Cross-country analysis of faecal sludge dewatering

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Acknowledgements

This study was funded by the Swiss Development Corporation (SDC), the Japan Society for the Promotion of Science (JSPS) under Grant Number JP 16H02748, and the Fonds de recherche du Québec - Nature et technologies (FRQNT).

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Dewatering of faecal sludge (FS) is indispensable for adequate FS management. However, comprehensive knowledge is lacking on FS dewatering performance. This study compared the dewatering performance of FS from different countries and onsite sanitation technologies, to assess influential characteristics on dewatering, and to compare dewatering performance of FS with wastewater sludge. We collected 73 FS samples from septic tanks, lined pit latrines, unlined pit latrines, and *johkasou* tanks in Uganda, Vietnam and Japan, and 18 samples of wastewater sludge in Switzerland. Capillary Suction Time (CST) and total solids (TS) of centrifuged sludge (%TS_{final}) were determined as metrics of dewatering rate and dewaterability, respectively, together with relevant sludge characteristics. Data was analysed by bootstrapping comparison of median results of each sample category, and by bootstrapping multiple regression analysis to quantify the relative importance of sludge characteristics on dewatering performance. Results showed that dewatering rate was significantly different between FS from different technologies, whereas dewaterability was significantly different within the same technology. FS had a significantly lower dewatering rate than wastewater sludge. In contrast, FS dewaterability was greater than wastewater sludge. However, this could be attributed to higher concentrations of sand in FS. Electrochemical properties such as NH_4-N and surface charge had the strongest correlation to dewatering rate, and solid properties such as sand content and total volatile solids to dewaterability. The results identify potential characteristics that could explain and predict the high variability of FS dewatering performance that is observed in the field.

Keywords: faecal sludge; dewatering rate; dewaterability; bootstrapping; multiple regression analysis

Introduction

Worldwide, the sanitation needs of 2.7 billion people are met by onsite sanitation technologies [1-2]. Typically, faecal sludge (FS) from these technologies is inadequately managed. FS is “the raw or partially digested, semisolid or slurry resulting from collection, storage or treatment of combinations of excreta and blackwater, with or without greywater" that accumulates in onsite sanitation technologies [3]. For example, in Kampala, Uganda; Dar es Salaam, Tanzania; Dakar, Senegal; Hanoi and Danang, Vietnam; and Nonthaburi, Thailand, sanitation needs of 75-100% people are met by onsite sanitation technologies and 21-82% of excreta is not safely managed [4-9]. This has significant economic, environmental and public health implications [10, 11].

In urban areas, FS collected by vacuum trucks typically contains more than 95% water [12-16]. This makes the dewatering of FS indispensable for adequate faecal sludge management. Increased performance of FS dewatering can reduce the amount of FS that needs to be transported, can decrease the required land area or increase the capacities of FS treatment plants, and can improve the resource recovery potential of FS treatment products [12, 13, 17].

In contrast to FS, comprehensive knowledge is available on the dewatering performance of wastewater sludge in relation to sludge characteristics [18-24]. FS dewatering rates are highly variable between cities and onsite sanitation technologies, and is less efficient than wastewater sludge [13, 25, 26]. For example, in Dakar, Senegal, septic tank FS had a lower dewatering rate compared to literature values for water and wastewater sludge [13]; in Accra, Ghana, public toilet FS had a lower dewatering rate than septic tank FS [26]. FS characteristics that influence dewatering rates and dewaterability have not been reported for different onsite sanitation technologies. Such knowledge could help to improve the design and operation of FS treatment plants. In addition, comparison of FS dewatering rates and dewaterability with wastewater sludge could aid in the transfer of knowledge and technologies from wastewater sludge to FS treatment.

The objective of this study was to quantify and compare the dewatering performance of FS from different countries and onsite sanitation technologies, to assess the influential sludge characteristics on the dewatering performance, and to compare the dewatering performance of FS with that of wastewater sludge.

Materials and methods

Sludge Sampling

As summarized in Table 1, 73 FS and 18 wastewater sludge samples were collected in Vietnam, Uganda, Japan and Switzerland.

