low quality dewatered solids in terms of NPK and organic matter; percolate with high contaminant loads; longer dewatering periods and high required footprint of about 0.05-0.08m^2/capita of land area requirement for treatment of FS to about 20-70%TS (Cofie *et al.* 2006; Heinss *et al.* 1998). These limitations have not been thoroughly addressed to-date and thus, they formed a basis for this research study.

Previous studies on FS dewatering have attempted to address these limitations by focussing on: the particle size of sand bed filters and their solid loading rates (Kuffour 2010); the use of greenhouses or mixing of FS on beds (Seck *et al.* 2015); and dewatering of FS using locally produced natural conditioners (Gold *et al.* 2016). Even though, the dewatering times improved, the quality of the solids for reuse in agriculture remained very low and with very high percolate contaminant load. Little focus has been placed on the sand filtering thickness so as to address the limitations with an aim of enhancing nutrient recovery in the resulting dry solids, contaminant load removal in percolate and shortening the dewatering time. Therefore, this research investigates the relationship between sand filtering media thickness and: i) dewatering time; ii) removal efficiency of contaminant load in percolate; iii) solids nutrient and microbiology quality (NPK and helminth eggs); and iv) solids generation rate.

Material and Methods

Pilot-scale faecal sludge dewatering facility

The study was conducted in Kampala, the capital city of Uganda at the geographical location of latitude 0°18′58″ N, longitude 32°34′55″ E and elevation of 1,223m above sea level. The pilot scale dewatering facility was designed and constructed at Lubigi FS treatment facility, National Water and Sewerage Corporation (NWSC). The facility consisted of three 1m^3 capacity FS storage PVC tanks, percolate storage containers, outlet drains, and 12 unplanted sludge drying beds of 1m^2 effective drying area (see Figure 1).

Bed preparation with different sand filtering media thickness

The drying beds were constructed with a raised plinth wall approximately 1m from the ground level. The beds comprised of three layers which included: bottom base supporting layer made of coarse aggregates with average particle size within the range of 10 - 19mm and thickness of 150mm; followed by middle supporting base of fine gravel with average diameter between 5 and 10mm and thickness of 100mm; and lastly, the top layer which is the sand filtering media of particle size within the range of 0.2 - 0.6mm (Kuffour *et al.* 2009). The sand media had a uniformity coefficient of 2.833. Nine out of the twelve sludge drying beds were constructed with three different sand filtering media thickness of 150 mm, 250 mm, and 350 mm. Each of these beds was constructed in triplicate and arranged in a randomised block design. A PVC mosquito net was placed on top of the sand filtering media so as to ease the removal of dewatered solids from the drying beds and to reduce sand media losses (Figure 1D and 1C).

Faecal sludge preparation and dewatering

Raw FS used in this study was collected from informal settlements located less than 0.5km from the project site (i.e., Bwaise, Kawempe and Makerere Kikoni). Sludge from VIP latrines (VIP sludge) and septic tanks (septage) was collected from the FS suction trucks that discharge to the Lubigi treatment plant and stored separately in 1m^3 PVC tanks. It was then transferred to the third PVC storage tank, where it was thoroughly mixed in the ratio of 1:2 (VIP sludge: septage) by volume prior to application on FS drying beds. Studies conducted in Ghana showed that this ratio resulted in good dewaterability characteristics (Cofie *et al.* 2006; Koné *et al.* 2007). The dosing depth of <200mm was applied on each drying bed.

