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Optimisation of centrifuge operating conditions for dewatering physically conditioned faecal sludge from urban slums

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HIGHLIGHTS

- Laboratory-scale centrifugation study can be a basis for centrifuge prototype design.
- Better centrifugation results when containers are 70–80% full of faecal sludge (FS).
- Conditioning FS with charcoal dust improves dewaterability better than sawdust.
- Conditioned FS dewaters at reduced speeds achievable in hand-powered centrifuges.

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ABSTRACT

Decentralised faecal sludge (FS) dewatering in urban slums using centrifugation technology has potential to reduce public health risks and environmental pollution caused by indiscriminate disposal of untreated FS. A laboratory-scale centrifuge was applied to dewater FS from lined pit latrines, conditioned with sawdust and charcoal dust. Response surface methodology and central composite design were used to construct and model relationships between independent variables (FS volume, centrifugation time and speed) and the dependent variable (per cent cake solids) for unconditioned and conditioned (sawdust and charcoal dust) FS. The results demonstrated that the centrifugation technology can yield more per cent cake solids at reduced speeds when physically conditioned. Rotational speed was a significant parameter for unconditioned (original) ($p = 0.0020$) and charcoal dust conditioned FS ($p = 0.0019$). Significant parameters for sawdust conditioned FS were speed ($p = 0.0001$) and quadratic effect of time ($p = 0.0494$). An optimal centrifugation time of 20 minutes and centrifugation container volume of 50 mL at 70–80% full of FS for conditioned FS were obtained. The centrifugation speeds tested in this paper provide critical information for proto-type design of a hand-powered centrifuge, the operating conditions and its subsequent set-up. This can serve as an option for dewatering FS from commonly used sanitation facilities in urban slums,

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thereby enabling decentralised treatment to reduce costs of FS management and support resource recovery at the source.

1. Introduction

Over 70% of the urban population in sub-Saharan Africa (SSA) reside in slum areas (the densely populated areas, lacking a road network, often located on marginal land and inhabited by the poor) (UN-HABITAT, 2006). Slum dwellers rely on on-site sanitation facilities such as septic tanks and pit latrines, with the later mainly in use in Kampala, Uganda, for example (Nakagiri et al., 2016; Tumwebaze et al., 2013). The on-site sanitation facilities contain partially digested semi-solid slurry known as faecal sludge (FS), whose management remains a challenge, once the facilities are full (Strande, 2014). Faecal sludge management (FSM) entails emptying/collection, transportation, treatment, end-use and/or disposal of FS. In most slum areas, infrastructure such as roads is lacking due to high density of housing units, hence making it costly and difficult for emptying trucks to access sanitation facilities. Consequently, over 50% of the generated FS remains uncollected (Blackett et al., 2014). The high FSM cost and limited access could be solved by managing FS at or near the point of generation within urban slums (decentralised level) (Semiyaga et al., 2015). However, this calls for technologies that can be used in FSM at a decentralised scale. Technologies such as *gulper*, *vacutags*, and others, have been developed to empty and collect FS from slums (Still, 2012). However, these technologies cannot solve all challenges of the FSM services chain such as the treatment and disposal or end-use of FS.

Since FS is over 90% water, dewatering presents an important first step of treating it effectively. A new pit latrine design incorporated with a removable dewatering unit (metal cage with filter bags) could be an innovative approach to reduce the cost of dewatering, emptying and subsequent transportation of FS (Hamawand and Lewis, 2016). The containers can easily be collected from places with limited access in slums. However, the high percentage of filled-up pit latrines, reported at 66% in the slums of Kampala (Nakagiri et al., 2015) and the limited space for new ones, would call for technologies of managing/dewatering FS from the already existing filled-up latrines. Technologies commonly used in dewatering sewage sludge at a centralised scale include; thickening tanks, sand beds, filter presses and centrifuges (Pan et al., 2003). The sand bed and filter press technologies have a challenge of large space requirement which may be limited in urban slum settings. Centrifugation technology has a small foot print in terms of area requirement, low operation costs and normally has a casing to enclose odour in densely populated areas (Broadbent, 2001; Drury et al., 2002). In addition, dewatering or sedimentation can be achieved faster due to enhancement of gravitational acceleration by centrifugal acceleration resulting from circular rotational motion of the centrifuge (Garrido et al., 2003). Such characteristics make centrifugation an appropriate dewatering technology for urban slums.

Centrifugation is based on the principle that when a suspension such as FS is swirled at a particular rotational speed, the denser solids move through a fluid in the direction tangential to the direction of rotation, under centrifugal acceleration (Vesilind and Zhang, 1984). A driving force for water removal from settled FS sets up, which reduces the cake moisture content (or increasing percent dry cake solids) in the settled solid fraction of FS. However, the use of rotational speed to hasten dewatering during centrifugation requires mechanical energy say from electric motors, hence, high operational and maintenance costs. This further limits their widespread application in some slum areas with no connection to the electricity grid.

Industrial/commercial centrifuges have been classified into sedimenting or filtering centrifuges, with underlying principles of gravity sedimentation and pressure filtration, respectively (Buerger and Concha, 2001). Extensive usage of sedimenting centrifuges has been reported, and it has been found that suspensions containing considerable amount of fine solids of less than 45 μm easily clog filtering centrifuges (Buerger and Concha, 2001). Semiyaga et al. (2017) reported that FS from pit latrines in Kampala slums contain over 70% fine particles of less than 45 μm, justifying the need for sedimentation centrifuge type.

