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A multiple regression model for prediction of optimal dose of *Moringa Oleifera* in faecal sludge dewatering

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ABSTRACT

Moringa Oleifera (MO) is a highly effective conditioner in the dewatering of Fecal sludge (FS). However, the model for the prediction of its optimal dose has not yet been documented. This article presents the results of the developed model for the prediction of MO optimal doses. The developed model was based on assessing the FS parameters and MO stock solution. The FS samples were obtained from a mixture of a pit latrine and septic tank and were analyzed at the water quality laboratory of the University of Dar es Salaam. The multiple linear regression model was used to establish a relationship between MO optimal dose as a function of FS characteristics (pH, Electrical Conductivity, Total Solids and Total Suspended Solids) and concentration of MO stock solution. The results indicated that the main contributing factors which determine the MO optimal dose were the concentration of MO stock solution, followed by pH of FS. The model results showed a good agreement between the predicted and observed MO optimal dose with a coefficient of determination of $R^2 = 0.72$ and 0.9 for calibration and validation respectively. Therefore, the model can be adapted to determine the MO optimal dose without running the Jar-test experiment.

Key words: dewatering, faecal sludge, model, *Moringa Oleifera*, multiple regression, optimal dose

HIGHLIGHTS

- Effect of physical-chemical Faecal sludge characteristics on *Moringa Oleifera* dose.
- Physical-chemical predictor of Faecal sludge dewaterability.
- Concentration of *Moringa Oleifera* solution on optimal dose of *Moringa Oleifera*.
- *Moringa Oleifera* optimal dose model.
- *Moringa Oleifera* optimal model validation.

1. INTRODUCTION

Proper and adequate Faecal Sludge Management (FSM) is key in addressing urban and rural sanitation challenges (Todman *et al.* 2020). However, several factors, such as FS quantity and quality variability, lack of proper methods and equipment for emptying FS from containments, transporting FS, and handling costs, hinder the proper sustainability of FSM throughout its entire sanitation value chain (Strande *et al.* 2014; Seleman *et al.* 2019). Over 90% of FS is water, which poses a significant challenge in treatment since it increases the volume and causes difficulties in the subsequent FSM processes (Strande *et al.* 2014; Faye *et al.* 2018). As a result, dewatering is the first and most important treatment process because it increases the efficiency of the treatment plant and lowers treatment costs (Strande *et al.* 2014; Borda 2020). Physical methods such as sand drying beds are the most common and affordable dewatering methods used in developing countries (Gold *et al.* 2016; Strande *et al.* 2018; Seck *et al.* 2019). Nevertheless, this process requires a large area and takes a longer time (Gold *et al.* 2016; Moto *et al.* 2018). Therefore, the dewatering process becomes a largely unaffordable treatment option in most cities of Sub-Saharan Africa, resulting in high volumes of illegal disposal of untreated FS into the environment (USEPA 1984; Gold *et al.* 2018).

Studies have reported the use of chemical conditioners such as Aluminium Sulphate (Alum), Ferric Chloride, and Lime as alternative approaches to dewatering physical methods by enhancing the FS dewatering rate (Gold *et al.* 2018; Zaid *et al.* 2019). However, the use of chemical conditioners in low- and middle-income countries has

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proved to be relatively expensive and their high ions concentration could contribute to increased toxicity in the soil where dewatered and dried sludge is applied (Liao *et al.* 2014). The reported weakness of chemical conditioners for FS dewatering could be offset by employing the use of locally available natural conditioners such as *Moringa Oleifera* (MO) as its alternative.

MO seeds have been proven in many applications to be effective as an FS disinfectant as well as an enhancer of dewaterability rates (Gold *et al.* 2016; Ngandjui *et al.* 2018). The optimal dose of natural conditioners can be defined as the dosage above which a consistent 75% increase in FS dewatering performance is attained (Gold *et al.* 2016). At the optimal dose, MO has been observed to have high efficiency as a chemical conditioner (Ndabigengesere *et al.* 1995). A study conducted in Ghana revealed the high efficiency of MO and *Jatropha Curcas* in FS dewatering at the optimal dose (Gold *et al.* 2016). The most commonly used method for determining the optimal dose for natural conditioners is a Jar test. This method entails using these conditioners by repeating an experiment to determine the optimal dose for high dewatering performance. Thus, the method is expensive because it consumes both time and chemicals. Despite MO's widespread use, the model for predicting its optimal dose has yet to be investigated and documented. This study attempted to develop an empirical relationship that explains the factors that determine the MO optimal dosage to improve FS dewatering. A multiple linear regression model was used to determine the relationship. The investigated factors include the FS parameters and concentration of MO stock solution.

2. MATERIALS AND METHODS

2.1. Study approach

The study was conducted in the laboratory using batch operations. The FS sampling was undertaken to obtain two different data sets. The first data set used for model calibration was obtained from 180 FS samples taken every morning from 8.00 am for a sampling duration of six months. The second data set, obtained from 30 FS samples collected for three months, was used for model validation. The FS samples were collected from a mixture of a pit latrine and septic tank FS and *Moringa Oleifera* (MO). The laboratory experimental setup is shown in Figure 1.