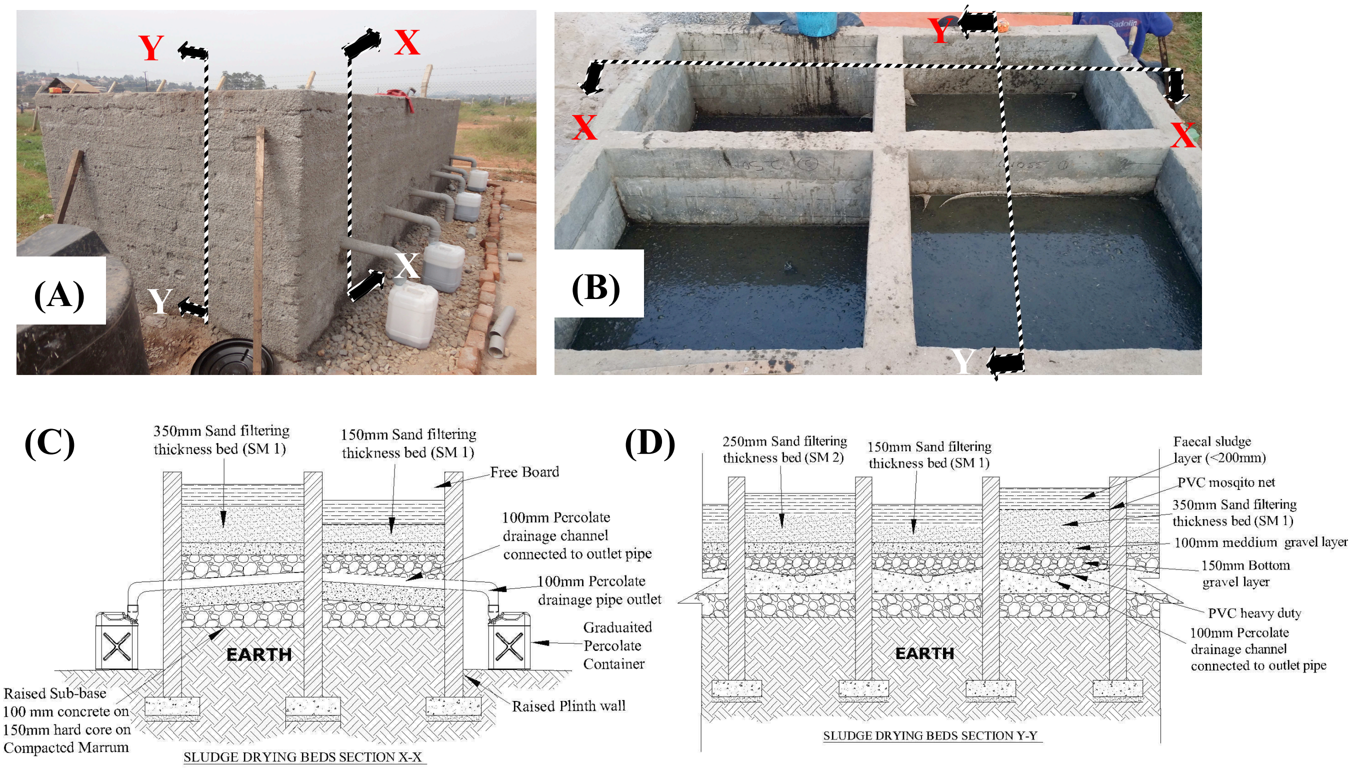

Figure 1: Views of the pilot-scale FS drying beds (A and B), including Cross Section X-X (C) and Longitudinal Section Y-Y (D) through the FS drying beds showing their construction details.

Monitoring FS dewatering phase

The percolate volume collected from each drying bed was measured every 24 hours and the total number of days taken for complete dewatering of sludge was recorded. Dewatering was considered complete once the flow of percolate from the drying bed stopped and the dewatered sludge could be removed easily from the drying beds with a spade. Five dewatering trials were conducted and monitored for a period of 7 months.

FS, percolate and dewatered solids sampling

For each cycle, raw FS sludge (VIP sludge and septage) delivered at the dewatering facility as well as the mixed FS was sampled and analysed immediately for physicochemical and microbiological parameters prior to dewatering on drying beds. At least 10 grab samples were taken from each FS storage tank at different sampling points. These were then thoroughly mixed to form a composite sample, which was taken to the laboratory for analysis. Percolate was collected daily from each drying bed and measured on site for temperature, Electrical Conductivity (EC) and pH until the dewatering cycle was complete. The percolate collected from each drying bed was stored separately at <4^{o}C until the completion of the dewatering cycles to prevent any microbial activity. On completion of the dewatering cycle, a composite sample of the percolate was formed from each drying bed and taken for analysis. From each filter bed, dewatered solids were removed carefully and weighed. It was then thoroughly mixed and analysed for physicochemical and microbiological parameters.

Laboratory analysis

Percolate and raw FS samples were analysed for: pH, EC, Total Solids (TS), Suspended Solids (SS), Total Volatile Solids (TVS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved COD (DCOD), Total Ammonia (TNH_3-N), Nitrate (NO_3), Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP) and Potassium (K). The dewatered solids were analysed for moisture content, TVS, TN (sum of TKN +NO_3-N), TP and K. These parameters were analysed at the NWSC laboratories following standardised analytical methods (APHA-AWWA-WEF. 2005). The raw FS, percolate and dewatered solids were also analysed for helminth eggs (i.e., *Ascaris* eggs) following the method developed by the U.S. EPA (2003).

Statistical analysis

The results were reported as average values ± one standard deviation of triplicate readings and subjected to statistical analysis using IBM SPSS Statistic 21.0 software. Data was analysed using non-parametric Friedman test to examine the significance of differences amongst mean values of each filter media configuration, with 95% confidence level. Spearman's rho test was also used to test the significance of the correlation coefficients between the dewatering time and the removal efficiency of contaminate loads from the raw FS based on a >95% confidence level. P≤0.05 was set as the statistical significance criterion.

Results and Discussion

Faecal sludge composition

The raw FS (i.e., a mixture of VIP sludge: Septage (1:2)) had large nutrient and pollutant concentrations (Table 1), which are 10-100 times stronger than typical domestic wastewaters in agreement with the findings of previous researchers (Strauss *et al.* 1997). However, such large concentrations pose a challenge in treating FS, especially in urban Africa when compared to treating wastewater. The values for TVS were very large but correlate well within the range of 0.16 - 65.60 g/l reported in the literature (Koottatep *et al.* 2001). This implies that the mixed raw FS had possibly undergone partial degradation or stabilisation while in on-site storage or before collection.