Data from batch laboratory-scale centrifugation studies have been used as a basis for design equations of large-scale continuous centrifuges or to know the performance of existing centrifuges, given the type of feedstock to be centrifuged (Brar et al., 2006). Continuous commercial centrifuges are designed on mechanical basis and cannot be easily modified. Indeed, centrifuge design is impossible in the absence of laboratory centrifugation studies. The performance of a commercial continuous centrifuge is governed by Eq. (1) (Brar et al., 2006).

$$\Sigma = \frac{Q\, t\omega^2}{g \ln (R_0/R_1)} \tag{1}$$

where Σ is the centrifuge parameter, dimension L^2 (m^2); Q is the feedstock flow rate (l/d), which is proportional to volume; t is the centrifugation time (s); g is the acceleration due to gravity (9.81 m s^{-2}); ω is the rotational speed (rad s^{-1}); R_0 is the maximum rotor radius (cm); R_1 is the minimum radius of liquid interface (cm). However, since some parameters are constant, volume of FS, rotational speed and time are the major operational parameters pertinent for the batch centrifugation process (Buerger and Concha, 2001).

Cake solids formation depends on both centrifugation operating conditions such as rotational speed, time, nature of FS material centrifuged, as well as the form of material pre-treatment such as using conditioners. Centrifugation has a drawback of achieving dewatering at very high rotational speeds. Pre-treatment of FS with chemical conditioners improves the dewatering rate or rate of cake formation (Gold et al., 2016). However, physical conditioners such as char, sawdust, bagasse, wheat dregs, coal fines and rice husks are reported to improve the extent of dewatering (cake dryness or percent dry solids in FS cake) and partly the dewatering rate (rate at which water filters out of FS) (Qi et al., 2011). The physical conditioners, being at lower moisture content absorb moisture from FS and also enhance the mechanical strength of the resulting cake by formation of rigid lattice structures which improve porosity of sludge cake; hence easing flow of water out of the cake (Qi et al., 2011; Semiyaga et al., in press).

Sawdust and charcoal dust conditioners are wastes from timber saw mills and wood charcoal, respectively. They have advantages of being biodegradable, readily available in urban slums at low or no cost, and the dewatered cake has improved utilisation potential especially during energy recovery (Diener et al., 2014). Sawdust and charcoal dust can improve dewatering extent and, hence a probable reduction in rotational speed required for centrifugation. However, when FS is conditioned and centrifuged, the centrifugation operation conditions of FS volume, rotational speed and time act differently and can affect one another. Consequently, optimisation of these factors is necessary in order to determine the best response in terms of percent cake solids achieved. In addition, centrifuges have been used in centralised wastewater treatment plants, but no studies exist on decentralised centrifugation of FS from pit latrines in slums areas.

This study was therefore carried out to determine the effect of sawdust and charcoal dust conditioning on optimum centrifugation operation parameters of FS. This study is considered of benefit to the process design and sizing efficient equipment pertinent in dewatering of FS from the sanitation facilities commonly used in urban slums, such as pit latrines. FS from lined pit latrines was considered in this study. This is because a study by Semiyaga et al. (2017) revealed that FS from lined pits had a lower dewatering extent compared to FS from unlined pit latrines.

2. Materials and methods

2.1. Collection of FS samples

FS samples for the study were collected from Bwaise, a typical urban slum in Kampala (Uganda) with limited access to mechanised pit emptying. A fabricated multi-stage sampler reported by Semiyaga et al. (2017) was used in obtaining FS samples from five purposively selected pit latrines. Grab samples of one litre were obtained from each of the three layers (top, middle and bottom) of each pit latrine through a squat hole and were mixed into a composite sample. Composite samples were obtained from five pit latrines and put in a 30 L HDPE plastic container. The container was immediately transported to the Public Health and Environmental Engineering Laboratory at Makerere University. While in the laboratory, the samples were stored at 4 °C until they were analysed. Prior to preparation and subsequent experiments, FS samples were removed from the refrigerator and left to attain room temperature.

2.2. Preparation of FS samples

Preparation of FS samples before analysis involved passing them through a 5 mm sieve to remove the extraneous materials (Burton, 2007; Semiyaga et al., 2017). The raw FS samples from lined pit latrines were characterised for total solids (TS), total volatile solids (TVS), ash content, pH, electrical conductivity (EC), sand content and bulk density (Table 1). TS, TVS and ash content of FS were determined according to standard methods (APHA/AWWA/WEF, 2012). EC and pH were measured using a calibrated portable meter (Hach HQ30d Flexi model). The TS concentration was determined gravimetrically by taking the weight of an oven dried sample at 105 °C for 24 h and expressed as a fraction of raw sample volume. TVS was determined by taking the weight difference between oven dried solids and the 2-h muffle furnace ignited sample at 550 °C and expressed as a percentage of TS. Ash content was the residue weight after ignition in the furnace at 550 °C for 2 h, also expressed as a percentage of TS. Sand content was determined using the acid method; where ash was washed with 0.1 M HCl solution into ash-less filter papers. The paper and content were ignited in a furnace at 550 °C for 2 h and the residue was taken as sand content, expressed as a percentage of TS. Three replicates were analysed for each sample to attest the reproducibility of the experimental results.

2.3. Faecal sludge conditioning

Preliminary conditioning experiments were performed on FS by varying sawdust and charcoal dust conditioner dosages from 0%, 25%, 50%, 75% and 125% (weight of dry conditioner as a ratio of FS dry solids). Sawdust and charcoal dust dosage of 75% FS total solids had the optimal dewaterability efficiency (for both indicators of dewatering rate and dewatering extent) (Semiyaga et al., in press). Therefore, in this study, FS was conditioned with sawdust and charcoal dust dosages of 75%TS. Charcoal dust was obtained from charcoal outlets within Bwaise slum, while sawdust was obtained from a timber sawing mill in the same slum area. Charcoal dust and sawdust particles were sieved to a size less than 2.36 mm to limit variability, oven dried for 24 h and stored in a vacuum desiccator, for consistency in dry weight during analysis

Table 1
Characteristics of original faecal sludge samples from pit latrines.