In Uganda, FS samples were collected from 16 lined pit latrines (Lined_UG), 13 septic tanks (Septic_UG) and five unlined pit latrines (Unlined_UG) in Kampala. Lined pit latrines are above or below ground, fully-lined tanks, with no overflow or infiltration [27]. Unlined pit latrines are fully unlined, or partially lined tanks, and thus allow for groundwater inflow or FS infiltration and septic tanks were below ground, fully-lined tanks, with an overflow [28]. Emptying frequencies are highly variable in Kampala, and the average frequency is not known. Lined_UG and Septic_UG samples were collected from vacuum trucks during discharge at Bugolobi Sewage Treatment Works, where FS was also treated with sewage. To obtain representative samples from each vacuum truck, approximately one-liter grab samples were collected four times during discharge and then mixed to one composite sample: once at the beginning, twice in the middle, and once at the end. Unlined_UG samples were collected from manual FS collection service providers during discharge at Bugolobi Sewage Treatment Works. Approximately eight litters of grab samples were collected from the entire FS volume, and mixed to one composite sample.

In Vietnam, FS samples were collected from ten septic tanks of private households (Septic_VN) and four septic tanks of public pay-for-use toilets (Public_Septic_VN) in Hanoi. Emptying frequencies have a high variability, with the median interval estimated at seven years [29]. Public_Septic_VN were collected from vacuum trucks discharging at the Cau Dien treatment plant. Septic_VN were obtained through an access port on the top of vacuum trucks with a core sampler.

In Japan, 16 lined pit latrine (Lined_JP) and nine *johkasou* tank (Johkasou_JP) FS samples were collected. Lined pit latrines in Japan are sealed tanks made out of Fiber-Reinforced Plastics, typically equipped with micro flush toilet pans (200-500 mL/flush). The FS is collected every few months by vacuum trucks. *Johkasou* are onsite wastewater treatment units for the treatment of blackwater, or black- and greywater. *Johkasou* can include different physical, chemical and biological treatments such as contact aeration, anaerobic filter, nitrification and denitrification, phosphorus removal, and chlorination. FS from *johkasou* is collected once a year by vacuum trucks [30]. Although the sludge from *johkasou* may be more similar to wastewater sludge as it may include primary and secondary sludge from a biological treatment unit, this paper defined *johkasou* as FS based on the definition of FS by Strande (2014) [3]. This definition specifies that FS comes from all types of onsite sanitation technologies that are not connected to sewers, and has been widely accepted by the sector. The FS samples were collected from receiving or storage tanks at five FS treatment plants in Kusatsu, Nakatsu, Nose, Togane and Goshogawara.

In Switzerland, six primary (Primary_CH), waste activated (Activated_CH) and anaerobically digested (Digested_CH) wastewater sludge samples were collected. Primary_CH was collected from primary sedimentation tanks, Activated_CH from aeration tanks and Digested_CH from anaerobic digesters. All treatment plants operated with nitrification, denitrification and chemical phosphorus removal. Activated sludge processes included plug flow or sequencing batch reactor configurations. Digested_CH is a mixture of primary sludge and waste activated sludge. Retention times in the anaerobic digester were 20-30 days [31]. Samples were collected from wastewater treatment plants in Fallaenden, Bassersdorf, Neuguth, Effretikon, Zurich-Werthoelzli and Uster. Multiple grab samples were collected from each tank and mixed to one composite sample per sample category.

All collected samples were kept refrigerated prior to analyses. FS samples were removed from the refrigerator and left to attain room temperature before analyses.

Sludge Analyses

Conventional mechanical dewatering such as belt filters or centrifuges remove the free water from sludge [32, 33]. In this study, dewaterability was defined as total solids (TS) following removal of free water during dewatering. It was estimated as %TS_{final}, the %TS of the pellet remaining at the bottom of a 50 mL centrifuge tube following centrifugation (3000 rpm, 20 minutes) and discarding of the supernatant. %TS_{final} has been used for the relative dewaterability of wastewater sludge [23, 34].

Dewatering rate was defined as the rate that free water is released from sludge, and was estimated by Capillary Suction Time (CST (sec)). CST was measured with a meter (304M CST, Triton Electronics Ltd, UK) according to Standard Methods [35]. The CST was normalized to TS (sec/(g TS/L)) to allow comparison of CST results between sludge samples with different TS concentrations [36, 37].

The following characteristics, which potentially influence dewatering performance [18-24], were analyzed: pH, electrical conductivity (EC), temperature, TS, total suspended solids (TSS), total volatile solids (TVS), volatile suspended solids (VSS), ash, sand content, chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4-N), crude protein, surface charge, and particle size distribution.