Table 1: Characteristics of raw FS (mixture of VIP sludge: Septage (1:2)) over 5 drying cycles

Parameter	(Mean ± SD)	Parameter	(Mean ± SD)	Parameter	(Mean ± SD)
pH	7.7±0.5	SS (g/l)	14.1±6.8	TKN (g N/l)	2.1±1.4
EC (mS/cm)	15.2±4.2	TS (g/l)	29.6±5.8	NO_3 (g N/l)	0.7±0.4
COD (g/l)	14.8±10.7	TVS (%)	62.9±8.4	TNH_3 (g N/l)	1.2±0.8
DCOD (g/l)	3.1±0.8	Viable *Ascaris* eggs (eggs/g)	98±58	TP (g P/l)	0.3±0.1
BOD_5 (g/l)	2.7±1.0			K (g/l)	1.6±0.1

± one standard deviation (SD)

Dewatering efficiency of different sand filtering media thickness

The mean dewatering times of sand filtering media thickness 150mm, 250mm and 350mm were 3.65, 3.83 and 4.02 days, respectively. This clearly indicates that the dewatering time increased slightly with the increase in the sand filtering media thickness, which is in agreement with Tchobanoglous *et al.* (2003), who reported that the drainage rate is reduced with the increase in the sand layer thickness. In Figure 2, it can be observed that there was a significant variation in the dewatering times of the five dewatering trials. This phenomenon was possibly due to the changes in the climate conditions during the dewatering periods. This is because the performances of the sludge drying beds basically rely on climatic and environmental conditions especially humidity, evaporation, temperature and precipitation. Possibly longer dewatering times were recorded whenever the temperatures were low (i.e., temperature varied from 15.7 - 20^0C as minima and 27 - 28.6^0C as maxima) and humidity was high (74% to 80%) during the dewatering periods. The longer dewatering times of T1, T2 and T3 (Figure 2) were also possibly because of the high solid loading rate of FS mixture, which was in the range of 324 - 535 kgTS/m^3/yr. Similar dewatering behaviour was also reported by (Kuffour *et al.* 2013), who concluded that dewatering time increases with increases in the solid loading rate. The variation in the dewatering time can also be attributed to the variation in the degree of raw FS mixture stability, given that different raw FS mixture with different degree of stability was prepared for each dewatering trial. This is because unstable sludge is characterised by poor dewatering properties as it cannot easily lend itself to dewatering. The average dewatering times of 3.65 - 4.02 days in this research compared very well and even better with those recorded by Evans *et al.* (2015) in Bangladesh and Heinss *et al.* (1998) in Ghana.

The different sand filtering media thickness 150mm, 250mm and 350mm were capable of dewatering FS with SLR of 230 - 535 kgTS/m^2/year in an average of 3.65, 3.83 and 4.02 days respectively. The dewatering results compared fairly well and even better than those of the research studies conducted in Ghana by Kuffour *et al.* (2009; 2013) and Cofie *et al.* (2006), where the dewatering periods were 9 -10 days, 4 - 7 days and 12 days for SLR of 217 - 360 kgTS/m^2/year, 379 - 438 kgTS/m^2/year and 196 - 321 kgTS/m^2/year, respectively. Regardless the observations discussed above, the Friedman test results at 95% confidence level indicated that the sand filtering media thickness configurations had no significant difference (P= 0.627) in the dewatering period. The average surface solid loading rate of 441 kgTS/m^2yr, 433 kgTVS/m^2yr and 422.1 kgTVS/m^2yr attained in this study for 150mm, 250mm and 350mm, respectively reflected 0.0165, 0.0169 and 0.0173m^2/capita of land area requirement for treatment of FS to about 37%TS. This result contradicts with those of previous researchers, who found a required footprint of about 0.05-0.08m^2/capita for land area required to treat FS to about 20-70%TS (Cofie *et al.* 2006; Heinss *et al.* 1998). This discrepancy in results could have been due to the differences in the characteristics of FS dewatered, climatic conditions as well as the quality of locally available filtering media materials used in the construction of the dewatering beds, all of which affect the performance of drying beds. This study results indicated 65 - 67% reduction in the land area requirement per capita for the treatment of FS to about 37%TS, which is very important in urban areas where land available for FS treatment is limited. The reduction in the sand filtering media from 350mm to 150mm resulted into a further 5% reduction in the land area requirement per capita. However, there was no statistically significant effect of the treatment on the land area requirement per capita.

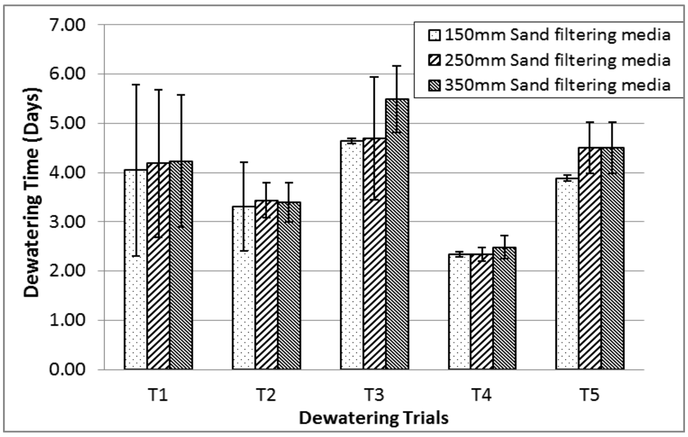

Figure 2: Dewatering time of different sand filtering media thickness

T1, T2, T3, T4 and T5 represent each dewatering trial. Dewatering time represents the mean values of triplicate beds (error bars are ± one standard deviation). Dewatering was considered complete whenever the percolate from the bed stopped flowing and dewatered sludge was spadable to be easily removed from the drying beds.

