

1 **Optimisation of centrifuge operating conditions for**
2 **dewatering physically conditioned faecal sludge from urban**
3 **slums**

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

19 **Abstract**

20 Decentralised faecal sludge (FS) dewatering in urban slums using centrifugation technology has
21 potential to reduce public health risks and environmental pollution caused by indiscriminate
22 disposal of untreated FS. A laboratory-scale centrifuge was applied to dewater FS from lined pit
23 latrines, conditioned with sawdust and charcoal dust. Response surface methodology and
24 central composite design were used to construct and model relationships between independent
25 variables (FS volume, centrifugation time and speed) and the dependent variable (per cent cake
26 solids) for unconditioned and conditioned (sawdust and charcoal dust) FS. The results
27 demonstrated that the centrifugation technology can yield more per cent cake solids at reduced
28 speeds when physically conditioned. Rotational speed was a significant parameter for
29 unconditioned (original) ($p=0.0020$) and charcoal dust conditioned FS ($p=0.0019$). Significant
30 parameters for sawdust conditioned FS were speed ($p=0.0001$) and quadratic effect of time
31 ($p=0.0494$). An optimal centrifugation time of 20 minutes and centrifugation container volume of
32 50 mL at 70-80% full of FS for conditioned FS were obtained. The centrifugation speeds tested
33 in this paper provide critical information for proto-type design of a hand-powered centrifuge, the
34 operating conditions and its subsequent set-up. This can serve as an option for dewatering FS
35 from commonly used sanitation facilities in urban slums, thereby enabling decentralised
36 treatment to reduce costs of FS management and support resource recovery at the source.

37 **Keywords**

38 Cake solids; Centrifugation speed; Centrifugation time; Faecal sludge; Response surface
39 methodology.

40 **1 Introduction**

41 Over 70% of the urban population in sub-Saharan Africa (SSA) reside in slum areas (the
42 densely populated areas, lacking a road network, often located on marginal land and inhabited
43 by the poor) (UN-HABITAT, 2006). Slum dwellers rely on on-site sanitation facilities such as
44 septic tanks and pit latrines, with the later mainly in use in Kampala, Uganda, for example
45 (Nakagiri et al., 2016; Tumwebaze et al., 2013). The on-site sanitation facilities contain partially
46 digested semi-solid slurry known as faecal sludge (FS), whose management remains a

47 challenge, once the facilities are full (Strande, 2014). Faecal sludge management (FSM) entails
48 emptying/collection, transportation, treatment, end-use and/or disposal of FS. In most slum
49 areas, infrastructure such as roads is lacking due to high density of housing units, hence making
50 it costly and difficult for emptying trucks to access sanitation facilities. Consequently, over 50%
51 of the generated FS remains uncollected (Blackett et al., 2014). The high FSM cost and limited
52 access could be solved by managing FS at or near the point of generation within urban slums
53 (decentralised level) (Semiyaga et al., 2015). However, this calls for technologies that can be
54 used in FSM at a decentralised scale. Technologies such as *gulper*, *vacutags*, and others, have
55 been developed to empty and collect FS from slums (Still, 2012). However, these technologies
56 cannot solve all challenges of the FSM services chain such as the treatment and disposal or
57 end-use of FS.

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

74 Centrifugation is based on the principle that when a suspension such as FS is swirled at a
75 particular rotational speed, the denser solids move through a fluid in the direction tangential to
76 the direction of rotation, under centrifugal acceleration (Vesilind and Zhang, 1984). A driving
77 force for water removal from settled FS sets up, which reduces the cake moisture content (or
78 increasing per cent dry cake solids) in the settled solid fraction of FS. However, the use of

79 rotational speed to hasten dewatering during centrifugation requires mechanical energy say
80 from electric motors, hence, high operational and maintenance costs. This further limits their
81 widespread application in some slum areas with no connection to the electricity grid.

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

89 Data from batch laboratory-scale centrifugation studies have been used as a basis for design
90 equations of large-scale continuous centrifuges or to know the performance of existing
91 centrifuges, given the type of feedstock to be centrifuged (Brar et al., 2006). Continuous
92 commercial centrifuges are designed on mechanical basis and cannot be easily modified.
93 Indeed, centrifuge design is impossible in the absence of laboratory centrifugation studies. The
94 performance of a commercial continuous centrifuge is governed by equation (1) (Brar et al.,
95 2006).