TS, TSS, VSS and TVS were analysed according to Standard Methods [35]. Ash was determined as the residue following TVS analysis. Sand content was analyzed gravimetrically after washing the residue of combustion at 550°C for two hours with 0.1 mole/L hydrogen chloride [23]. Following washing until the filtrate remained clear, the residue was combusted again at 550°C for two hours. COD, TN and NH_4-N were analyzed with Hach vials according the manufacturer's directions. Crude protein was used as a proxy for EPS (Extracellular Polymeric Substances) and approximated based on an organic nitrogen-to-crude protein conversion factor of 6.5 [38]; organic nitrogen (N_{org}) was estimated as the difference between TN and NH_4-N. pH, temperature and EC were measured with handheld pH, temperature and EC probes.

Surface charge was analyzed with small modifications from the colloidal titration method [39, 40]. Samples were diluted to a solution of around 5 g TS/L. Following, 10 mL of 2.5 mmol/L polydiallyldimethylammonium chloride (PDAC) standard solution (WAKO, Osaka, Japan) were added to 90 mL of distilled water and mixed for one minute. After the addition of 2 mL of phosphate urea magnesium buffer, 10 mL of the diluted sample were slowly added and mixed for ten minutes. Subsequently, a few drops of toluidine blue were added and mix for five minutes and the solution was titrated with 2.5 mmol/L potassium polyvinylsulfate (PVSK) standard solution (WAKO, Osaka) until a change of color from blue to pink.

Particle size distribution was determined gravimetrically by serial filtration based on Tchobanoglous et al. [41]. Between 15-260 mL of sample were poured in serial through a 1 mm, 0.075 mm and 0.032 mm sieve and 0.01 mm filter (Whatman Nuclepore Track-Etched) followed by weighing the dry mass of the residue on each sieve and filter. A sample volume of 2-40 mL was used to allow for complete filtration with the 0.01 mm filter. The sum of the mass of residues on the sieves and filter for each sample had around ±20% difference compared to the TS for the same sample. Particle sizes were grouped based on Karr and Keinath [19] into settleable (75 µm < particles < 5000 µm), supracolloidal (32 µm < particles < 75 µm) and colloidal-dissolved (10 µm < particles < 32 µm) solids.

Large particles in FS interfere with analysis. Therefore, samples were screened through a 5 mm sieve before all analyses. In addition, samples were homogenized with a blender before analysis of TS, TSS, TVS, sand content, surface charge and $\%TS_{final}$.

Data analysis

Results of sludge analyses in this study were non-parametrically distributed. For data comparison across sample categories, medians were compared with bootstrapping in Python with Anaconda 4.4.0. Bootstrapping was chosen based on the small sample number and the large variability of analyses results [42]. According to Schmid and Huber [42], results are presented as the 75% confidence interval of the median of 10,000 bootstrapping experiments for each sample category. Significant differences among sample categories were identified by comparing medians in each bootstrapping experiment. Sample categories were considered as significantly different if the median was higher or lower in at least 95% of bootstrapping experiments. Public_septic_VN and Unlined_UG were excluded in the comparison among sample categories of dewatering rate and dewaterability due to the small sample number.

Stepwise multiple linear regression analysis was conducted with bootstrapping in R version 3.3 [43] with the package relaimpo version 2.2-2 [44] to evaluate the influence of FS characteristics on CST and $\%TS_{final}$. To simplify the regression analysis, wastewater sludge and Johkasou_JP were excluded from the regression analysis since these sludges are generated in highly-controlled treatment processes that are very different from conditions in septic tanks and lined or unlined pit latrines.

Bootstrapping regression analysis was repeated 1,000 times. Prior to regression analysis, characteristics with co-linearity ($-0.7 < r < 0.7$) were excluded from the data set with a Spearman's rank correlation matrix (see supplemental material Table S2). Following, 14 characteristics (regressors) were selected for regression analysis, namely: pH, EC (mS/cm), TS (g/L), settleable solids (%TS), sand content (%TS), NH_4-N (mg/g TS), COD (mg/g TS), crude protein (mg/g TS), TVS (%TS), surface charge (meq/g TS), supracolloidal solids (%TS), TSS (%TS), TDS (g/L) and VSS (%TSS). Two separate bootstrapping multiple regression analyses were conducted: 1.) with TSS (%TS), TDS (g/L) and VSS (%TSS) excluded from regression due to a lack of results for most FS samples from Uganda (*n*=50); and 2.) with all 14 characteristics included, but the sample number reduced due to the lack of data in Uganda (*n*=40). The first analysis is reported in this paper, the second analysis is included in the supplemental material (Figure S1). Characteristics to be included in a regression model and their contributions to R^2 varied in each bootstrapping experiment. The relative importance, which is the influence of each regressor on R^2 of the regression model [44], was calculated so that the influence of each parameter on the regression models of CST and $\%TS_{final}$ could be compared. Characteristics that had a median relative importance higher than 10% were considered as having a significant influence on the regression models.