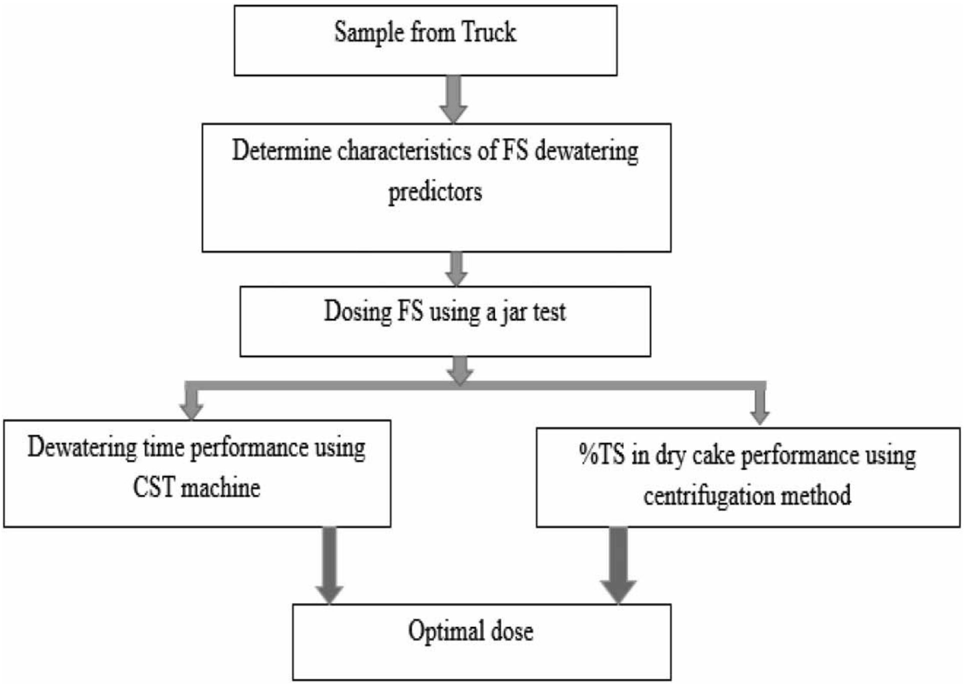

Figure 1 | The schematic layout for the experiment set up.

2.2. Data collection

2.2.1. The source of faecal sludge and the sampling procedure

A composite sampling technique was used to collect FS samples from trucks that transport FS that has been emptied from pit latrine and septic tank systems. Trucks eventually discharge FS at the Vingunguti Waste

Stabilization Ponds (WSPs). The FS samples from trucks were collected at three different sampling intervals. First, a ten-litre grab sample was collected at the start of the discharge when the truck tank volume was full. Second, a twenty-litre sample was collected in the middle of discharge when the truck tank volume was half full as indicated by the gauge. Last, the ten-litre sample was collected at the near end of discharge when the volume was about a quarter full. The three samples were then thoroughly mixed in a 50 L container to make a composite sample for both pit latrine and septic tank systems. This sampling protocol was adopted from Bassan *et al.* (2013). The 10-litre composite sample from the pit latrine and the 10-litre sample from the septic tank were transported separately to the UDSM laboratory using the cool box. Upon arrival, they were stored at around 4 °C for not more than 12 hours after sampling.

2.2.2. Faecal sludge sample preparation

Before the start of each experiment, the required volume of FS sample was taken outside from the cold room to room temperature for not more than 3 hours. After cooling, a10- litre FS composite sample from the pit latrine and one from the septic tanks were mixed in a 20-litre container to produce the FS sample which was then taken to the laboratory for analysis. A total of 180 FS composite samples for model calibration were analysed for six months. Another 30 FS samples for model validation were analysed for three months.

2.2.3. FS sample analysis

FS samples were analyzed for physical-chemical parameters that affect FS dewaterability. These parameters include temperature, pH, Electrical Conductivity (EC), Total Solids (TS), Total Suspended Solids (TSS) and Total Volatile Solids (TVS). Samples were analyzed according to the Standard Methods for Examination of Water and Wastewater. The pH and temperature of the FS were measured in-situ using a digital pH measuring kit with a probe (pH meter PT-15), and also the EC was measured in the field with a Metrohm E587 conductivity meter. The gravimetric method was used in the laboratory to determine TS, TSS, and TVS.

2.2.4. Preparation of *Moringa Oleifera* seeds powder

The MO seeds used in this study were procured from the Arusha Moringa company. A 10 kg of MO seeds were deshelled by hand to get clean seeds (Figure 2(a)). Then total dryness of shelled seeds was achieved at a temperature of 45 °C for 48 hours following (Ndabigengesere *et al.* 1995; Gold *et al.* 2016). Dry seeds were crushed by a

Figure 2 | Preparation of *Moringa Oleifera* seeds powder. (a) Deshelled MO seeds, (b) MO seeds powder, (c) oil extraction from MO seeds powder, and (d) yield of MO seeds powder.

household blender and sieved through a mesh size of 0.58 using Laborsreb machine model EML 200-67 for fine powder (Figure 2(b)). Oil in the seed powder, which interferes with the coagulation process, was extracted by Soxhlet apparatus (Figure 2(c)). Furthermore, defatted cake was dried in the oven at 37 °C for about 15 minutes to obtain fine and completely dry seed powder (Figure 2(d)) (Sayyar *et al.* 2009).

2.2.5. Preparation of *Moringa Oleifera* stock solution

The salts (salting method) were used to improve the extraction process of a large amount of coagulation agents from MO seed powder (Ndabigengesere *et al.* 1995; Sayyar *et al.* 2009). The active coagulant of MO seed was extracted by dissolving 1–10 g powder in 100 mL NaCl solution (0.6 M) to make a 1–10%w/v solution. A magnetic stirrer was used to blend the solution for about 30 minutes. To be accurate and systematic, all suspension was filtered first through 0.2–0.85 mm pore size filters. Because the active agent was obtained after filtration, the concentration of the active coagulant was expressed in millilitres of the added amount per FS volume using Jar-test experiment.