Parameter	Unit	Mean values ± *SD*
pH		8.77 ± 0.03
Electrical conductivity	mS cm^{-1}	7.66 ± 0.09
Temperature	°C	24.4 ± 0.6
Total solids (TS)	g L^{-1}	31.0 ± 0.8
Moisture content	%	97.0 ± 0.1
Total volatile solids (TVS)	%TS	58.6 ± 0.5
Ash content	%TS	41.4 ± 0.5
Sand content	%TS	31.2 ± 5.6
Bulk density	kg m^{-3}	1240 ± 0.3

Notes: *SD* standard deviation.

Table 2
Characteristics of physical conditioners (sawdust and charcoal dust).

	Unit	Sawdust	Charcoal dust
Specific gravity		0.065	0.053
Bulk density (loose)	kg m^{-3}	173.9 ± 10.8	868.5 ± 7.8
Water content (wet basis)	wt%	18.4 ± 1.3	11.6 ± 0.4
TVS	wt%	79.0 ± 1.0	61.3 ± 2.2
Ash content	wt%	2.5 ± 0.6	24.7 ± 3.1
Gross heating value (dry basis)	MJ kg^{-1}	19.7 ± 0.1	23.7 ± 0.7
Crude protein	mg g^{-1} solids	2.6	10.3

Table 3
Particle size distribution of sawdust and charcoal dust conditioners (Semiyaga et al., in press).

Particle size (mm)	Sawdust		Charcoal dust	
	Mass retained (%)	Cumulative mass passing (%)	Mass retained (%)	Cumulative mass passing (%)
2.360	0.0	100.0	0.0	100.0
1.180	36.6	63.4	31.4	68.6
0.600	37.4	26.0	22.6	46.0
0.425	11.6	14.4	9.4	36.6
0.300	7.2	7.2	8.9	27.7
0.212	3.6	3.6	6.4	21.3
0.150	1.6	2.0	5.2	16.1
0.750	0.8	1.2	7.2	8.9
Pan	1.2	N/A	8.9	N/A

(Luo et al., 2013). The characteristics and particle size distribution of sawdust and charcoal dust are presented in Tables 2 and 3, respectively.

2.4. Centrifugation experimental design

A laboratory based electrical centrifuge (MISTRAL1000 type, UK) equipped with four centrifuge cells of 50 mL capacity each, with a respective rotational speed and time limit of 6000 rpm (centrifugal acceleration of 6040 g) and 99 s was used in the study. Centrifugation experiments were carried out by varying independent variables (factors) of FS volume, rotational speed and time to obtain the dependent variable of percent cake solids (dewatering extent) for different factors. A predetermined FS volume was centrifuged at a particular speed for a known time. The dry solids of the settled dewatered cake obtained at oven temperature of 105 °C and expressed as a percentage of wet dewatered cake was taken as percent cake solids. The following minimum and maximum values of factors were used; volume (30–50 mL), speed (600–1800 rpm, with respective centrifugal accelerations of 60–540 g) and time (10–30 min).

Combinations of different factors were determined using the central composite design (CCD) and response surface methodology (RSM) in JMP software package, version 10 (SAS Institute). CCD and RSM were used for constructing and exploring approximate relationships between the independent variables of the centrifugation process (i.e. FS volume, speed and time) and the response variable (percent cake solids). The mentioned range values for the factors were entered in JMP software and 16 runs were automatically generated (Table 4) with different combinations of volume, speed and time.

The objective was to maximise the percent cake solids for the various combinations of independent variables. The values of percent cake solids shown in Table 4 were obtained experimentally for 16 runs of original FS (FS without conditioners), 16 runs (each) of sawdust and charcoal dust conditioned FS. Experiments were carried out using two replicates, hence, each percent cake solid value reflecting average of the replicates.

Table 4
Central composite design for experimental variables (volume, rotational speed and time) and response (% cake solids).

Run No.	Volume (mL)	Speed (rpm)	Time (min)	Cake solids (%)		
				Original FS	Sawdust conditioner	Charcoal dust conditioner
1	30	600	10	8.7	11.2	12.1
2	30	600	30	9.1	11.9	14.8
3	30	1200	20	10.9	14.1	18.9
4	30	1800	10	12.3	14.9	17.6
5	30	1800	30	12.0	15.6	16.8
6	40	600	20	9.5	14.0	14.5
7	40	1200	10	10.8	13.4	15.3
8	40	1200	20	11.0	14.1	16.7
9	40	1200	20	14.1	15.3	18.2
10	40	1200	30	12.2	14.9	17.4
11	40	1800	20	13.8	16.7	19.2
12	50	600	10	10.1	12.6	13.6
13	50	600	30	9.5	11.7	14.1
14	50	1200	20	12.2	15.3	17.8
15	50	1800	10	13.2	15.6	15.8
16	50	1800	30	13.2	16.5	19.6

2.5. Data analysis

Statistical design of experiments and data analysis was performed using the statistical software package JMP, version 10 (SAS Institute) for the regression analysis of the data and to estimate the coefficient of regression equations. The experimental data obtained (Table 4) was modelled by the system described through an empirical second-order equation (2). Second order model gives a good estimate of the response surface and can be used to locate optimum response (% cake solids) and at the same time explain the centrifugation process.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{i \neq j=1}^{k} \beta_{ij} x_i x_j + \varepsilon. \tag{2}$$

Here, Y is the predicted response or dependent variable (% cake solids); β_0 is a constant coefficient (intercept); β_i, β_{ii} and β_{ij} refer to the regression coefficient for linear, quadratic, and interaction effects (between factors i and j), respectively; x_i and x_j are the independent variables (i.e. FS volume, centrifugation speed and time); k is the number of factors (independent variables) and ε denotes the random error of prediction (residuals).