96
$$\Sigma = \frac{Qt\omega^2}{g \ln(R_0/R_1)} \quad (1)$$

97 Where Σ is the centrifuge parameter, dimension L^2 (m^2); Q is the feedstock flow rate (l/d), which
98 is proportional to volume; t is the centrifugation time (s); g is the acceleration due to gravity
99 (9.81 ms^{-2}); ω is the rotational speed (rads^{-1}); R_0 is the maximum rotor radius (cm); R_1 is the
100 minimum radius of liquid interface (cm). However, since some parameters are constant, volume
101 of FS, rotational speed and time are the major operational parameters pertinent for the batch
102 centrifugation process (Buerger and Concha, 2001).

103 Cake solids formation depends on both centrifugation operating conditions such as rotational
104 speed, time, nature of FS material centrifuged, as well as the form of material pre-treatment
105 such as using conditioners. Centrifugation has a drawback of achieving dewatering at very high
106 rotational speeds. Pre-treatment of FS with chemical conditioners improves the dewatering rate
107 or rate of cake formation (Gold et al., 2016). However, physical conditioners such as char,

108 sawdust, bagasse, wheat dregs, coal fines and rice husks are reported to improve the extent of
109 dewatering (cake dryness or per cent dry solids in FS cake) and partly the dewatering rate (rate
110 at which water filters out of FS) (Qi et al., 2011). The physical conditioners, being at lower
111 moisture content absorb moisture from FS and also enhance the mechanical strength of the
112 resulting cake by formation of rigid lattice structures which improve porosity of sludge cake;
113 hence easing flow of water out of the cake (Qi et al., 2011; Semiyaga et al., 2017b).

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

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

131 **2 Materials and methods**

132 **2.1 Collection of FS samples**

133 FS samples for the study were collected from Bwaise, a typical urban slum in Kampala
134 (Uganda) with limited access to mechanised pit emptying. A fabricated multi-stage sampler
135 reported by Semiyaga et al. (2017a) was used in obtaining FS samples from five purposively
136 selected pit latrines. Grab samples of one litre were obtained from each of the three layers (top,
137 middle and bottom) of each pit latrine through a squat hole and were mixed into a composite
138 sample. Composite samples were obtained from five pit latrines and put in a 30 litre HDPE

139 plastic container. The container was immediately transported to the Public Health and
 140 Environmental Engineering Laboratory at Makerere University. While in the laboratory, the
 141 samples were stored at 4°C until they were analysed. **Prior to preparation and subsequent**
 142 **experiments, FS samples were removed from the refrigerator and left to attain room**
 143 **temperature.**

144 2.2 Preparation of FS samples

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

160 **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) | gL ⁻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 | kgm ⁻³ | 1240 ± 0.3 |

161 Notes: SD standard deviation.

162 2.3 Faecal sludge conditioning

163 Preliminary conditioning experiments were performed on FS by varying sawdust and charcoal
164 dust conditioner dosages from 0, 25, 50, 75 and 125 % (weight of dry conditioner as a ratio of
165 FS dry solids). Sawdust and charcoal dust dosage of 75 % FS total solids had the optimal
166 dewaterability efficiency (for both indicators of dewatering rate and dewatering extent)
167 (Semiya et al. unpublished results). Therefore, in this study, FS was conditioned with sawdust
168 and charcoal dust dosages of 75 %TS. Charcoal dust was obtained from charcoal outlets within
169 Bwaise slum, while sawdust was obtained from a timber sawing mill in the same slum area.
170 Charcoal dust and sawdust particles were sieved to a size less than 2.36 mm to limit variability,
171 oven dried for 24 hours and stored in a vacuum desiccator, for consistency in dry weight during
172 analysis (Luo et al., 2013). The characteristics and particle size distribution of sawdust and
173 charcoal dust are presented in Table 2 and Table 3, respectively.

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

| | Unit | Sawdust | Charcoal dust |
|---------------------------------|---------------------------|------------|---------------|
| Specific gravity | | 0.065 | 0.053 |
| Bulk density (loose) | kgm ⁻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) | MJkg ⁻¹ | 19.7±0.1 | 23.7 ± 0.7 |
| Crude protein | mg g ⁻¹ solids | 2.6 | 10.3 |

175

176 **Table 3** Particle size distribution of sawdust and charcoal dust conditioners (Semiya et al., 2017b)

| 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 |

177

178 2.4 Centrifugation experimental design

179 A laboratory based electrical centrifuge (MISTRAL1000 type, UK) equipped with four centrifuge
180 cells of 50 mL capacity each, with a respective rotational speed and time limit of 6000 rpm
181 (centrifugal acceleration of 6040 g) and 99 seconds was used in the study. Centrifugation