2.2.6. Determination of appropriate concentration of *Moringa oleifera* stock solution

Three trial experiments were conducted to determine the MO stock solution that provided the best FS dewaterability results. It was carried out on a total of 30 different FS samples, which were tested with MO stock solution concentrations ranging from 1 to 10%w/v. First, FS samples were tested with a stock solution of 1–3%w/v. Secondly, FS samples were dosed with a stock solution of 4–7%w/v and finally, FS samples were dosed with a concentration of 8–10%w/v.

2.2.7. Dewatering performance

The performance of FS dewaterability was determined using the dewatering rate. It is measured using the capillary suction time (CST (s)), which can be defined as the time required for FS free water to filter through filter paper. As described in the standard method, it is measured using a CST instrument (Type 304 M, Triton, England, UK) equipped with an 18-mm-diameter reservoir funnel and chromatography paper (APHA 2017). CST values were normalized based on TSS in the sample (sL/gTSS), to compare results across samples with different solids concentrations (Pengen *et al.* 2011; APHA 2017). Dewatering extent is another parameter used to measure the dewaterability of FS and it is defined as the total dry solids in the dewatered dry sludge cake after centrifugation. The cake solids were determined using a centrifuge (MISTRAL1000 type, UK). A 50 mL FS sample was centrifuged at 3,000 rpm for 20 min, which corresponds to 1,500 g (Semiyaga *et al.* 2017). The supernatant was decanted, and the wet and oven-dried (1050C) cake weights were analyzed using the standard method to determine the per cent solids content (wet basis) in the centrifuged cake (APHA 2017). Measurement replicates for parameters were performed according to recommended quality assurance and quality control (QA/QC) measures stipulated in standard methods (APHA 2017). The values reported are the averages of measurement replicates. R-software was used for statistical analysis and regressions.

2.3. Data analysis

2.3.1. Analysis of general optimal dose predictors

Descriptive statistics were used to analyzed the FS dewaterability predictors. Histogram diagrams were used to analyze the normality of data. Deviation, skewness and kurtosis values were used to test the normality of collected data. The Factor Analysis (FA) was used to determine all factors that affect the optimal dose model (Landau & Everett 2004). The multi-linear regression model was used to understand the relationship between the explanatory variables (FS parameters and MO stock solution) and the response variable (MO optimum dose) (Mendenhall & Sincich 2012; Keith 2014). The Variance Inflation Factor (VIF) was used to analyze the multi-collinearity among a set of explanatory variables (Landau & Everett 2004). A scatter plot diagram was employed to determine the linearity relationship between each explanatory variable (X values) and the response variable (Y- values). Plots of the standardized residuals and standardized predicted values were used to test the homoscedasticity. The R^2 values were used to determine the performance of the developed model (Montgomery & Runger 2014). The model development was performed using R-software. Furthermore, the Kruskal-Wallis test was performed to examine the significance of the explanatory variables in the model (Montgomery & Runger 2014). The *P*-value for the *F* statistic was used to test the significance of the model at the level of significance of $\alpha = 0.05$ (Mendenhall & Sincich 2012; Gold *et al.* 2018).

2.3.2. Model development

The response variable was assumed to be directly related to a linear combination of explanatory variables. Multiple Linear Regression (MLR) models were used to fit the data (Grabill & Iyer 1994). The model aims to establish the relationship between the optimal dose of Moringa Oleifera in FS dewatering as a response variable denoted by Y and the pH, TS, TSS of FS and concentration of MO stock solution as explanatory variables represented by X_1, X_2, X_3 for and X_4. The relationship between the response variable and the explanatory variables is represented by Equation (1).

$$Y = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \ldots\ldots\ldots \beta j i_n x_{ji} + \varepsilon_i \tag{1}$$

where, β_j, j = 0,1,2,3,4……….K are regression coefficients for explanatory variables, the subscript denotes the number of observations, ε_i is an error term assumed to be normally distributed with the properties that the errors have constant variance $\sum \varepsilon_i = 0$ such that Var $(\varepsilon_i = \sigma^2)$ and Cov $(\varepsilon_i, \varepsilon_j)$ for $I \neq j$; from this, we obtain $Y' = E(Y|X = X_i = \beta_0 + \beta_1 X_1 + \ldots\ldots \beta_j X_{ij}$. The MLR model was developed starting with the linear combination of the response variable with the explanatory variables. The process of developing and analyzing the model was performed using R.

The model structure used was the multi-linear regression model. The multiple regression model aimed to determine the relationship between the optimal dose of *Moringa Oleifera* in FS dewatering as a response variable (Y) and the explanatory variables of Temperature, pH, EC, TS, and TSS of FS (X_1, X_2, X_3, X_4 X_5 respectively) and concentration of MO stock solution (X_6). The relationship between the response variable and the explanatory variables is represented by Equation (2).