Solids recovery in dry sludge and removal from percolate efficiencies

The configured sand filter media thickness of 150mm, 250mm, and 350mm achieved high average recovery efficiencies of TS, TVS and SS from raw sludge into the resulting solids (dry sludge), in the ranges of 81.0-83.8%, 79.4-84.9% and 94.7-97.0% respectively (Table 2). However, the contaminant loads in the percolate were still higher than Uganda's recommended standards for discharge into the environment (N.E.M.A. 1999). This means that the percolate needs further treatment before discharge to the environment. The mean solids recovery efficiency results achieved in this study compared well with those reported by previous researchers (Kuffour *et al.* 2009; Heinss *et al.* 1998). 350mm filtering media thickness achieved the best performance for the recovery of TS, TVS and SS from raw sludge (Table 2). Friedman test results at 95% confidence level indicated that this treatment had a significant difference (P=0.0001) in the recovery efficiency of SS, TVS and TS. This improved performance may be due to the increased total particle surface area of the 350mm filter media for removal of finer FS particles as the liquid infiltrates through the sand media. On the other hand, the higher TS and TVS removal efficiencies recorded by 350mm filtering media may have been due to the slightly longer dewatering periods exhibited by such filtering media configuration. This observation was supported by the Spearmen's rho test, which revealed a stronger positive correlation between the dewatering time and TS and TVS removal efficiency (see Table 5). In the present study, there was no significant correlation observed between the dewatering time and SS removal efficiency (see

Supplementary Information

Table 5), which contradicts with the findings of Kuffour (2010). This difference in results could have been due to differences in dewatering times, wherein the present study the dewatering times were too short to exhibit a significant correlation between the two variables. Furthermore, the results show that the filter with a 350mm media had the potential of generating more solids for co-composting with other organic wastes hence enabling the optimum reuse of FS organic matter and nutrients. Based on this study, it was observed that an increase in the sand filtering media by 100mm leads to 24.9%, 12.9% and 7.7% recovery of SS, TVS and TS respectively from the percolate, which thus implies an increase in the quantity of solids retained by the unplanted sludge drying filter for reuse or composting.

Table 2: Percolate quality and solids removal and recovery efficiencies

Parameter (Units)	*N.E.M.A. (1999) Discharge Standards*	*Percolate quality (Mean ± SD)*			*% Recovery*and Removal** (Mean ± SD)*		
		150mm	**250mm**	**350mm**	**150mm**	**250mm**	**350mm**
SS (g/l)	0.10	0.72±0.68	0.51±0.42	0.41±0.38	94.70±3.90	96.10±2.70	97.00±2.20
TS (g/l)	-	5.41±1.51	5.03±1.50	4.61±1.52	81.00±7.00	82.30±6.80	83.80±6.70
TVS (g/l)	-	3.67±1.00	3.21±0.95	2.78±0.95	79.40±6.60	82.40±3.50	84.90±3.00

*% of concentrations retained in the solids fraction by the filtering media based on the initial FS concentration.
** % of concentrations remained in the percolate after dewatering based on the initial FS concentration.

Nutrient removal from percolate and recovery in dry sludge

Removal efficiencies of TNH_3-N from raw sludge were high for all the media thickness (Table 3); however, the remaining average concentration of ammonium in the percolates were still high for disposal into the environment – i.e., 0.27gN/l in 150mm; 0.19gN/l in 250mm; and 0.15gN/l in 350mm. This might be as a result of hydrolysis of organic nitrogen, thus resulting into release of total ammonia. The recorded TNH_3-N concentrations in percolate were not any close to the recommended Uganda standards of 0.01gNH_3-N/l for discharge into the environment (N.E.M.A. 1999). TNH_3-N removal efficiency increased gradually with the increase of the sand filtering media thickness (Table 3). The reductions in TNH_3-N might possibly be a result of its NH_4-N fraction reduction, which could be linked to the organic matter (TVS) removal and nitrification. This is because literature suggested that during loading of the sludge drying beds, NH_4-N is absorbed onto the organic matter and bed media, which contains oxygen for accelerated nitrification by nitrifying aerobic bacteria (Lienard *et al.* 2005; Tchobanoglous *et al.* 2003). Therefore, as the thickness of the filtering media increases, the oxygen within the sand filtering media also increases and so the nitrification rate for NH_4-N hence TNH_3-N reduction.

All the filter media thickness attained a relatively high percentage removal of TN, in a range of 60.7 – 83.0%. This possibly might have been as a result of nitrogen loss by denitrification in the sand filtration system, organic nitrogen mineralisation and high organic matter (TVS) removal (Epstein 2003; Panuvatvanich *et al.* 2009). The nitrate concentration in the percolate increased gradually with the increase of the sand filtering media thickness 150mm (0.29gN/l), 250mm (0.43gN/l), 350mm (0.75gN/l), yet the removal efficiency reduced (Table 3). This can possibly be attributed to the nitrification of NH_4-N fraction to NO_2-N and finally to NO_3-N in the filtering media, which is supported by the oxygen stored in the interstitial spaces of the sand matrix and also in biofilms surrounding surfaces of sand particles. This leads to rapid consumption of available nitrogen substrates by aerobes (Tanner *et al.* 2002). Therefore, the results of this study suggest that improvement of the nitrification rate in the unplanted drying bed treating FS can be achieved by an increase in the sand filtering media thickness. In Table 3, it can be noted that the NO_3-N concentrations detected in percolate did not comply with the Uganda wastewater discharge standards of 0.02gNO_3-N/l, which implies the percolate needs further treatment.