Results and discussion

Descriptive statistics of faecal sludge characteristics

Results of physical and chemical characteristics of FS samples are reported in Table 2, together with values from the literature for comparison. The mean TS, TVS, COD and NH_4-N were 2.0-3.2%, 50.9-73.2%TS, 16.3-33.9 g/L and 184-598 mg/L for septic tank FS samples, and 1.1-2.2%, 54.0-60.6%TS, 10.9-21.6 g/L and 1417-1654 mg/L for lined pit latrine FS samples. The mean CST and $\%TS_{final}$ were 11-28 sec/(g TS/L) and 11-18% for septic tank FS samples, and 49-63 sec/(g TS/L) and 18-20% for lined pit latrine FS samples. These results are in reason to those reported in the literature (see Table 2), which could corroborate the results of this study.

Results of this study were not normally distributed, as indicated by the large difference between the mean and median, and had a large variability, as indicated by the standard deviation. The large variability of FS characteristics has also been reported by previous studies (see Table 2). Considering the non-parametric distribution and large variability of results, bootstrapping data analysis was applied in this study as it does not require a parametric distribution and can visualize the variability of results by confidence intervals.

Sludge dewatering performance

Dewatering rate (CST)

CST, reported in Figure 1, was used as a metric of sludge dewatering rate. As has been previously reported [13, 25, 26], in this study, FS had a slower dewatering rate compared to wastewater sludge, with the median CST of FS of 19-61 sec/(g TS/L) (75% confidence interval of bootstrapped median), compared to the median CST of wastewater sludge of 3-19 sec/(g TS/L). The median CST was 48-60 sec/(g TS/L) for Lined_UG, 31-61 sec/(g TS/L) for Lined_JP, 22-54 sec/(g TS/L) for Johkasou_JP, 19-38 sec/(g TS/L) for Septic_UG, 19-29 sec/(g TS/L) for Septic_VN, 10-19 sec/(g TS/L) Digested_CH, 4-5 sec/(g TS/L) for Primary_CH and 3-5 sec/(g TS/L) for Activated_CH. The results indicate that co-treatment of sludge from septic tanks and wastewater sludge can decrease the overall dewatering rate compared to wastewater sludge, as reported by [25].

FS from lined pit latrines had significantly slower rates of dewatering than FS from septic tanks, except for Lined_JP and Septic_UG. Dewatering rates within the same technology types were not significantly different, even between different countries (i.e. septic_UG and septic_VN, Lined_UG and Lined_JP), suggesting that dewatering rate could be influenced by the types of onsite sanitation technologies. This could be due to factors such as the technology design, construction and operation (e.g. emptying frequency, waste products entering the technology). This also illustrates the importance of designing solutions for the local context based on different types of onsite sanitation technologies, and conducting laboratory and pilot-scale experiments to validate the design of dewatering technologies [49].

Another aspect illustrated by the confidence intervals in Figure 1, is the increased variability of FS results compared to wastewater sludge. This is not surprising, as wastewater is homogenized during transport in the sewer, and samples were collected from homogenization tanks at centralized treatment plants. FS is not homogenized, and samples were collected from individual pits or tanks at the household level. Storage tanks or settling-thickening tanks could be a way to reduce this variability at FS treatment plants, and facilitate dewatering operations, but they would have to be quite large. For example, in Japan where there are around 1,000 FS treatment plants, storage tanks typically have a volume of three times the daily treatment capacity for equalization [50].

Dewaterability (%TS_{final})

%TS_{final}, reported in Figure 2, was used as a metric of sludge dewaterability, and the results were variable between sample categories. The %TS_{final} of Septic_VN of 11-12 %TS (75% confidence interval of bootstrap median) and Johkasou_JP of 6-9 %TS were significantly lower than of Primary_CH of 12-15 %TS. The %TS_{final} of all types of

FS except for Johkasou_JP was significantly higher than Activated_CH of 5-6 %TS and Digested_CH of 8-9 %TS. Johkasou_JP had a similar $\%TS_{final}$ to that of Activated_CH and Digested_CH. The similarity of Johkasou_JP and wastewater sludge is likely due to the similarity of treatment technologies, as most *johkasou* employ the activated sludge process [30]. Results for septic tank and pit latrine FS indicate that some types of FS could have a higher dewaterability than activated sludge and digested wastewater sludge; however, the higher dewaterability associated with high sand contents may pose a negative impact on FS resource recovery and final disposal, as mentioned below.