182 experiments were carried out by varying independent variables (factors) of FS volume,
 183 rotational speed and time to obtain the dependent variable of percent cake solids (dewatering
 184 extent) for different factors. A predetermined FS volume was centrifuged at a particular speed
 185 for a known time. The dry solids of the settled dewatered cake obtained at oven temperature of
 186 105°C and expressed as a percentage of wet dewatered cake was taken as per cent cake
 187 solids. The following minimum and maximum values of factors were used; volume (30-50 mL),
 188 speed (600-1800 rpm, with respective centrifugal accelerations of 60-540 g) and time (10-30
 189 minutes).

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

197 **Table 4:** Central composite design for experimental variables (volume, rotational speed and time) and response (%
 198 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 |

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

204 2.5 Data analysis

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

$$211 \quad Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^k \sum_{i \neq j=1}^k \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

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

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

233 **3 Results**

234 **3.1 Statistical analysis of models for original and conditioned FS**

235 The regression coefficient (R^2) values for models of original, sawdust and charcoal dust
 236 conditioned FS of 0.84, 0.94 and 0.88, respectively, indicate that respective 84, 94 and 88 % of
 237 the variations in per cent cake solids (response) can be explained by the factors of FS volume,
 238 speed and time. Models for conditioned and original FS used were significant ($p = 0.005$ and
 239 0.034 for sawdust and charcoal dust conditioned FS, respectively) (Table 5). The probability of
 240 lack of fit (PLOF) for original and conditioned FS were more than 0.05, implying that the second-
 241 order model fits the experimental data well and thus its application is eligible to interpret the
 242 response values of per cent cake solids. Additionally, the sawdust conditioned FS model was
 243 better explainable by variables because of the higher R^2 and $Adj R^2$. Concurrently, a relatively
 244 lower coefficient of variation (CV) for the same model of 11.8 % indicated a more precise and
 245 reliable model.

246 **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 |

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

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

253 $Y = 12.16 + 0.52x_1 + 1.76x_2 + 0.09x_3 + 0.04x_1x_2 - 0.09x_1x_3 - 0.01x_2x_3 - 0.42x_1^2 - 0.32x_2^2 - 0.47x_3^2$ (3)

254 $Y = 14.99 + 0.40x_1 + 1.79x_2 + 0.29x_3 + 0.05x_1x_2 - 0.18x_1x_3 + 0.23x_2x_3 - 0.43x_1^2 + 0.22x_2^2 - 0.98x_3^2$ (4)

255 $Y = 17.75 + 0.07x_1 + 1.99x_2 + 0.83x_3 + 0.03x_1x_2 + 0.30x_1x_3 - 0.03x_2x_3 + 0.44x_1^2 - 1.06x_2^2 - 1.56x_3^2$ (5)

257 **Table 6:** Model parameter estimates and ANOVA results for response surface second-order model terms
 258 for per cent 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 |

259 Notes: * statistically significant at $p < 0.05$

260 When the significance of each term's contribution to the three model equations (3, 4 and 5) was
 261 determined, it suffices to note that the intercept coefficient terms for all the three models were
 262 highly significant ($p < 0.0001$ for equations 3, 4 and 5, each). The linear coefficients of speed

263 significantly contributed to % cake solids for all the three models ($p = 0.0020$, 0.0001 and
264 0.0019 for original, sawdust and charcoal dust conditioned FS, respectively). However, the
265 quadratic effect of time had significant contribution ($p = 0.0494$) to % cake solids for only
266 sawdust conditioned FS.

267 After elimination of non-significant terms, reduced model equations for original and charcoal
268 dust conditioned FS were still valid, since residual plots were close to a straight line
269 (Supplementary S1). Unlike for sawdust conditioned FS, the significant terms of speed and
270 time² had plots quite away from the straight line. An adjustment was therefore made to avoid
271 eliminating the terms for speed² and the interaction of speed and time. This produced a plot,
272 where the residual plots were very close to the straight line (Supplementary S1). After
273 eliminating model terms and checking for validity, the following reduced equations 6, 7 and 8 for
274 original, sawdust and charcoal dust conditioned FS respectively were generated. These can be
275 reliably used to produce % cake solids for different factor consideration.