The nutrient recovery efficiencies in the range of 51.9 – 56.6% and 34.7 - 48.3% for TP and K respectively, achieved in this study were comparable with those reported by previous researchers (Kuffour 2010). The 350mm media filter exhibited an outstanding performance over the others for recovery of TKN, TP and K from raw sludge with an average of 83.0%, 56.6% and 48.3% respectively. This implies that percolate from this media thickness contained less nutrients as the greater fraction was retained in the solids. It is important to note from Table 3 that the concentrations of all the nutrients in the percolate were still higher than the recommended discharge standards into the environment, despite the high recovery efficiencies, which implies that percolate needs further treatment before discharge to the environment.

In respect to the above discussion, the Friedman test results at 95% confidence level show that the treatment had a significant difference with P=0.0001 in the percolate concentration and recovery efficiency of TNH_3-N, TKN, and TP. However, there was no significant difference (P= 0.487) observed at $p<0.05$ that the treatment had on the percolate concentration of K. The results from this study indicate that an increase in the sand filtering media by 100mm led to 27.4%, 33.0% and 10.7% reduction in TNH_3-N, TKN, and TP concentrations in the percolate. This confirms the role of sand filtering media thickness on nutrient recovery from FS by using unplanted drying beds. In this study, no significant correlation was observed between the dewatering time and removal efficiencies of K, TKN, NO_3-N, and TNH_3-N (Table 6). This implies that dewatering time had little influence on the removal of such nutrients during FS dewatering.

Table 3: Percolate quality, nutrient removal (percolate) and recovery (solids) efficiency

Parameter (Units)	***N.E.M.A. (1999)*** Discharge Standards***	***Percolate quality (*Mean ± SD)**			***Recovery and Removal efficiency, % (*Mean ± SD)**		
		150mm	**250mm**	**350mm**	**150mm**	**250mm**	**350mm**
TP (g P/l)	0.01	0.11±0.02	0.10±0.02	0.09±0.02	51.9±18.1	54.2±18.4	56.6±17.7
K (g/l)		1.07±0.10	0.96±0.15	0.85±0.35	34.7±10.1	41.5±11.2	48.3±21.4
TKN (g/l)	0.01	0.61±0.17	0.46±0.16	0.27±0.03	60.7±22.3	71.1±17.5	83.0±7.5
NO_3 (g N/l)	0.02	0.29±0.23	0.43±0.38	0.75±0.51	60.7±6.2	42.1±15.7	-2.4±1.9
TNH_3 (g N/l)	0.01	0.27±0.05	0.19±0.02	0.15±0.01	69.4±15.2	77.4±11.0	80.7±11.3

*% of concentrations retained in the solids fraction by the filtering media based on the initial FS concentration.
** % of concentrations remained in the percolate after dewatering based on the initial FS concentration.
*** N.E.M.A. ?

Biodegradable organics removal from the percolate and recovery in dry sludge efficiencies

The results from this study reveal that all the filtering media thickness of 150mm, 250mm, and 350mm achieved a high average removal efficiency of COD, DCOD and BOD, in the ranges of 91.3- 93.4%, 67.9-77.7% and 85.6-92.8%, respectively (Table 4). The configured filter media thickness exhibited an impressive performance with results that compared well and even better than those reported by Kuffour (2010), Cofie *et al.* (2006) and (Heinss *et al.* 1998) , which were in the range of 70-91%, 65.8-77.7% and 70-90% for COD, DCOD and BOD respectively. However, the average contaminant loads of COD and BOD in the percolate, which were in the range of 1.08-1.33 g/l and 0.16-0.31 g/l respectively, were higher than the recommended Uganda standards of 0.10g/l (COD) and 0.05g/l (BOD_5) for discharge of effluent to the environment (N.E.M.A. 1999). This possibly might have been due to the high contaminant load in the raw sludge because of the short storage duration of FS in the on-site sanitation prior to collection and transportation to the dewatering facility. This implies that raw FS had undergone partial degradation or stabilisation since the storage duration was not enough for sufficient biodegradation of organic pollutants. An excellent DCOD decrease exhibits the presence of dissolved organics for microbial action (Tchobanoglous *et al.* 2003). The high removal efficiency of COD, DCOD and BOD achieved in this study might possibly be due to the availability of oxygen in the sand filter media for aerobic microorganisms that biodegrade the available organics aerobically, and the presence of easily biodegradable FS organics for bacterial action. The presence of these easily biodegradable FS organic constitutes is proposed based on the low COD/BOD ratio of (5.4) (Heinss *et al.* 1998). The high removal efficiency of organics could also be attributed to the high percentage removal of solids from raw FS achieved by all the media thickness.

The 350mm filtering media exhibited an outstanding performance over 250mm and 150mm in the removal of COD, DCOD and BOD from raw FS with an average of 93.4%, 77.7%, and 92.8% respectively. This impressive performance of 350mm might possibly be due to its ability to achieve high solids removal efficiency, deepest sand filtering media thickness which provides an increase in surface area and also maintains sufficient aerobic conditions for microbial actions that biodegrade dissolved organics thus a higher reduction in the dissolved organics, COD, DCOD and BOD concentration. Thus, the results of this study support the suggestion that an improvement in the removal of BOD, COD, and DCOD in the unplanted drying bed treating FS can be achieved by an increase in the sand filtering media thickness. This is because the increase in the sand thickness maintains sufficient oxygen for aerobic microbial, which contribute to the breakdown of organic pollutants in FS. In support of the above discussion, the Friedman test results at 95% confidence level indicated that the sand filter media configuration had a significant difference with P=0.0001 in the removal efficiency of BOD, COD, and DCOD. In Table 7, it can be noted that no significant correlation was observed between the dewatering time and removal efficiency of organic pollutants during composting.