The estimates of the model coefficients were calculated by least squares multiple regression. Analysis of variance (ANOVA) was used for model adequacy and analysis of experimental data to obtain the interaction between the independent variables and the response. The statistical significance of the model was checked by Fisher's F-test and the quality of model fit was expressed by the regression coefficient R^2. The significance of the model terms in Eq. (2) were evaluated at p-values ≤ 0.05 (95% confidence interval). The mathematical equations for original and conditioned FS which relate factors and the response were developed. Thereafter, the non-significant model terms ($p > 0.05$) were eliminated to obtain reduced model equations. The validity of the reduced model equations (after dropping the non-significant terms) were checked by computing the model residuals and examining the normal probability plots. A reduced model was considered valid when the residual plots were very close to a straight line (normally distributed). Lastly, canonical curvature analysis was performed to predict the shape of the curve generated by the multiple regression models. Three-dimensional (3D) surface plots and their respective two-dimensional (2D) contour plots were obtained for the original and physical conditioned (sawdust and charcoal dust) FS, based on response (% cake solids) and the independent variables (FS volume, centrifugation speed and time).

3. Results

3.1. Statistical analysis of models for original and conditioned FS

The regression coefficient (R^2) values for models of original, sawdust and charcoal dust conditioned FS of 0.84, 0.94 and 0.88, respectively, indicate that respective 84%, 94% and 88% of the variations in percent cake solids (response) can be explained by the factors of FS volume, speed and time. Models for conditioned and original FS used were significant ($p = 0.005$ and 0.034 for sawdust and charcoal dust conditioned FS, respectively) (Table 5). The probability of lack of fit (PLOF) for original and conditioned FS were more than 0.05, implying that the second-order model fits the experimental data well and thus its application is eligible to interpret the response values of percent cake solids. Additionally, the sawdust conditioned FS model was better explainable by variables because of the higher R^2 and $AdjR^2$. Concurrently, a relatively lower coefficient of variation (CV) for the same model of 11.8% indicated a more precise and reliable model.

Table 5
ANOVA and model fitting results for the response (% cake solids) for original and conditioned FS.

	P	R^2	Adj. R^2	CV (%)	RMSE	MOR	PLOF	F-value
Original (FS only)	0.067	0.84	0.61	15.0	1.07	11.4	0.98	0.08
FS + Sawdust	0.005*	0.94	0.85	11.8	0.65	14.2	0.78	0.51
FS + Charcoal dust	0.034*	0.88	0.70	13.3	1.20	16.4	0.57	1.34

Notes: P—probability; PLOF—probability of lack of fit; CV—coefficient of variation; RMSE—root mean square error; MOR—mean of response; * Statistically significant at $p < 0.05$.

Table 6
Model parameter estimates and ANOVA results for response surface second-order model terms for percent cake solids.

	Model term	Coefficient estimate	Degrees of freedom	Sum of squares	F-value	P-value ($P > F$)
Original	Intercept	12.16				<0.0001*
	X_1	0.52	1	2.70	2.34	0.1766
	X_2	1.76	1	30.98	26.86	0.0020*
	X_3	0.09	1	0.08	0.07	0.7999
	$X_1 X_2$	0.04	1	0.01	0.01	0.9245
	$X_1 X_3$	−0.09	1	0.06	0.05	0.8254
	$X_2 X_3$	−0.01	1	0.00	0.00	0.9748
	$X_1 X_1$	−0.42	1	0.46	0.39	0.5530
	$X_2 X_2$	−0.32	1	0.26	0.23	0.6502
	$X_3 X_3$	−0.47	1	0.57	0.50	0.5079
FS + Sawdust	Intercept	14.99				<0.0001*
	X_1	0.40	1	1.60	3.78	0.1000
	X_2	1.79	1	32.04	75.62	0.0001*
	X_3	0.29	1	0.84	1.98	0.2085
	$X_1 X_2$	0.05	1	0.02	0.05	0.8352
	$X_1 X_3$	−0.18	1	0.25	0.58	0.4758
	$X_2 X_3$	0.23	1	0.41	0.96	0.3660
	$X_1 X_1$	−0.43	1	0.50	1.17	0.3201
	$X_2 X_2$	0.22	1	0.12	0.29	0.6102
	$X_3 X_3$	−0.98	1	2.56	6.03	0.0494*
FS + Charcoal dust	Intercept	17.75				<0.0001*
	X_1	0.07	1	0.05	0.03	0.8598
	X_2	1.99	1	39.60	27.49	0.0019*
	X_3	0.83	1	6.89	4.78	0.0714
	$X_1 X_2$	0.03	1	0.01	0.00	0.9549
	$X_1 X_3$	0.30	1	0.72	0.50	0.5061
	$X_2 X_3$	−0.03	1	0.01	0.00	0.9549
	$X_1 X_1$	0.44	1	0.52	0.36	0.5694
	$X_2 X_2$	−1.06	1	2.94	2.04	0.2034
	$X_3 X_3$	−1.56	1	6.38	4.43	0.0801

Notes: *Statistically significant at $p < 0.05$.