$$276 \quad Y = 12.16 + 1.76x_2 \quad (6)$$

$$277 \quad Y = 14.99 + 1.79x_2 + 0.23x_2x_3 + 0.22x_2^2 - 0.98x_3^2 \quad (7)$$

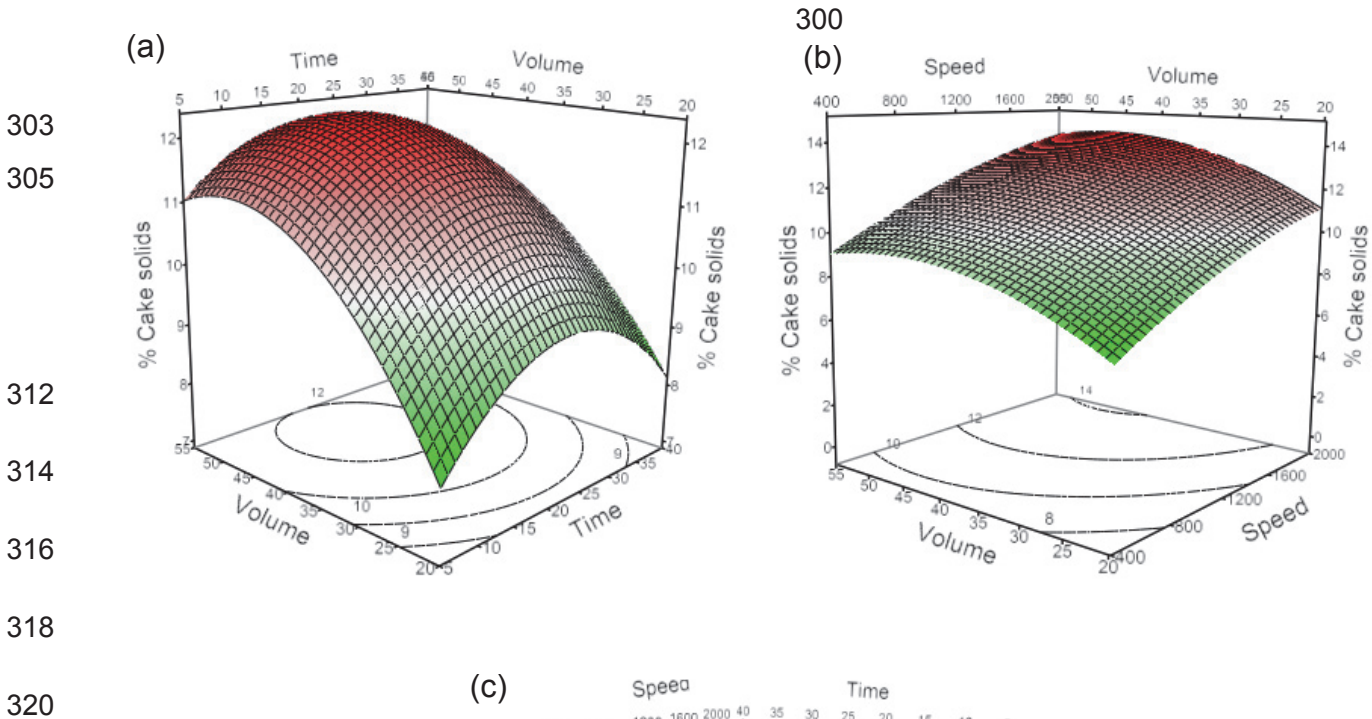
$$278 \quad Y = 17.75 + 1.99x_2 \quad (8)$$

279 **3.2 Effects of parameters on process optimisation**

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

284 When the original FS was centrifuged under varying conditions of volume, speed and time, the
285 mean of % cake solids for all runs was 11.4 % (Table 5). Increase in time from 5 to 20 minutes
286 at volumes of 20 mL or speed of 400 rpm only improved cake solids from 8 to 9 %. Increase in
287 volume (40-50 mL) by about twice at the same time of 20 minutes increased cake solids from 8
288 to 12.3 % (Figure 1). Time increase beyond 20 minutes generally reduced the per cent cake
289 solids. The converging of contours reflected interactions between; volume and time (elliptical
290 contours reflect a perfect interaction between volume and time), volume and speed; and time
291 and speed, although the interactions were not significantly changing the per cent cake solids (p
292 > 0.05). However, visualising the way the various factors influence the dewatering process
293 helps to improve the centrifuge design.

294 Furthermore, at optimal rotational time of 20 minutes and volume of ~ 45 mL, the average %
 295 cake solids of 11.4 (Table 5) could be achieved at a speed of 920 rpm. Increase in speed from
 296 400 to 2000 rpm linearly improved % cake solids at slight quadratic effects of volume and time
 297 (Figure 1b and c). Similarly, increasing speed from 920 to 2000 rpm at constant time of 20
 298 minutes improved % cake solids from average of 11.4 to 14.1 % (Figure 1c).