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i} + \beta_6 X_{6i} + \varepsilon_i \tag{2}$$

3. RESULTS

3.1. Faecal sludge characteristics

Results of FS physical-chemical characteristics and concentration of a stock solution and that of existing literature values are presented in Table 1. The FS characteristics values and the variability observed in this study are similar to those reported in other studies. The average TSS concentration from this study was in the range of reported average TSS concentrations of 1,300–19,900 mg/l. However, the TS concentration ranged from 1,370 to 47,228 mg/l, implying that the values of 10,063 ± 8,434 mg/l were at the low end of the published range. FS samples from this study were a mixture of FS from pit latrines and from septic tanks, which had dilution effects due to the use of water for anal cleansing. Moreover, TVS concentration values from this

Table 1 | FS characteristics of explanatory variables

	Descriptive statistics						
Parameters	**N**	**Min**	**Max**	**Mean**	**Median**	**STD**	**Literature values(mean)**
Temp (°C)	180	25	31	26.95	26	1.99	N/A
pH	180	5.6	8.10	6.93	7	0.74	6.9–8.5[a,c]
EC(μS/cm)	180	596	11,970	3,488	2,770	1.30	2,000–18,000[d]
TS(mg/l)	180	1,370	47,228	10,062	7,859	8,434	1,000–52,000[b,d]
TSS(mg/l)	180	214	16,218	3,258	1,182	6,028	1,300–19,900[f,g]
TVS(mg/l)	180	120	29,436	4,010	2,566	10.36	200–38,480[e]
Concentration. (w/v%)	180	4.0	7.0	5.5	6	1.10	N/A

[a] (USEPA 1984).
[b] (Lowe *et al.* 2009).
[c] (Ndabigengesere *et al.* 1995).
[d] (Gold *et al.* 2018).
[e] (Strande *et al.* 2018).
[f] (Seck *et al.* 2019).
[g] (Strande *et al.* 2014).

study were in the 120–2,9436 mg/l range, whereas the published range was 200–38,480 mg/l. The findings indicated that the minimum EC values were lower than those reported in previous studies, which were 2,000 μS/cm.

3.2. Effects of MO stock solution concentration on FS dewaterability time and extent

Table 2 shows values of concentration MO stock solution that were dosed in FS. The results indicated that at MO concentrations ranging from 1 to 3%w/v, there were no significant differences ($p > 0.05$) in dewatering rate (CST) and dewaterability extent (%TS of dry cake) when compared to unconditioned FS. There were significant changes in the dewatering rate and %TS of dry cake at the MO concentration of 4–7%w/v. The results indicated that there was no further improvement in FS dewatering time and extent at a concentration of 8–10%w/v. As a result, 7%w/v was chosen as an appropriate MO concentration to achieve the desired dewatering performance. In the experiments, this would not necessitate an MO stock solution concentration of 8–10%w/v. Furthermore, the findings indicated that the 5%w/v concentration of the stock solution is the best and economical for FS dewatering. Similar results were reported by Gold *et al.* (2016).

Table 2 | Effect of concentration of MO stock solution on FS dewaterability time and extent

Concentration of MO stock solution (w/v%)	Dewatering time reduced CST(s)	Amount of total solids in dry FS (%TS)	*P*-values ($\alpha = 0.05$)
Unconditioned (0)	418	20	
1	415	22	0.32
2	416	22.5	0.41
3	413	22.6	0.21
4	170	79.8	0.03**
5	154	85.5	0.002**
6	150	84.9	0.004**
7	168	85.6	0.002**
8	168	85.6	0.002**
9	169	86	0.001**
10	169	86	0.001**

**Significant at *P*-value $\alpha \leq 0.005$.

3.2.1. Normality of each explanatory variable

Figure 2 uses histogram graphs to demonstrate the normality of the explanatory data. The results indicated that all explanatory variables of FS are not normally distributed. As a result, the non-parametric method was used to analyze data for all explanatory variables.

3.2.2. Fitness of explanatory variable in model development

Table 3 presents the results of factor analysis (FA) and the model fitness information (*P*-values) for model predictor on the MO optimal dosage. The results of *P*-values and FA loading indicated that temperature and TVS were found to have little effect on model calibration due to high P and low FA values. Therefore, temperature and TVS were removed from the model calibration of the MO optimal dose.

3.2.3. Relationship between FS characteristics and MO stock solution on dewatering time and extent

Figure 3 depicts the results of explanatory variables on dewatering performance (dewatering rate as represented by CST and %TS in dry sludge) at different concentrations of the MO stock solution. The results show that at pH values less than 6.7 and greater than 7.5, there were low dewatering time and cake solid formation in dry FS (Figure 4(a) and 4(b)). pH values ranging from 6.7 to 7.5 were found to increase both dewatering time and % TS in a dry cake. Furthermore, the results show that an increase in EC corresponds to decrease in both dewatering time and %TS in dry cake (Figure 4(c) and 4(d)). A high concentration of TS was found to reduce dewatering time from 731 to 18 seconds (Figure 4(e) and 4(f)). This corresponds to an increase in dewatering times from 1.9

Table 3 | Model fitness of explanatory variables in development of model

Explanatory variables	*P*-values	FA values
Temp (°C)	0.992	0.002
pH	0.004***	0.976
EC (μS/cm)	0.034***	0.963
TS (mg/l)	0.027***	0.987
TSS (mg/l)	0.049***	0.834
TVS (mg/l)	0.062	0.001
Concentration (w/v (%)	0.000***	0.973

Significant difference at $P \leq 0.05$ and factor loading 0.3.

to 20.8 for unconditioned FS. In different concentrations of stock solution, the percent of TS in dry cakes increased from 9.5 to 22 percent, which is 1.5–3.3 times higher than the unconditioned one. The findings also indicated that a higher %TS in dry cake and shorter dewatering time were associated with lower TSS (Figure 4(g) and 4(h)).

3.3. Stata output of FS characteristics and MO stock solution

Table 4 presents the multiple regression model findings of the Stata output of the MO optimum dosage, FS characteristics and MO stock solution. The findings revealed that the combinations of FS characteristics and MO stock solution have a significant impact on the MO optimal dosage. The coefficient of determination, R^2 value, obtained by all explanatory variables was 0.725. This implies that FS characteristics and MO stock solutions contributed 72.5% of the MO optimum dosage, which can be considered the main factors. The F–statistic (F (5, 133) = 25.69) with *p*-value 0.00001 at the level of significance 0.05 suggested that the combination of these explanatory variables significantly contributes to predicting the optimal dose of MO in FS dewatering.