The coefficient estimates of the regression terms for original and conditioned FS were obtained from JMP software output (Table 6); resulting in the Eqs. (3), (4), and (5) for original, sawdust and charcoal dust conditioned FS, respectively. The response (% cake solids), denoted as Y, while the factors of FS volume, speed and time were coded as x_1, x_2 and x_3, respectively.

$$Y = 12.16 + 0.52x_1 + 1.76x_2 + 0.09x_3 + 0.04x_1x_2 - 0.09x_1x_3 - 0.01x_2x_3 - 0.42x_1^2 - 0.32x_2^2 - 0.47x_3^2 \quad (3)$$

$$Y = 14.99 + 0.40x_1 + 1.79x_2 + 0.29x_3 + 0.05x_1x_2 - 0.18x_1x_3 + 0.23x_2x_3 - 0.43x_1^2 + 0.22x_2^2 - 0.98x_3^2 \quad (4)$$

$$Y = 17.75 + 0.07x_1 + 1.99x_2 + 0.83x_3 + 0.03x_1x_2 + 0.30x_1x_3 - 0.03x_2x_3 + 0.44x_1^2 - 1.06x_2^2 - 1.56x_3^2. \quad (5)$$

When the significance of each term's contribution to the three model Eqs. (3)–(5) was determined, it suffices to note that the intercept coefficient terms for all the three models were highly significant ($p < 0.0001$ for Eqs. (3)–(5), each). The linear coefficients of speed significantly contributed to % cake solids for all the three models ($p = 0.0020$, 0.0001 and 0.0019 for original, sawdust and charcoal dust conditioned FS, respectively). However, the quadratic effect of time had significant contribution ($p = 0.0494$) to % cake solids for only sawdust conditioned FS.

After elimination of non-significant terms, reduced model equations for original and charcoal dust conditioned FS were still valid, since residual plots were close to a straight line (Supplementary S1). Unlike for sawdust conditioned FS, the significant terms of speed and time^2 had plots quite away from the straight line. An adjustment was therefore made to avoid eliminating the terms for speed^2 and the interaction of speed and time. This produced a plot, where the residual plots were very close to the straight line (Supplementary S1). After eliminating model terms and checking for validity, the following reduced Eqs. (6)–(8) for original, sawdust and charcoal dust conditioned FS respectively were generated. These

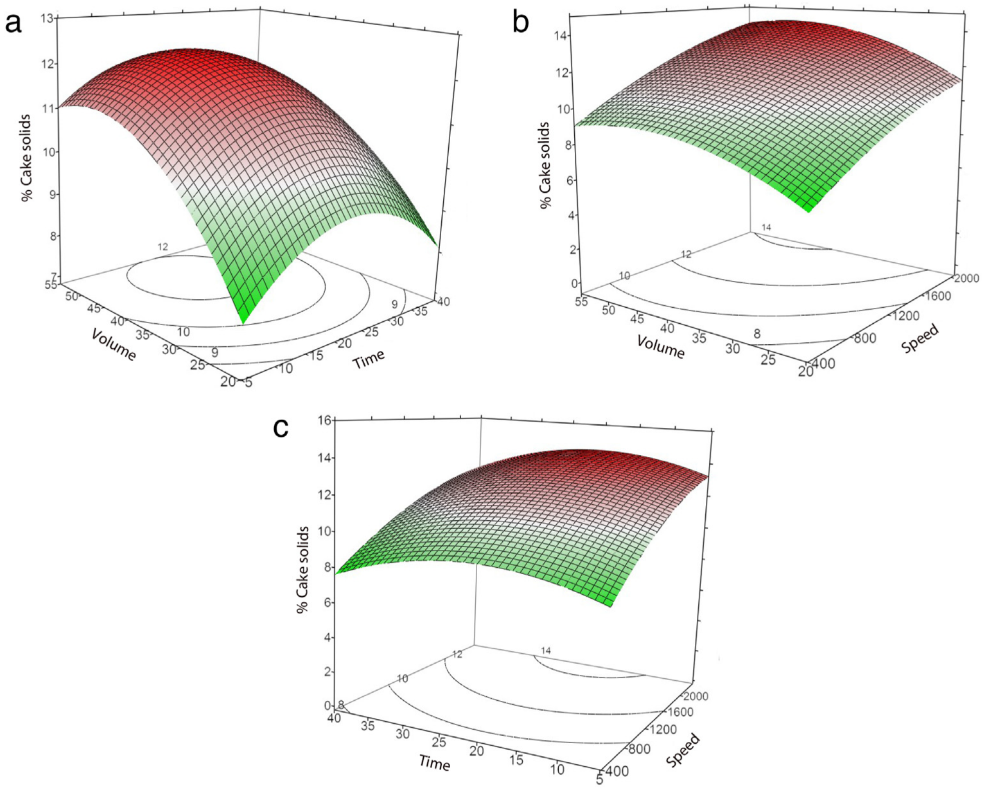

Fig. 1. Three-dimensional surface plots of percent cake solids for unconditioned FS from lined pit latrine (original) as a function of: (a) volume and time; (b) volume and speed; (c) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

can be reliably used to produce % cake solids for different factor consideration.

$$Y = 12.16 + 1.76x_2 \tag{6}$$

$$Y = 14.99 + 1.79x_2 + 0.23x_2x_3 + 0.22x_2^2 - 0.98x_3^2 \tag{7}$$

$$Y = 17.75 + 1.99x_2. \tag{8}$$

3.2. Effects of parameters on process optimisation

The regression model equations were graphically represented on three-dimensional (3D) surface and two-dimensional (2D) contour plots for the original, sawdust and charcoal dust conditioned FS from pit latrines. This was to visualise the relationship between interaction of independent variables and the corresponding percent cake solids yield under these conditions.

When the original FS was centrifuged under varying conditions of volume, speed and time, the mean of % cake solids for all runs was 11.4% (Table 5). Increase in time from 5 to 20 min at volumes of 20 mL or speed of 400 rpm only improved cake solids from 8% to 9%. Increase in volume (40–50 mL) by about twice at the same time of 20 min increased cake solids from 8% to 12.3% (Fig. 1). Time increase beyond 20 min generally reduced the percent cake solids. The converging of contours reflected interactions between; volume and time (elliptical contours reflect a perfect interaction between volume and time), volume and speed; and time and speed, although the interactions were not significantly changing the percent cake solids ($p < 0.05$). However, visualising the way the various factors influence the dewatering process helps to improve the centrifuge design.