322
324 **Figure 1** Three-dimensional surface
 326 solids for unconditioned FS from
 328 as a function of: (a) volume and
 330 speed; (d) time and speed. Below
 332 contour plot showing interaction
 334 variables.

323 plots of per cent cake
 323 lined pit latrine (original)
 323 time; (b) volume and
 323 each graph is a 2D
 323 contour plot showing interaction
 323 variables between the two

336 When 75 %TS dosage of
 338 mixed with FS, the mean of %
 340 increased to 14.2 %. Increase in
 342 mL or speed of 400 rpm improved cake
 344 to 20 minutes, respectively. Increase in volume (40-50 mL) by about twice, at the same time of
 345 20 minutes, increased cake solids from 9.3 to 15 % (Figure 2a). Time increase beyond 20
 346 minutes generally reduced the per cent cake solids. The 2D contours reflect some interactions
 347 between; volume and time (also, the elliptical contours reflect a perfect interaction between
 348 volume and time), volume and speed; time and speed. The speed and quadratic effect of time

349 were significantly contributing to the per cent cake solids for sawdust conditioned FS ($p =$
350 0.0001 and $p = 0.0494$, respectively). At optimal time of 20 minutes and volume of ~ 45 mL, the
351 average per cent cake solids of 14.2 (Table 5) could be achieved at speed of 890 rpm. Similarly,
352 the 11.2 % cake solids at a rotational speed of 920 rpm in the original FS can be achieved at
353 virtually no rotation, but only through sedimentation or absorption effect. Increase in speed from
354 400 to 2000 rpm linearly improved per cent cake solids at slight quadratic effects of volume and
355 time (Figure 2b and c). Similarly, increasing speed from 890 to 1800 rpm, at a constant time of
356 20 minutes, improved per cent cake solids from average of 14.2 to 17.0 % (Figure 2c).

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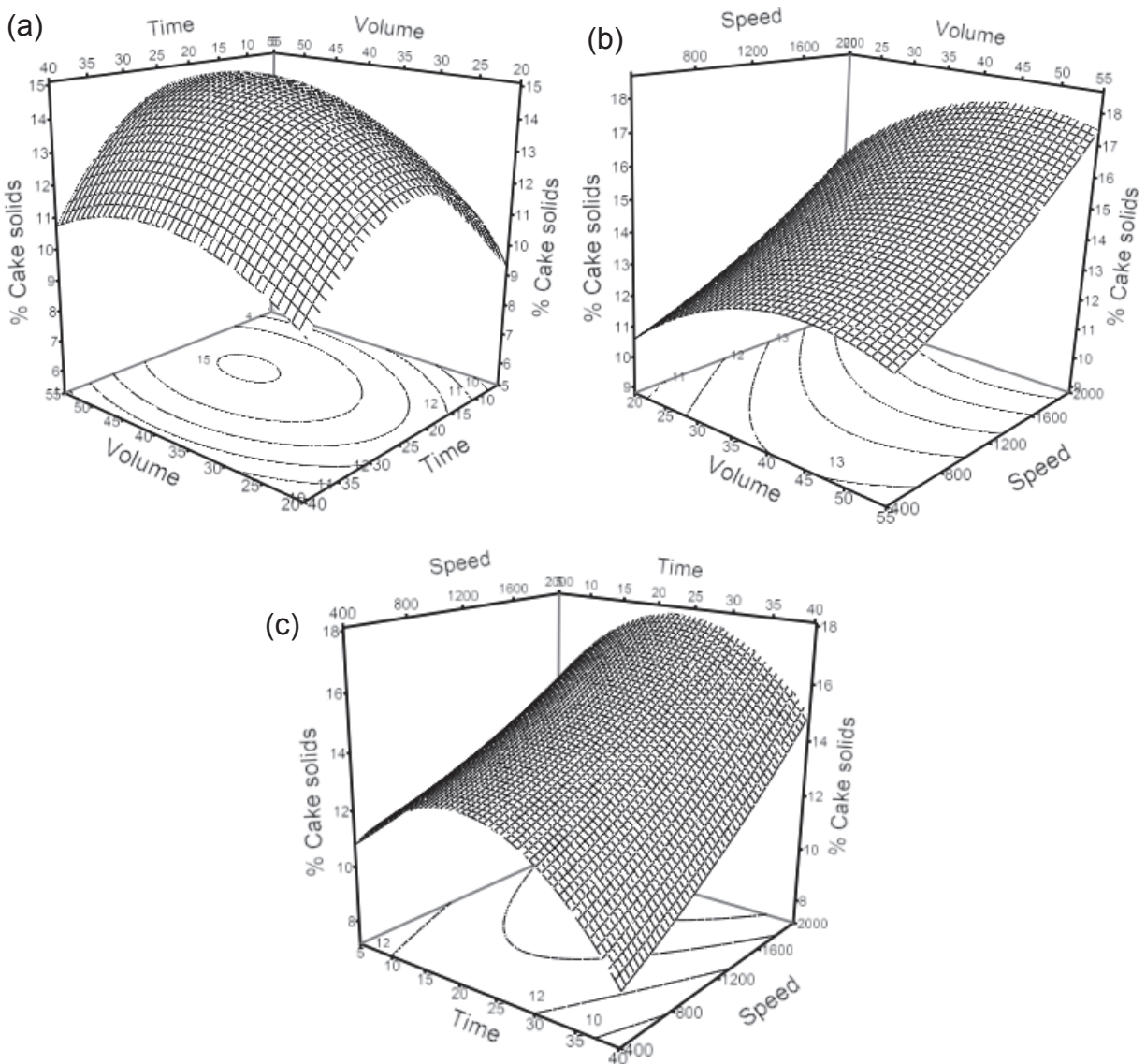