3.4. The relative importance of each FS characteristic and MO stock solution on the optimal dose of the MO model

3.4.1. Effect of pH, TS and concentration on MO optimal dose model

Equation (2) depicts the empirical relationships between the explanatory variables (pH, TS concentration and stock solution) and response variable (MO optimal dose). During calibration, the findings indicated that there was a good relationship between MO optimal dose and these explanatory variables, with $R^2 = 0.79$. The findings showed that all predictors contribute significantly to the model, with *p*-values of 0.002,0.0000, 0.000 for pH, TS, and concentration of the stock solution respectively ($\alpha \leq 0.05$). The pH of faecal sludge was the main contributing factor in determining the MO optimal dose.

$$\text{Optimal dose} = 82.91 - 2.93\text{pH} - 6.60\text{Conc} + 0.001\text{TS} \tag{3}$$

3.4.2. Effect of pH, EC and concentration of the stock solution on MO optimal dose model

Equation (3) shows the empirical relationship between the explanatory variables pH, EC of FS, and concentration of the stock solution and the optimal dose. The results indicated that there was a good relationship of MO optimal dose with these explanatory variables, with $R^2 = 0.699$. The results indicated that all predictors contribute to the model, with *p*-values of 0.002,0.0031, 0.000 for pH, EC, and concentration of the stock solution respectively ($\alpha \leq 0.05$). However, the concentration of MO stock solution was found to have a significant contribution in the model followed by the pH of faecal sludge.

$$\text{Optimal dose} = 77.50 + 0.001\text{EC} - 2.68\text{pH} - 6.46\ \text{Conc} \tag{4}$$

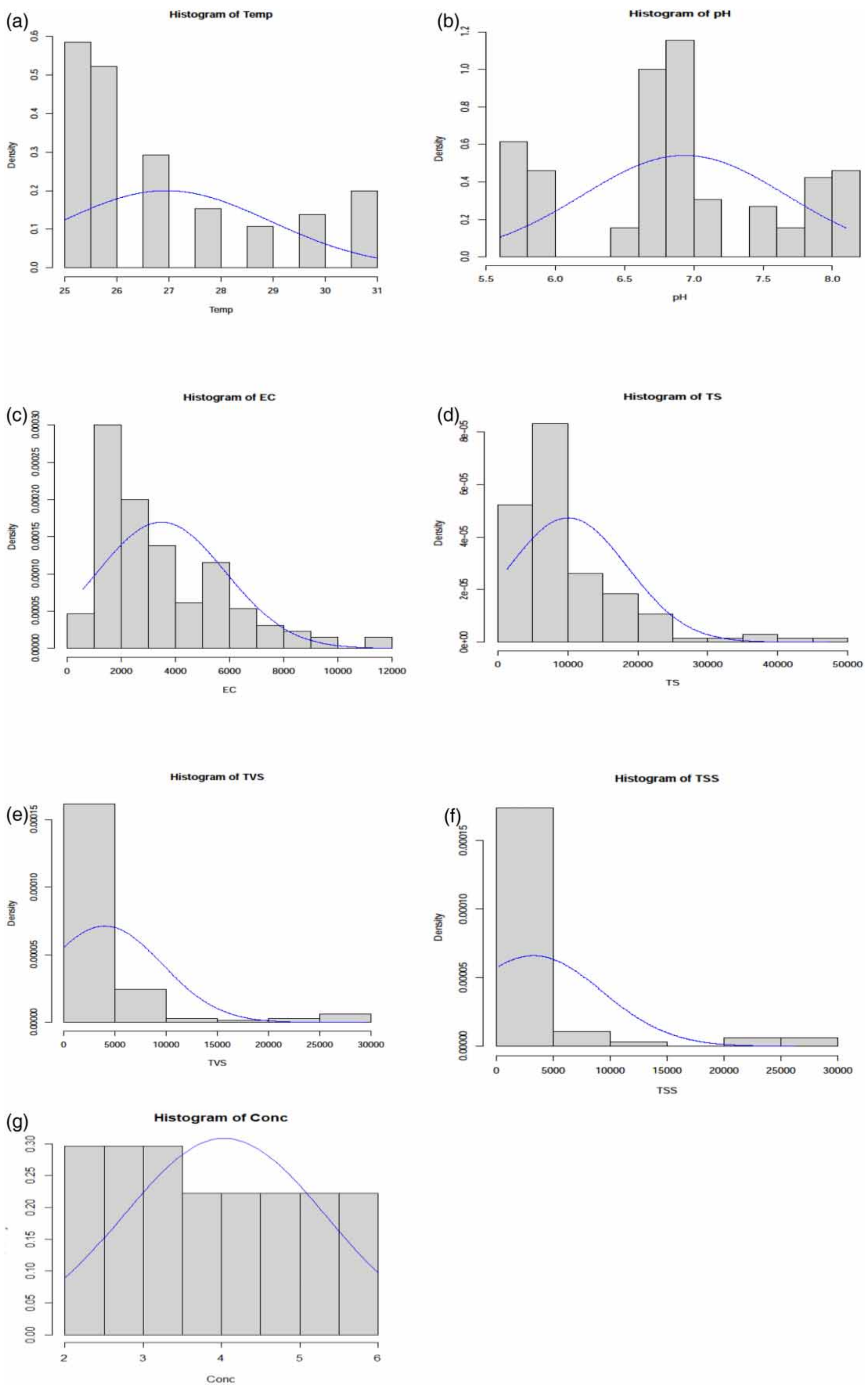

Figure 3 | Normality distribution of explanatory data.