Furthermore, at optimal rotational time of 20 min and volume of ∼45 mL, the average % cake solids of 11.4 (Table 5) could be achieved at a speed of 920 rpm. Increase in speed from 400 to 2000 rpm linearly improved % cake solids at slight quadratic effects of volume and time (Fig. 1(b) and (c)). Similarly, increasing speed from 920 to 2000 rpm at constant time of 20 min improved % cake solids from average of 11.4% to 14.1% (Fig. 1(c)).

When 75%TS dosage of sawdust conditioner was mixed with FS, the mean of % cake solids for all runs increased to 14.2%. Increase in time at volumes of 20 mL or speed of 400 rpm improved cake solids from 9.3% to 12.5% from 5 to 20 min, respectively. Increase in volume (40–50 mL) by about twice, at the same time of 20 min, increased cake solids from 9.3% to 15% (Fig. 2(a)). Time increase beyond 20 min generally reduced the percent cake solids. The 2D contours reflect some

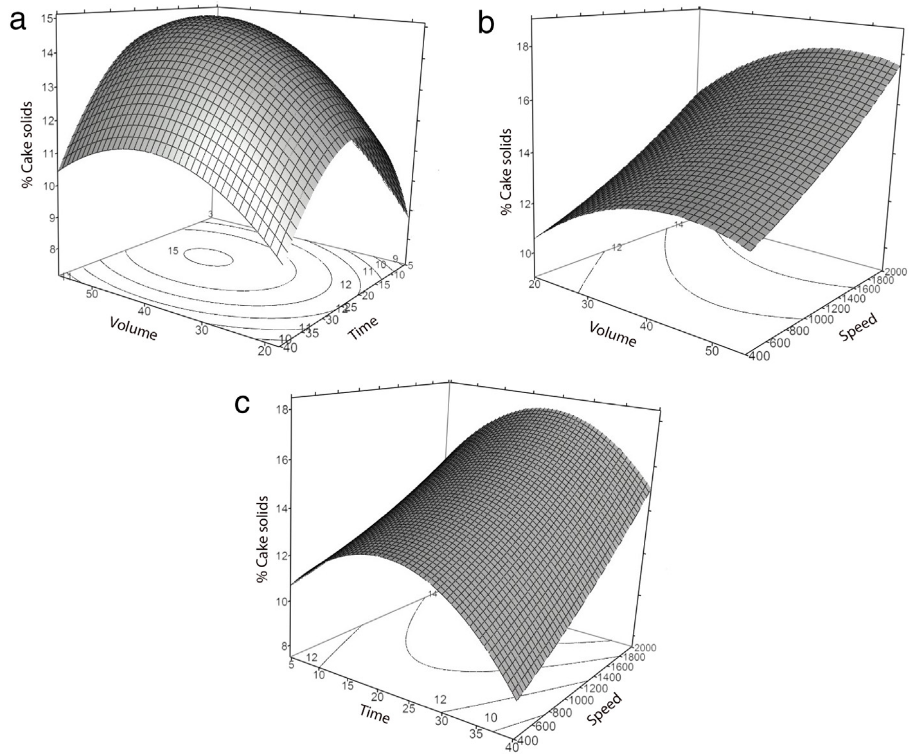

Fig. 2. Three-dimensional surface plots of percent cake solids for sawdust-conditioned pit latrine FS as a function of: (a) volume and time; (b) volume and speed; (c) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

interactions between; volume and time (also, the elliptical contours reflect a perfect interaction between volume and time), volume and speed; time and speed. The speed and quadratic effect of time were significantly contributing to the percent cake solids for sawdust conditioned FS ($p = 0.0001$ and $p = 0.0494$, respectively). At optimal time of 20 min and volume of ∼45 mL, the average percent cake solids of 14.2 (Table 5) could be achieved at speed of 890 rpm. Similarly, the 11.2% cake solids at a rotational speed of 920 rpm in the original FS can be achieved at virtually no rotation, but only through sedimentation or absorption effect. Increase in speed from 400 to 2000 rpm linearly improved percent cake solids at slight quadratic effects of volume and time (Fig. 2(b) and (c)). Similarly, increasing speed from 890 to 1800 rpm, at a constant time of 20 min, improved percent cake solids from average of 14.2% to 17.0% (Fig. 2(c)).

A 75%TS dosage of charcoal dust conditioner mixed with FS increased the mean of percent cake solids for all runs to 16.4% (Table 5). Per cent cake solids increased at lower and higher volumes, with the least observed values at intermediate volumes at all times. However, the maximums at lower (<30 mL) and higher volumes (>42 mL) and minimum at intermediate volume (35 mL), all occurred at time of 20 min (Fig. 3(a)). Thus, some interactions of volume and time were realised at lower and higher volumes, although not significant ($p = 0.506$). A similar effect on volume interaction with speed was observed at lower and higher volumes ($p = 0.955$), with a saddle point at 35 mL. Higher cake solids (>20%) were achieved at a speed of 1600 rpm with lower or higher volumes (Fig. 3(b)). There was an almost perfect interaction between speed and time (elliptical contours), though it was not significant ($p = 0.954$). The quadratic effect of time was reflected; with the maximum being 20 min. The optimum cake solids of 13.3% could be obtained at maximum time of 20 min at volume and speed of 35 mL and 400 rpm, respectively. However, cake solids increased to an optimum of 18.7% at a speed of 1600 rpm, beyond which percent cake solids decreased.