Figure 2 Three-dimensional surface plots of per cent cake solids for sawdust-conditioned pit latrine FS as a function of: (a) volume and time; (b) volume and speed; (d) time and speed. Below each graph is a 2D contour plot showing interaction between the two variables.

380 A 75 %TS dosage of charcoal dust conditioner mixed with FS increased the mean of per cent
381 cake solids for all runs to 16.4 % (Table 5). Per cent cake solids increased at lower and higher
382 volumes, with the least observed values at intermediate volumes at all times. However, the
383 maximums at lower (<30 mL) and higher volumes (>42 mL) and minimum at intermediate
384 volume (35 mL), all occurred at time of 20 minutes (Figure 3a). Thus, some interactions of
385 volume and time were realised at lower and higher volumes, although not significant ($p =$
386 0.506). A similar effect on volume interaction with speed was observed at lower and higher

387 volumes ($p = 0.955$), with a saddle point at 35 mL. Higher cake solids (>20 %) were achieved at
388 a speed of 1600 rpm with lower or higher volumes (Figure 3b). There was an almost perfect
389 interaction between speed and time (elliptical contours), though it was not significant ($p =$
390 0.954). The quadratic effect of time was reflected; with the maximum being 20 minutes. The
391 optimum cake solids of 13.3 % could be obtained at maximum time of 20 minutes at volume and
392 speed of 35 mL and 400 rpm, respectively. However, cake solids increased to an optimum of
393 18.7 % at a speed of 1600 rpm, beyond which per cent cake solids decreased.

394 At optimal time of 20 minutes and volume of 35 mL, the average per cent cake solids of 16.4
395 (Table 5) could be achieved at speed of 870 rpm. Consequently, increasing speed from 870 to
396 1600 rpm at constant time of 20 minutes improved per cent cake solids from average of 16.4 to
397 18.6 % (Figure 3c). For comparison with the original FS, average 11.2 % cake solids at speed of
398 920 rpm can be achieved at about 160 rpm, when conditioned with charcoal dust.