3.4.3. Effect of pH, TVS and concentration of a stock solution on MO optimal dose model

The empirical relationships between explanatory variables pH, TSS of FS and concentration of the stock solution and the MO optimal dose is presented in Equation (4). The results indicated that there was a fair correlation of explanatory variables on the prediction of the MO optimal dose by these explanatory variables with $R^2 = 0.694$. Also, the results indicate that the TSS parameter has fairly less contribution to the model, with a *P*-value of 0.051,

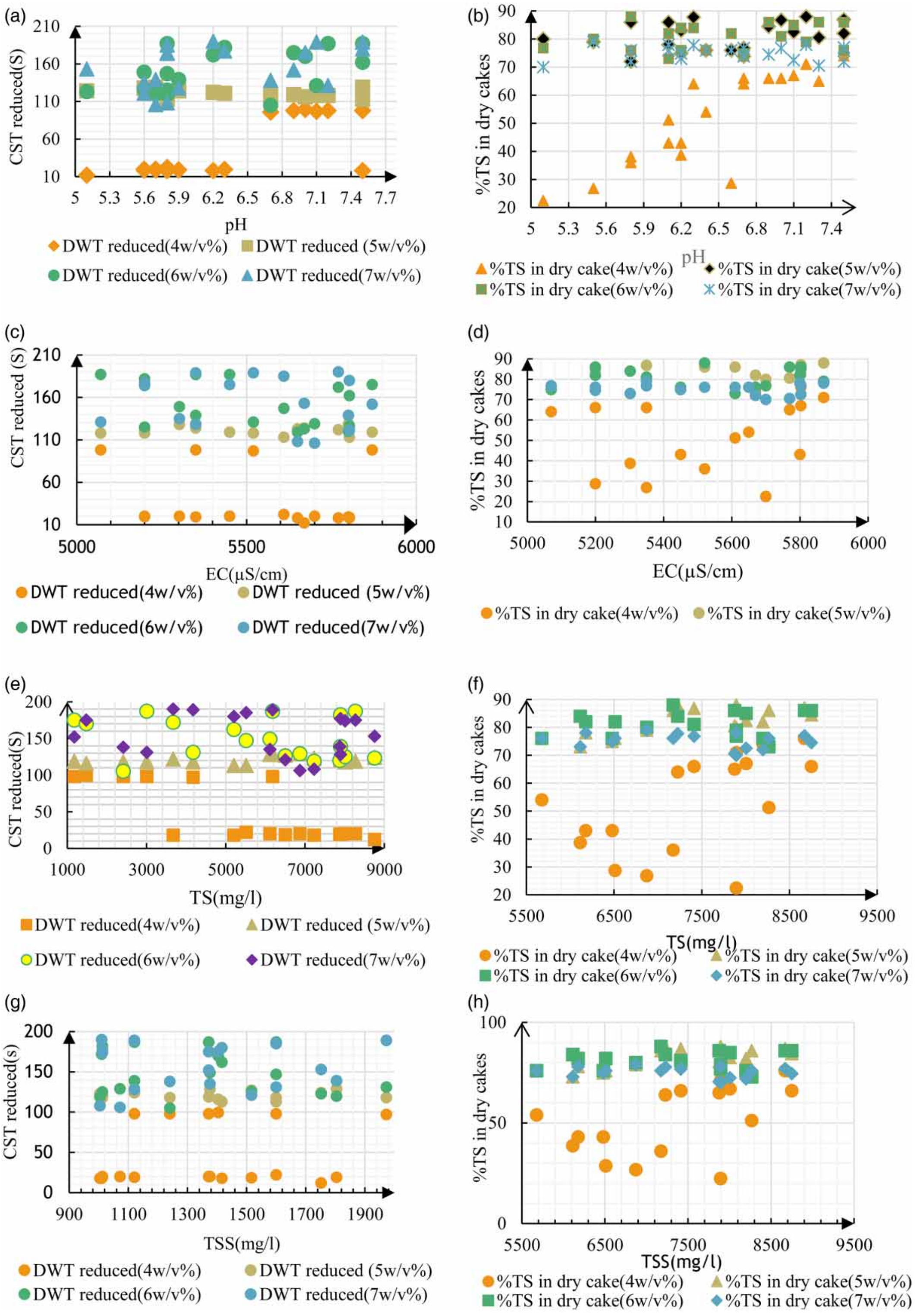

Figure 4 | Relationship between explanatory variables and dewaterability parameters.

while pH and concentration contribution with P-value = 0.002 and 0.000 respectively at ($\alpha \leq 0.05$).

$$\text{Optimal dose} = 79.96 - 2.84\text{pH} - 6.49\text{Conc} + 0.0001\text{TSS} \tag{5}$$

Table 4 | Stata output MO optimal dosage to pH, EC, TS, TSS and concentration

Model	SS	df.	MS	Number of observation = 180
	7,717.41	**5**	**1,543.48**	**F(5,133) = 25.69**
Residual	7,448.31	124	60.07	Prob. >F = 0.0000000
Total	15,165.72	129		R-squared = 0.725
				R-Adjusted = 0.72

Y	$\hat{\beta}_j$ coefficient	Sth. err	t	$P < \|\|t\|\|$	(95% Conf. interval)
pH	−2.74	0.93	−2.93	0.004	***
EC	0.001	0.57	1.85	0.034	***
TS	0.001	0.05	−2.23	0.027	***
TSS	0.004	0.49	0.35	0.049	***
Conc	−6.54	0.62	−10.5	0.000	***
Constant	79.48	6.2790776	10.48	0.00	***