Table 4: Percolate quality, Organic pollutants removal (from percolate) and recovery (in dry sludge) efficiency

Parameter (Units)	*N.E.M.A. (1999) Discharge Standards*	*Percolate quality (*Mean ± SD*)*			*% Recovery* and Removal** (*Mean ± SD*)*		
		150mm	**250mm**	**350mm**	**150mm**	**250mm**	**350mm**
COD (g/l)	0.10	1.33±1.09	1.23±1.16	1.08±1.03	91.3±1.0	92.4±2.3	93.4±2.0
DCOD (g/l)	-	0.97±0.31	0.85±0.34	0.67±0.16	67.9±9.6	72.3±9.6	77.7±6.6
BOD (g/l)	0.05	0.33±0.25	0.24±0.20	0.16±0.14	85.6±14.7	89.4±11.3	92.8±8.1

*% of concentrations retained in the solids fraction by the filtering media based on the initial FS concentration.
** % of concentrations remained in the percolate after dewatering based on the initial FS concentration.

Helminth eggs removal efficiency

The three designed filter media thickness achieved 100% helminth eggs removal efficiency from percolate in comparison to raw sludge, which means that all of the helminth eggs were retained in the dewatered solids. This result is consistent with that of previous researchers (Evans *et al.* 2015; Heinss *et al.* 1998). In comparison to the helminth eggs in raw FS mixture, the filtering media thickness 150mm, 250mm, 350mm achieved 55.6%, 64.3%, 72.1% average percentage reduction of helminth eggs in the dewatered solids with a moisture content of 60.6% -66.4%. However, these helminth eggs reductions were much higher than the 30%-50% reductions reported by Evans *et al.* (2015) in the field study conducted in Bangladesh on unplanted sludge drying beds, where the moisture content was in the range of 50%-69%. The significant reductions in the helminth eggs attained in this study can be attributed to the thermal destruction of helminth eggs, which may have been due to the exposure of the dewatering FS to solar radiation and relatively high ambient temperatures, especially during the dry season. Similar behaviour has been reported by other authors (Seck *et al.* 2015; Nordin 2010). On the other hand, this significant reduction in the helminth eggs can be explained by the reduction in moisture since pathogens have been reported to be extremely sensitive to moisture loss during sludge drying, with their numbers reducing dramatically with moisture losses (Öğleni and Özdemir, 2010).

It is interesting to note that helminth eggs concentrations in the solids generated by configured sand filtering media thickness reduced gradually with increase in the sand filtering media thickness from 150mm (43egg/g), 250mm (35 egg/g) to 350mm (27 egg/g) (Figure 3(A)). This might possibly have been due to the entrapment of helminth eggs within the sand filtering media as FS containing eggs infiltrates through the filtering media. Therefore, as filtering media thickness increases the quantity of eggs entrapped increases too and thus their reduction in the solids. This implies that more helminth eggs are trapped within the sand filtering media and therefore further research is required to establish the most appropriate way for inactivation of helminth eggs entrapped within sand filtering media. The results of viable helminth eggs in the solids recorded in this study collaborate well with those reported by Koné *et al.* (2007) in Ghana, which was in the range of 25-83 eggs/g.

Although a significant reduction in helminth eggs was observed in this study, their concentrations in the dewatered solids were considerably higher than the threshold egg count of ≤ 1 egg/litre suggested by World Health Organisation (2006) nematode guideline for biosolids safe for agricultural use. This result is not surprising, given that the dewatering FS was exposed to the high ambient temperatures and solar radiations for a very short duration to achieve complete die-off of helminth eggs, yet the temperature-time relationship is a key factor for responsible for the thermal destruction of helminth eggs (Koné et al. 2007). Secondly, the dewatering process was also of very short storage duration (3.65 – 4.02 days), and the moisture content in the dewatered solids was not low enough to influence the inactivation of helminth eggs. Literature has shown that the moisture content must be reduced to ≤5% (≥ 95%) in the dewatered solids so as to ensure complete inactivation of helminth eggs at ambient temperature (Feachem et al. 1983). Therefore, this implies that dewatered solids need further treatment such as co-composting with organic waste so as to inactivate the helminth eggs and other pathogen indicators to comply with the guidelines prior to reuse in agriculture.

Characteristics and quantity of dewatered solids

Given the average accumulation rate of dry solids (TS) and organic matter (TVS) for all configured filter media thickness (Figure 4B and 4C), it can be noted that 350mm had a potential to generate the highest amount of dry solids and organic matter with an average rate of 87.8% and 70.9% respectively. The outstanding performance of 350mm in the generation of TS and TVS was possibly due to its potential to achieve the highest solids (TS and TVS) removal efficiency from percolate as discussed previously. Based on the average dewatering time of each filter media thickness, the annual average solids production and their corresponding organic matter accumulation rate (kg TVS/m^2/yr) were estimated (Figure 4 (D)). Interestingly, 150mm had the highest average annual generation rate of dry solids, which was 441 kgTS/m^{2}yr compared to 433 kgTVS/m^{2}yr and 422 kgTVS/m^{2}yr for 250mm and 350mm respectively. This could possibly be attributed to shortest dewatering times that 150mm achieved in all dewatering trials. However, 350mm had the highest annual generation rate of organic matter which was 300kg TVS/m^{2}yr compared to 295 kgTVS/m^{2}yr and 299 kgTVS/m^{2}yr for 150mm and 250mm respectively. Irrespective of the above discussion, the Friedman test results at 95% confidence level showed that the treatment had no significant difference with P=0.549, and P=0.127 in the generation of dry solids (TS) and TVS respectively.