At optimal time of 20 min and volume of 35 mL, the average percent cake solids of 16.4 (Table 5) could be achieved at speed of 870 rpm. Consequently, increasing speed from 870 to 1600 rpm at constant time of 20 min improved percent cake solids from average of 16.4% to 18.6% (Fig. 3(c)). For comparison with the original FS, average 11.2% cake solids at speed of 920 rpm can be achieved at about 160 rpm, when conditioned with charcoal dust.

4. Discussion

4.1. Use of sawdust and charcoal dust conditioners in centrifugal dewatering of FS

The average percent cake solids for original FS, sawdust and charcoal dust conditioned FS were 11.4, 14.2 and 16.4, respectively. Percent cake solids increased by 24.6% and 43.8% when conditioned with 75%TS of sawdust and charcoal dust, respectively. The cake solids increase in FS conditioned with charcoal dust is much higher than the observed 28.2% increment by Albertson and Kopper (1983), when sewage sludge was conditioned with coal fines. The interaction effects for volume and time in original and sawdust conditioned FS signified sedimentation of particles with time. However, the quadratic effect of time, where it takes 20 min for cake solids to increase to maximum and thereafter decreases, was significant for sawdust conditioned FS. Centrifugation beyond 20 min resulted in re-suspension of settled solids probably due to high absorptive nature of sawdust (Lin et al., 2001; Luo et al., 2013). The result therefore suggests that sawdust significantly re-absorbed moisture during batch centrifugation to decrease the percent cake solids after 20 min. Therefore, the quadratic effect of time needs to be considered during the operation of a centrifuge by limiting centrifugation time.

The use of sawdust and charcoal dust conditioners improved the cake solids recovery due to water absorption and increased porosity of FS cake. Semiyaga et al. (in press) reported 89% and 56% reduction in FS cake moisture after addition of sawdust and charcoal dust, respectively, due to absorption and the remaining percentage may be attributed to improved porosity. The decrease in moisture content of conditioned FS cake after dewatering is comparable to that of sewage sludge cake, when sawdust and coal fly ash additives were increased from 0% to 100% (Chen et al., 2010; Ding et al., 2014; Lin et al., 2001). The particles of sawdust/charcoal dust are bridged between FS solids, creating voids for water to flow out of the cake. This improvement in porosity makes subsequent management options for separated FS solid and liquid streams simpler. For example, the drying process of solid fraction quickens, since the convective heat from surrounding air could easily be conducted to the interior of the FS cake, thus increasing the interior temperature which affects the diffusion of water and vapour from the interior to the surface, and later evaporated to the ambient (Lei et al., 2009). This can be achieved by conventional drying of FS on sand beds, enhanced by greenhouse effect or use of solar dryers (Murray Muspratt et al., 2014). The later enhanced technologies could be more feasible in an urban slum setting due to space limitations. Further, the improved porosity of FS cake can enhance the composting process through increased internal spaces for air flow (Lin et al., 2001). Subsequently, usage of sawdust/charcoal dust conditioned FS as an organic soil amendment improves soil productivity, not only because of nutrients present in FS, but also increased aeration and water holding capacity of soils due to improved porosity (Kelley and Martens, 1984).

4.2. *Effect of rotational speed on cake solids yield*

Generally, the higher the centrifugation speed, the more the centrifugal acceleration and hence faster sedimentation rate of solids for the original and sawdust/charcoal dust conditioned FS. This is in agreement with a study by Garrido et al. (2003) who reported increased sedimentation with centrifugation rotational speed. In addition, conditioned FS contains larger and more particles than original FS (Table 3), hence the increased sedimentation rate of conditioned FS, since larger particles tend to settle out quicker (Chu and Lee, 2002). Moreover, the particles of sawdust and charcoal dust are bridged between the original FS particles. These break the capillary water between FS particles, hence, creating voids (Schubert, 1984).

Further rotational speeds set up centrifugal compaction of settled solid particles causing more water to be released, hence the observed drier cake after physical conditioning with sawdust/charcoal dust. However, charcoal dust conditioned FS yielded dryer cake solids than sawdust (16% and 14% cake solids, respectively) at similar rotational speeds. This could be because the density of charcoal dust (869 kgm^{-3}) is much higher than that of sawdust (174 kgm^{-3}) (Table 2), since Vesilind and Zhang (1984) reported centrifugal compaction to be a function of particle density. Hence, more compaction takes place in charcoal dust conditioned FS and consequently more percent cake solids yield. Therefore, the observed increase in % cake solids with speeds in original and sawdust conditioned FS could be due to increasing compaction of FS cake. An interesting result is for charcoal dust conditioned FS, where an optimum speed of 1600 rpm occurred, beyond which percent cake solids reduced. The higher density of charcoal dust particles could have caused the sedimentation and compaction processes to be completed by this speed. FS conditioning results therefore depict increased capacity of centrifuges to handle more FS volumes and hence significant reductions in space requirements in urban slums.

4.3. *Implications on faecal sludge management in urban slums*

A typical centrifuge is known to consist of a rotor, spin by a drive motor which is powered by electrical supply that makes it to rotate (Gutierrez, 2005). The observed reduced centrifugation speeds after modifying FS properties with the sawdust/charcoal dust conditioners can be realised by hand-powered centrifuge devices. Here, a user physically spins the device and energy is transformed into rotation of the rotor through gears. This could help in dewatering of FS from slum areas that are not supplied with electricity, or where the use of electricity to run the centrifuge is more expensive as compared to hand-powered. In some cases, cycle-powered centrifuge devices could also be appropriate, where the pedalling actions of bi/tricycles are transformed into rotor motion. Never-the-less, hand/cycle-powered centrifuge devices could become energy intensive in times where people have to operate them for long durations, owing to large volumes of emptied FS. In such cases, the centrifuge design could be modified to allow a 12 V DC battery power source (Turvaville et al., 1999) to rotate the devices in slum areas. The DC battery can be recharged from places with electricity and used for running centrifuge or usage of DC solar batteries charged by solar panels could be appropriate since solar energy is available in most of the low-income countries. Local fabrication of hand/cycle powered centrifuge devices can provide a low cost technology that is easily adoptable by low-income urban slum population.