In contrast to the dewatering rate, dewaterability was different between FS from the same type of onsite sanitation technology. Whereas no significant difference was observed between Lined_UG (16-18 %TS) and Lined_JP (17-21 %TS), Septic_UG (14-20 %TS) had a significantly higher $\%TS_{final}$ than Septic_VN. Lined_UG, Lined_JP and Septic_UG had a significantly higher $\%TS_{final}$ than Septic_VN. In contrast to the CST results, these results indicate that dewatering of FS cannot be predicted based on the onsite sanitation technology. In addition, based on the size of confidence intervals in Table 2, the variability of FS had a smaller influence on dewaterability than dewatering rate.

Influence of faecal sludge characteristics on the dewatering performance

Multiple linear regression analysis with bootstrapping was used to identify analysed characteristics of FS that have a strong correlation to dewatering performance. All of the FS samples were analyzed together, other than Johkasou_JP due to its similarity to wastewater sludge. The results of the analyses are presented in Figure 3 as the $\%R^2$ of the dewatering rate (as CST) and in Figure 4 as dewaterability (as $\%TS_{final}$). The median R^2 of 1,000 bootstrapping experiments was 0.67 for CST and 0.76 for $\%TS_{final}$, which are reasonable considering the large variability of FS characteristics.

As shown in Figure 3, characteristics related to the electrochemical properties of sludge had the largest contribution to R^2 in the CST regression model. NH_4-N (mg/g TS) had a median relative importance of 22%, surface charge (meq/g TS) of 20%, EC (mS/cm) of 12%, and crude protein (mg/g TS) of 12%. NH_4-N and EC positively correlated to increased CST, whereas surface charge and crude protein negatively correlated.

These results are similar to those observed with wastewater sludge. Cations play an important role in the dewatering of wastewater sludge. A high concentration of monovalent cations, such as NH_4^+, Na^+ and K^+,~~-N~~ destabilize flocs and increase CST (i.e. decrease dewatering rate) by replacing divalent cations [51-53]. In this study, an increase of NH_4-N was observed to also correlate to increase CST. However, this study did not investigate Na^+ and K^+, which could also have had an impact. The increase in CST with a decrease in surface charge is likely due to electrostatic forces on the sludge surface that repel particles [20, 54, 55]. The influence of EC on CST is likely due to the correlation to NH_4-N (r=0.6, see supplemental material Table S2). High NH_4-N concentrations could also inhibit anaerobic digestion which could influence dewatering rate [56, 57]. It was hypothesized that crude protein as a metric of EPS would correlate to increased CST, as protein is a major component of EPS, and EPS increased CST in wastewater sludge [58, 59]. However, crude protein correlated to a decreased CST, which could be due to a poor correlation between crude protein and EPS, as EPS is also comprised of carbohydrates. Crude protein was also negatively correlated to NH_4-N (r=0.5, see supplemental material Table S2), which did correlate to an increased CST.

As shown in Figure 4, characteristics related to the solid properties of sludge had the largest contribution to R^2 in the $\%TS_{final}$ regression model. Sand content (%TS) had a median relative importance of 31%, TVS (%TS) of 18% and TS (mg/L) of 10%.

Surface charge (meq/g TS) and COD (mg/g TS) were also significant with median relative importance of 13% and 11%, respectively. Other than surface charge, the characteristics that correlated to dewaterability were different to those that correlated to the dewatering rate.

Sand content and TVS accounted for almost 50% of R^2. TVS correlated to a decreased %TS_{final}. This is in line with results from wastewater sludge. Skinner et al. [24] observed that TVS correlated to decreased dewaterability of wastewater sludge. COD also correlated to a decreased %TS_{final} as COD and TVS are both metrics of organic matter in sludge. In contrast, sand content correlated to an increased %TS_{final}. This is also similar to previous observations, as inorganic particles measured as sand or ash have been observed to increase dewaterability [23]. This can be explained as inorganics having weaker or no surface charge, in comparison to organics, which have a lower compressibility, and can also provide channels for the drainage of free water.