The nutrient content (NPK) of the solids generated by the different filter media thickness 150mm, 250mm and 350mm were generally high and these were comparable with those reported by Kuffour (2010). 150mm had the potential to generate solids with the highest TN content of 5.01% of TS whereas 350mm generated those with the highest TP and K, which were 26.6 P g/kg and K of 4.64 K g/kg respectively (see Figure 3). This study noted that the loss of TN content in the generated solids increase with an increase in the sand filtering media thickness. This TN loss is attributed to the high NH_3-N volatilisation which is due to the longer dewatering times of SM 3. TN loss behaviour attained in this study is similar to that reported by Panuvatvanich *et al.* (2009) in the field investigation on vertical-flow constructed wetlands. An increase in the sand filtering media by 100mm led to 25.54% increase in the TN loss of the generated solids. However, TP and K increased with increase in the sand filtering media. This might possibly be attributed to 350mm's potential to achieve the highest TP, K and solids recovery efficiency from FS as previously discussed. In respect to the above discussion, the Friedman test results at 95% confidence level indicated that the treatment had a significant difference with P=0.003, P=0.0001 and P=0.002 in the generation of dry solids with TN, P and K respectively.

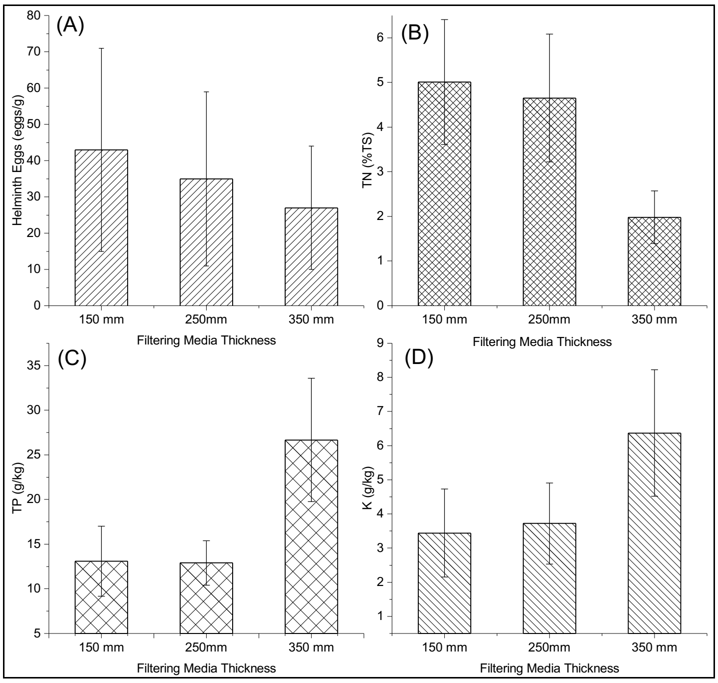

Figure 3: Helminth eggs and nutrient (NPK) content of solids generated by configured filtering media thickness.

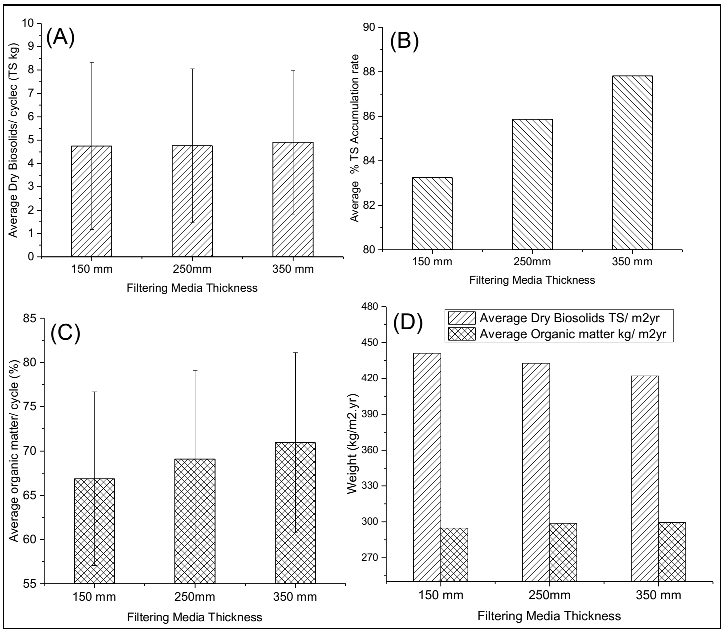

Figure 4: (A) Average dry solids per cycle, (B) Average percentage TS accumulation rate, (C) Average organic matter per cycle and (D) average dry solids and organic matter per m^2/year generate by the configured filtering media thickness.