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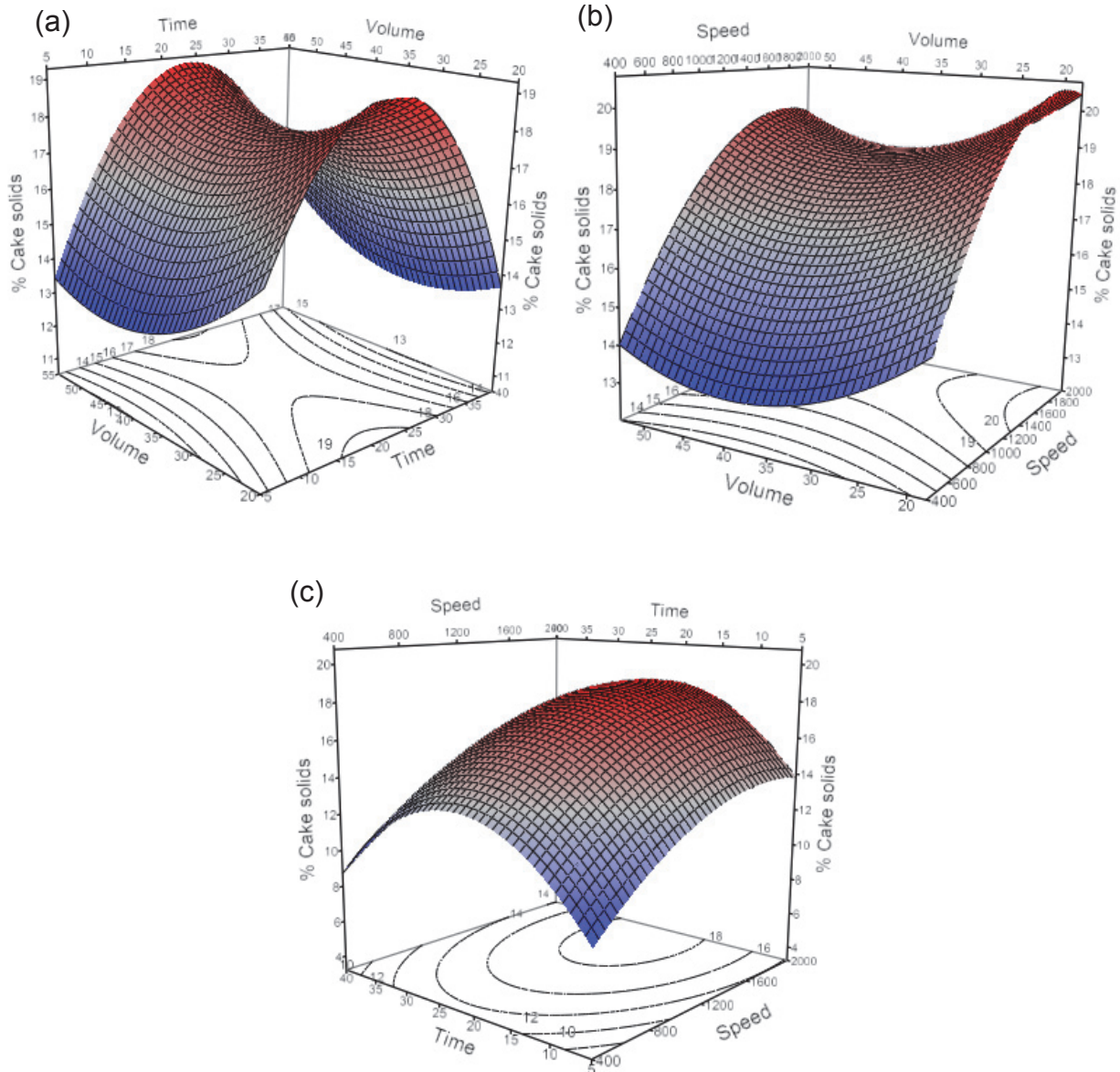
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420 **Figure 3** Three-dimensional surface plots of per cent cake solids for charcoal dust-conditioned FS from pit latrine as
421 a function of: (a) volume and time; (b) volume and speed; (d) time and speed. Below each graph is a 2D contour plot
422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

423 **4 Discussion**

424 **4.1 Use of sawdust and charcoal dust conditioners in centrifugal dewatering of FS**

425 The average per cent cake solids for original FS, sawdust and charcoal dust conditioned FS
426 were 11.4, 14.2 and 16.4, respectively. Per cent cake solids increased by 24.6 and 43.8 %

427 when conditioned with 75 %TS of sawdust and charcoal dust, respectively. The cake solids
428 increase in FS conditioned with charcoal dust is much higher than the observed 28.2%
429 increment by Albertson and Kopper (1983), when sewage sludge was conditioned with coal
430 fines. The interaction effects for volume and time in original and sawdust conditioned FS
431 signified sedimentation of particles with time. However, the quadratic effect of time, where it
432 takes 20 minutes for cake solids to increase to maximum and thereafter decreases, was
433 significant for sawdust conditioned FS. Centrifugation beyond 20 minutes resulted in re-
434 suspension of settled solids probably due to high absorptive nature of sawdust (Lin et al., 2001;
435 Luo et al., 2013). The result therefore suggests that sawdust significantly re-absorbed moisture
436 during batch centrifugation to decrease the per cent cake solids after 20 minutes. Therefore, the
437 quadratic effect of time needs to be considered during the operation of a centrifuge by limiting
438 centrifugation time.