***Significant at $P \leq 0.05$.

3.5. Multiple regression model for MO optimal dose

A multi-regression model revealed that the MO optimal dose is the function of the combined MO stock solution concentrations and FS characteristics (pH, EC, TS and TSS). The coefficients of the explanatory variable from Table 3 were substituted in an equation of model (1). The obtained model for MO optimal dose on FS dewatering is presented in Equation (5). The equation's results confirm that the model for determining MO optimal dose is reliant on the FS characteristics, specifically pH, EC, TS TSS, and Concentration of MO stock solution with *P*-values, as presented in Table 3. Moreover, the standardized coefficients of the developed model showed that the concentration of MO stock solution has the standardized coefficient with the largest absolute value, followed by pH then TS, EC and TSS. Therefore, the most predominant factors affecting optimal dose based on MLGM were concentration of a stock solution of MO followed by pH, EC and TS of faecal sludge.

$$\text{Optimal dose} = 79.48 - 2.74\text{pH} + 0.001\text{EC} + 0.001\text{TS} + 0.00004\text{TSS} - 6.54\text{Conc} \tag{6}$$

3.6. Model assumptions

(a) Multi-collinearity of explanatory variables

Table 5 presents the results of multi-collinearity, which shows the correlation between a set of explanatory variables. The numerical values of variance inflation factors (VIFs) for all explanatory variables were found to be less than 3. This means that all explanatory variables contribute independently to the determination of MO optimal dose. As a result, each explanatory variable independently contributes to the optimal dose of MO (Y) without interfering with the others.

(b) Homoscedasticity

Figure 5 shows the pattern of error variations of the sample data. The results indicated that error intervals

Table 5 | Variance inflation factors for the explanatory variables

	Multi-collinearity status	
Variables	Tolerance	VIF
pH	0.983	1.017
EC(μS/cm)	0.914	1.094
TS(mg/l)	0.933	1.071
TSS (mg/l)	0.985	1.015
Concentration (mg/l)	0.994	1.010

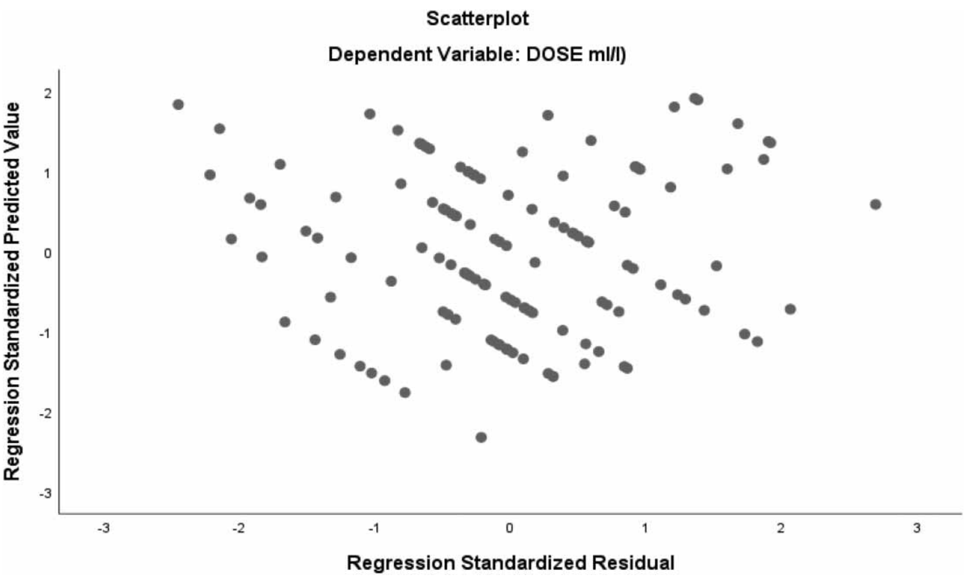

Figure 5 | Residual error variation plot.

between explanatory variables were evenly spread, resulting in a non-pattern cloud of dots surrounding the regression line. Therefore, data points were distributed fairly randomly, with a fairly even spread of residuals at all predicted values. This means that the error term's variance is constant and very low, making it suitable for model development.

(c) Independent errors

The errors between explanatory variables are small and independent from one another because the autocorrelation analysis performed using Durbin-Watson statistics produced a value of 1.17. Therefore, the error terms were uncorrelated and all values of the outcome were derived from different variables.

(d) Linearity of explanatory variables over the response variable

The results show that all variables are linearly related to one another and to the dependent variable. Therefore, all of the explanatory variables contribute in different ways to determining the response variable (MO optimal dose), and thus model development.

3.7. Model application on the prediction of MO optimal dose

3.7.1. Model validation

Table 6 shows descriptive statistics of FS characteristics, MO stock solution, predicted optimal dose obtained using the equation, and laboratory optimal dose obtained by the Jar test experiment for the second data set. The results showed that the measured values of MO dose using the second data set are close to model's prediction. As a consequence, the experimental results of the optimal dose were predicted by a mathematical equation of MO optimal dose. Thus, the model can be adapted to predict the MO optimal dose for FS dewatering.