Conclusion

This research study aimed at investigating the effect of sand filtering media thickness on the performance of FS drying bed. The following conclusions can be drawn based on the findings obtained:

The sand filtering media thickness of unplanted sludge drying beds can be reduced to 150mm thickness if the purpose of the drying beds is to optimise annual generation of solids with highest TKN content. In this study, 150 mm media thickness proved robust as it had the shortest dewatering time regardless of the variation in the quality of raw FS mix and climatic conditions, yet it lowers the construction costs of the beds. The dewatering time of the beds was not significantly influenced by the sand filtering media thickness configurations. The improved dewatering performance attained in this study results into 65 - 67% reduction in the land area required per capita for the treatment of FS to about 37%TS. The reduction in the sand filtering media from 350mm to 150mm could result into a further 5% reduction in the required land area/ capita. The recommended design criteria for SLR is XXXX kg/m2/year.

Where the purpose of the drying bed is to improve on the percolate quality, the sand filtering media thickness can be increased to 350mm thickness. This study reveals that the removal efficiency of the contaminant loads (TNH_3-N, COD, DCOD and BOD) from raw sludge had a statistically significant difference influenced by sand filtering media thickness configurations. Thus, the contaminant load (TNH_3-N, COD, DCOD and BOD) removal efficiency increased with increase in the sand filter media thickness. This shows that problems of overloading downstream FS treatment facilities (such as stabilisation ponds or wetlands) with organic pollutants can possibly be gradually reduced with the increase of the filtering media thickness. Although the removal efficiency of contaminant loads achieved by all the filter media thickness was generally high, their concentrations in the percolate were still high and thus percolate needed further treatment (e.g., using stabilisation ponds or constructed wetlands) before discharge to the environment. Although, if the final stabilisation of the resulting dry sludge is conducted by (co-) composting, the percolate can be use to maintain moisture in the piles and hence, helping to fully recover nutrients from raw FS.

The recovery efficiency of nutrients (TN, TP, K) and solids (TS, TVS, SS) from percolate and raw FS mix increased with increase in the sand filtering media thickness. This implied that more solids and nutrients were retained by 350mm filtering media for reuse in agriculture. This solids and nutrient recovery efficiency was significantly influenced by the sand filtering media thickness configurations.

There were significant differences in the nutrient content (NPK) of the solids generated by the different filter media thickness. 150mm filtering media thickness had a potential to generate annually the highest solids but with the highest TN content whereas 350mm generated those with the highest organic matter, TP and K content. The study noted the TN loss in the generated solids increased with increase in the sand filtering thickness and the reverse was true for organic matter, TP and K.

100% of the helminth eggs were retained in dewatered solids by all the configured media filtering thickness, which implied that solids needed further treatment either through composting or storage so as to inactivate the eggs prior to reuse in agriculture. Interestingly, the configured filtering media thickness achieved between 55.6% - 72.1% helminth eggs inactivation in dewatered solids during the dewatering phase.

The study reveals that 350mm filtering media had the highest potential of optimising the nutrients recovery from FS by generating the solids with highest organic matter and nutrient content for reuse in agriculture.

Acknowledgements

The authors wish to acknowledge the funding provided by the University of Leeds through the Leeds International Research Scholarship (LIRS) Award for Mr Musa Manga's PhD study. They also wish to express their sincere appreciation to National Water and Sewerage Corporation (NWSC) for offering us space for our experiment and laboratory works. More thanks to the research assistants Emma, Sharon, Kirabo and Kigenyi. Lastly, thanks to Dr. Babu, Phyllis, Julie, Robinah, Madam Julie and Dr. Irene Nansubuga for the colaboration and support while at NWSC.

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Supplementary Information

Table 5: Correlation coefficients between dewatering time and percolate solids removal efficiency of different filtering media

Parameter (Units)	*Filtering Media Dewatering time*					
	150mm		**250mm**		**350mm**	
	***p*-values**	**r**	***p*-values**	**r**	***p*-values**	**r**
SS (g/l)	0.934	0.023	0.879	0.043	0.726	0.099
TS (g/l)	0.018*	0.601	0.011*	0.636	0.007*	0.661
TVS (g/l)	0.052*	0.510	0.031*	0.556	0.006*	0.674

* indicates significant at $P<0.05$ respectively.

Table 6: Correlation coefficients between dewatering time and percolate nutrient removal efficiency of different filtering media

Parameter (Units)	*Filtering Media Dewatering time*					
	150mm		**250mm**		**350mm**	
	***p*-values**	**r**	***p*-values**	**r**	***p*-values**	**r**
TP (g P/l)	0.098	0.444	0.007*	0.667	0.030*	0.561
K (g/l)	0.235	0.441	0.983	0.008	0.185	0.485
TKN (g/l)	0.066	0.487	0.054	0.506	0.168	0.375
NO_3 (g N/l)	0.198	0.352	0.482	0.197	0.603	0.146
TNH_3 (g N/l)	0.226	0.333	0.412	0.229	0.243	0.321

* indicates significant at $P<0.05$ respectively.

Table 7: Correlation coefficients between dewatering time and percolate organic pollutants removal efficiency of different filtering media

Parameter (Units)	*Filtering Media Dewatering time*					
	150mm		**350mm**		**250mm**	
	***p*-values**	**r**	***p*-values**	**r**	***p*-values**	**r**
COD (g/l)	0.423	0.224	0.445	0.214	0.201	0.350
DCOD (g/l)	0.423	0.224	0.849	0.054	0.771	0.082
BOD (g/l)	0.575	0.157	0.345	0.262	0.248	0.318