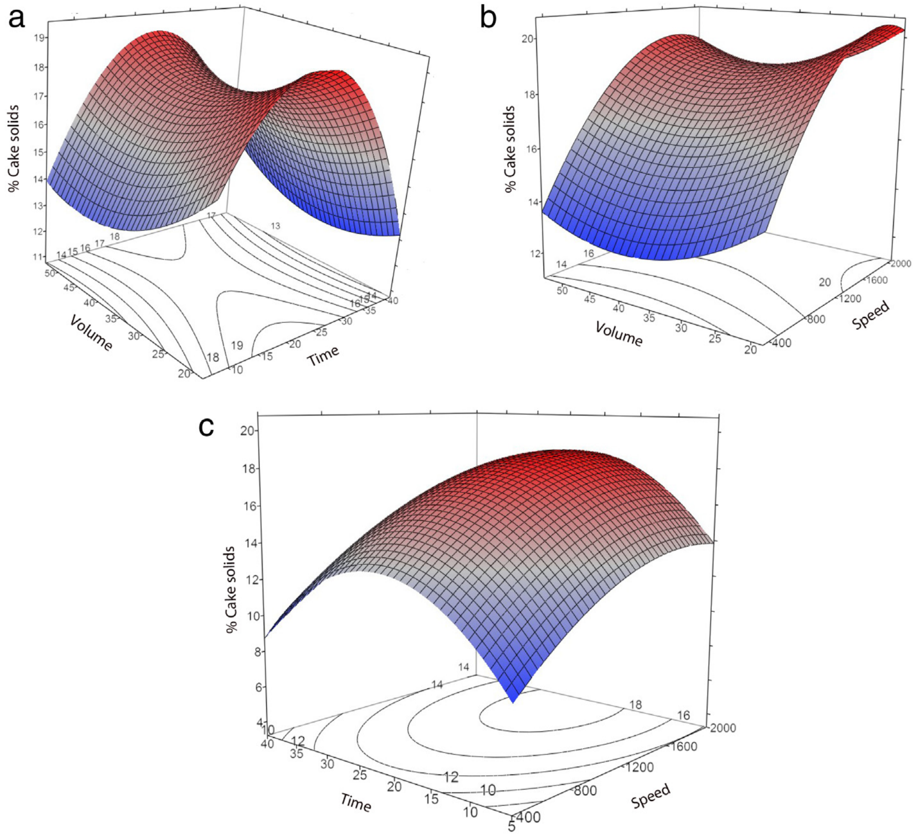

Fig. 3. Three-dimensional surface plots of percent cake solids for charcoal dust-conditioned FS from pit latrine as a function of: (a) volume and time; (b) volume and speed; (c) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

After centrifugation, the separated liquid fraction (centrate/leachate) could be further treated in a low-cost crushed filter (sand, soil or lava rock) unit such as that developed by Katukiza et al. (2014) to reduce the pollutant loads from wastewater in urban slums. The treated centrate is likely to suit non-portable purposes such as irrigation of tower gardens for urban agriculture (Kulabako et al., 2011), mortar additive for construction purposes (Katukiza et al., 2014), or toilet flushing (Hamawand and Lewis, 2016). This has the potential to improve health and increase environmental protection that would otherwise emanate from indiscriminate disposal of untreated FS in a slum environment. The dewatered solid fraction can be transformed into a number of products utilisable by the slum population (Semiyaga et al., 2015).

Implementation of centrifugation technology in dewatering FS at household or community level in slums requires FS emptying and treatment of the separated FS streams, before and after centrifugation, respectively. People/slum dwellers are involved during execution of these activities at all stages of emptying, dewatering and treatment/end-use of liquid and solid streams. Since raw emptied FS contains high pathogen load (Still and Foxon, 2012), this poses health risks to the users of the centrifugation technology. Therefore, a need for further investigation on the fate of pathogens such as *E.coli* and helminth eggs across centrifugal dewatering process in an urban slum setting is necessary in order to protect the operators of this process and subsequent processes/handling and/or reuse downstream.

5. Conclusions

The centrifugation rotational speed has been identified as a key design parameter. In addition, the centrifugation time significantly influenced dewatering of sawdust conditioned FS. The effect of time on percent cake solids yield was quadratic, with an optimum value at 20 min. Centrifugation beyond this time further reduced percent cake solids due to re-absorption of moisture by the dewatered cake conditioned with sawdust/charcoal dust.

When FS was conditioned with charcoal dust, the saddle point created at midway volumes (35 to 40 mL) suggested that operating a centrifuge when full or less than half-full would yield higher cake solids. For original and sawdust conditioned FS, optimum cake solids were obtained between volume of 40 to 45 mL. Therefore, making the centrifuge container full lowered the percent cake solids. Charcoal dust conditioned FS exhibited an optimum percent cake solids yield at a speed of 1600 rpm, but cake solids were linearly increasing with speed for original and sawdust conditioned FS. Rotational speed required to achieve a certain percent cake solids reduced with addition of sawdust and charcoal dust. Such low rotational speeds can be achieved by hand/cycle powered centrifuge devices, fabricated locally, thereby, providing a low cost technology adaptable for dewatering FS in low-income urban slums. The next stage would be to develop a pilot-scale centrifuge unit and test it with FS from sanitation facilities commonly used by urban slum dwellers, such as pit latrines.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.eti.2017.03.005.

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