439 The use of sawdust and charcoal dust conditioners improved the cake solids recovery due to
440 water absorption and increased porosity of FS cake. Semiyaga et al. (2017b) reported 89 and
441 56 % reduction in FS cake moisture after addition of sawdust and charcoal dust, respectively,
442 due to absorption and the remaining percentage may be attributed to improved porosity. The
443 decrease in moisture content of conditioned FS cake after dewatering is comparable to that of
444 sewage sludge cake, when sawdust and coal fly ash additives were increased from 0 to 100 %
445 (Chen et al., 2010; Ding et al., 2014; Lin et al., 2001). The particles of sawdust/charcoal dust are
446 bridged between FS solids, creating voids for water to flow out of the cake. This improvement in
447 porosity makes subsequent management options for separated FS solid and liquid streams
448 simpler. For example, the drying process of solid fraction quickens, since the convective heat
449 from surrounding air could easily be conducted to the interior of the FS cake, thus increasing the
450 interior temperature which affects the diffusion of water and vapour from the interior to the
451 surface, and later evaporated to the ambient (Lei et al., 2009). This can be achieved by
452 conventional drying of FS on sand beds, enhanced by greenhouse effect or use of solar dryers
453 (Murray Muspratt et al., 2014). The later enhanced technologies could be more feasible in an
454 urban slum setting due to space limitations. Further, the improved porosity of FS cake can
455 enhance the composting process through increased internal spaces for air flow (Lin et al.,
456 2001). Subsequently, usage of sawdust/charcoal dust conditioned FS as an organic soil
457 amendment improves soil productivity, not only because of nutrients present in FS, but also
458 increased aeration and water holding capacity of soils due to improved porosity (Kelley and
459 Martens, 1984).

460 **4.2 Effect of rotational speed on cake solids yield**

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

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

484 **4.3 Implications on faecal sludge management in urban slums**

485 A typical centrifuge is known to consist of a rotor, spin by a drive motor which is powered by
486 electrical supply that makes it to rotate (Gutierrez, 2005). The observed reduced centrifugation
487 speeds after modifying FS properties with the sawdust/charcoal dust conditioners can be
488 realised by hand-powered centrifuge devices. Here, a user physically spins the device and
489 energy is transformed into rotation of the rotor through gears. This could help in dewatering of
490 FS from slum areas that are not supplied with electricity, or where the use of electricity to run
491 the centrifuge is more expensive as compared to hand-powered. In some cases, cycle-powered

492 centrifuge devices could also be appropriate, where the pedalling actions of bi/tricycles are
493 transformed into rotor motion. Never-the-less, hand/cycle-powered centrifuge devices could
494 become energy intensive in times where people have to operate them for long durations, owing
495 to large volumes of emptied FS. In such cases, the centrifuge design could be modified to allow
496 a 12 volts DC battery power source (Turvaville et al., 1999) to rotate the devices in slum areas.
497 The DC battery can be recharged from places with electricity and used for running centrifuge or
498 usage of DC solar batteries charged by solar panels could be appropriate since solar energy is
499 available in most of the low-income countries. Local fabrication of hand/cycle powered
500 centrifuge devices can provide a low cost technology that is easily adoptable by low-income
501 urban slum population.

502 After centrifugation, the separated liquid fraction (centrate/leachate) could be further treated in a
503 low-cost crushed filter (sand, soil or lava rock) unit such as that developed by Katukiza et al.
504 (2014) to reduce the pollutant loads from wastewater in urban slums. The treated centrate is
505 likely to suit non-portable purposes such as irrigation of tower gardens for urban agriculture
506 (Kulabako et al., 2011), mortar additive for construction purposes (Katukiza et al., 2014), or
507 toilet flushing (Hamawand and Lewis, 2016). This has the potential to improve health and
508 increase environmental protection that would otherwise emanate from indiscriminate disposal of
509 untreated FS in a slum environment. The dewatered solid fraction can be transformed into a
510 number of products utilisable by the slum population (Semiyaga et al., 2015).

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

520 **5 Conclusions**

521 The centrifugation rotational speed has been identified as a key design parameter. In addition,
522 the centrifugation time significantly influenced dewatering of sawdust conditioned FS. The effect

523 of time on percent cake solids yield was quadratic, with an optimum value at 20 minutes.
524 Centrifugation beyond this time further reduced per cent cake solids due to re-absorption of
525 moisture by the dewatered cake conditioned with sawdust/charcoal dust.

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

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