Table 6 | Descriptive statistics of characteristics of explanatory variables and predicted optimal dose

	Characteristics of FS parameters				MO stock solution parameters		
Descriptive statistics	**pH**	**EC (μS/cm)**	**TS (mg/l)**	**TVS (mg/l)**	**Conc (w/v%)**	**Expected dose (mg/l)**	**Lab dose (mg/l)**
N	30		30	30	30	30	30
Min	6.8	151	4,587	1,048	4	25.5	22.5
Max	6.92	5,400	22,572	7,568	7	61.4	57.5
STD	0.07	1,417	4,650	1,976	1.14	9.9	9.3
Mean	6.9	2,582	9,063	4,047	5.5	41	38
***P*-values ($\alpha = 0.05$)**	0.0041**	0.0023**	0.001**	0.0200**	0.000**		N/A

3.7.2. Experimental optimal dose and predicted optimal dose

Figure 6 presents the results of experimental optimal doses and predicted optimal doses obtained from the model. The obtained results showed that experimental data of MO optimal dose from a Jar test fit fairly well to that predicted by the model. Therefore, there was a strong positive correlation between predicted (simulated) and observed optimal dose (laboratory) with $R^2 = 0.9118$ which is near to 1.

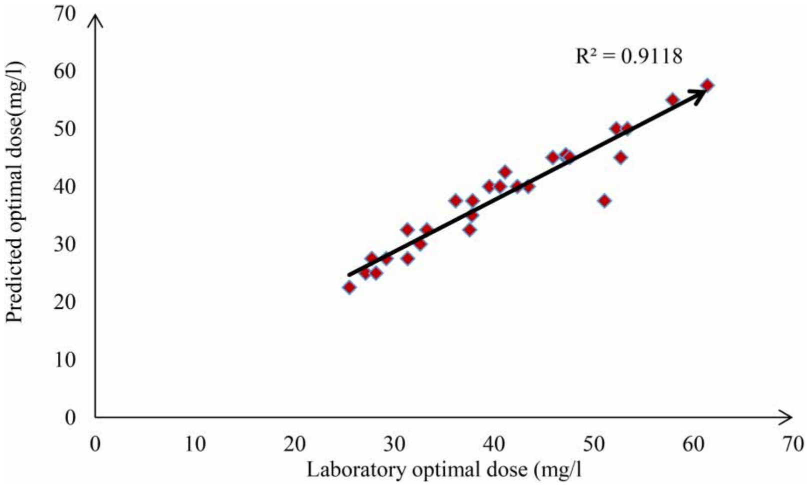

Figure 6 | Model validation.

4. DISCUSSION

This study attempted to understand the factors that determine the MO optimal dose for FS dewaterability. It was achieved through the model development, which assessed the contributions of FS parameters and MO stock solution in predicting the optimal dose of MO required in FS dewaterability. The variations in an optimal dose of MO are best explained by changes in pH, EC, TS, TSS FS predictors, and concentration of MO stock solution. FS and TSS temperature had little effect in determining the MO optimal dose. The four observed explanatory variables were combined to determine the optimal dose of MO for improving the dewaterability of FS. Other studies had reported similar findings on the effect of pH, EC, TS, TSS, and MO stock solution concentration in determining the optimal dose of MO conditioner in dewatering of FS (Pritchard *et al.* 2010; Gold *et al.* 2016; Ward *et al.* 2019).

pH values of FS (6.7–7.5) are favorable in maintaining the MO protein and making its surface more electropositive, which improves FS dewatering by destabilizing the colloidal charges and causing particles to agglomerate into larger and denser flocs, which easily settle (Karr & Keinath 1978). To maintain the optimum pH ranges, a low concentration of coagulants was used to shorten the duration for FS dewatering and increasing the concentration of % TS in dry cakes. Increasing the EC, on the other hand, causes the sludge surface to become more electronegative, causing electrostatic repulsion within the flocs (Christensen 1983; Kopp & Dichtl 1998). As a result, longer dewatering times and lower % TS in dry cakes are required. High concentrations of TS cause clogging of filters and pores in sludge cakes, resulting in a long dewatering time but a higher amount of solids in the cakes. This means that fine organic particles obstruct the flow of water by blinding the filter cake.

The pH effect can be explained by considering the isoelectric pH of the active cationic protein of MO seeds. The cationic protein of MO has an isoelectric pH of 10.0. (Ndabigengesere *et al.* 1995), which means that they remain positively charged as long as the pH is less than 10.0. Therefore, the dewatering of negatively charged particles by the cationic protein from MO seed solution was considered across the pH range, using the well-known mechanism of adsorption and charge neutralization for MO conditioner. This implies that a wide range of MO could be applied across different locations in FS dewatering enhancement to achieve optimal solid-liquid separation with little or no adjustment of the pH. In practice, an optimal dose of MO can be achieved at a low dose of FS, resulting in lower chemical and time costs.

Additionally, there was a high positive correlation between predicted (simulated) and observed optimal dose (laboratory) at $R^2 = 0.9118$ which is close to 1. When looking at the graphs in Figure 5, it is clear that the model and experimental results are in sync. The findings of this study provide a very good arrangement for using MO optimal dose model without performing a Jar test. It also provides support in the operation and monitoring of FS and wastewater treatment plants. Therefore, using the values of pH, EC, TS, TSS of FS, and the concentration of MO stock solution, the empirical formula (Equation (5)) could be used to determine the optimal dose of conditioners instead of using the Jar test.

5. CONCLUSION AND RECOMMENDATION

The findings of this study revealed that pH, EC, TS, TSS and concentration of MO stock solution have a significant impact on the optimal dose of MO conditioner for FS dewatering. The results have shown a potential contribution of pH and concentration of MO stock solution in determining the optimal dose of MO for FS dewatering. Based on the study results, all parameters have shown a strong contribution in the determination of optimal dosage of MO for a P-value less than 0.05 as the significance level. Therefore, the mathematical model for predicting MO optimum dose for FS dewatering can be adapted in different cities and types of onsite technology. As a result, without performing a Jar-test experiment, this empirical model for determining the optimal dose of MO can be used for dewatering.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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