However, high %TS_{final} of FS may pose a negative impact on FS resource recovery and final disposal. For example, Unlined_UG that was not included into multiple regression analysis due to the small sample size, had a sand content of 45-69 %TS and a %TS_{final} of 22-37% (see supplemental material Table S1). Although its %TS_{final} was high, this high concentration of sand contents would cause difficulties for resource recovery from sludge (e.g. incineration [15]), and increased costs for disposal in landfills.

Application and limitations of results

FS characteristics that were identified to correlate to dewatering rate and dewaterability based on bootstrapping multiple linear regression models could be used to predict dewatering performance, and may explain the differences in dewatering rate and dewaterability across the FS sample categories examined in this study. To evaluate this potential, Figure 5 and Figure 6 include sludge characteristics for the different sample categories that had a significant relative importance in the regression models. Public_Septic_VN and Unlined_UG were excluded from this evaluation due to small sample number.

Lined_UG had a significantly lower CST than Septic_UG and Septic_VN, and Lined_JP had a significantly lower CST than Septic_VN (see Figure 1). These results could be explained by NH_4-N and EC, that had a significant relative importance in the regression model for CST. As shown in Figure 5, NH_4-N and EC that correlated with increased CST was significantly different between sample categories. Lined_UG and Lined_JP had significantly higher median NH_4-N and EC than Septic_VN and Septic_UG: 52-152 mg/g TS vs. 7-54 mg/g TS; 11-17 mS/cm vs. 2-6 mS/cm. High NH_4-N and EC are characteristic of FS from lined pit latrines due to more concentrated FS with no overflow [26, 60]. These results imply that the NH_4-N and EC could be responsible for the observed poor dewatering performance of pit latrine FS compared to septic tank FS. If so, this result could be very valuable in the design and operation of onsite sanitation technologies, and treatment technologies. In contrast, surface charge (see Figure 5) and crude protein (see supplemental material Table S1) which did have a strong correlation to CST were not significantly different between sample categories. Results for crude protein were not significantly different between sample categories and are therefore not included in Figure 5.

Septic_UG, Lined_UG and Lined_JP had a significantly higher $\%TS_{final}$ than Septic_VN (see Figure 2). These results could be explained by TVS, COD and sand content, that had a significant relative importance in the regression model for $\%TS_{final}$, because as shown in Figure 6, TVS, COD and sand content were significantly different among the sample categories. TVS that correlated to decreased $\%TS_{final}$ were significantly higher for Septic_VN (71-77%TS) than for Septic_UG (49-60%TS), Lined_UG (53-60%TS) and Lined_JP (59-67%TS). COD that correlated to decreased %TS_{final} were significantly higher for Septic_VN (1,152-1,345 mg/g TS) than for Lined_UG (962-1,112 mg/g TS). However, results for Lined_JP indicate limitations of explaining the dewaterability by single characteristics. Lined_JP had significantly lower sand content (7-9%TS) than the other types of FS (11-32%TS), which based on this explanation would be in contradiction to Lined_JP having significantly higher %TS_{final} than Septic_VN (see Figure 2). These results are likely due to the interrelation of multiple characteristics having an influence on dewaterability. Further, as mentioned in the previous section, high sand contents would pose a negative impact on resource recovery and final disposal although it was strongly correlated to increased %TS_{final}. Results for TS were only significantly different between lined_UG and lined_JP and are therefore not included in Figure 6.

The different observed concentrations of TVS, COD and sand content in the different types of FS, are due to the wide ranging differences in the design, construction and operation of onsite technologies, including the solids retention time, influx of sand due to poor construction, and types and volumes of waste products. For example, lined pit latrines in Japan are made of Fibre-Reinforced Plastic and are constructed at factories, whereas lined-pit latrine in Uganda are constructed in situ with bricks. This difference alone could contribute to the higher sand concentrations that were observed for Lined_UG FS. Thus, differences in types of construction, different materials, and modes of operation, could potentially also provide ways to predict dewaterability of FS.

Conclusions

Highly variable dewatering performance of FS greatly complicates the reliable design and operation of treatment plants. These results provide the first published reference comparing dewatering rates and dewaterability of FS from different regions around the world. The results identify potential characteristics that could explain and predict the high variability that is observed in the field. Future research in this area is needed for the improved design and operation of FS treatment plants. Findings include:

- FS samples had a significantly higher CST, indicating lower dewatering rate than wastewater sludge;
- FS samples had an equal or higher $\%TS_{final}$ compared to wastewater sludge;
- However, if higher $\%TS_{final}$ are caused by high sand contents, it would pose a negative impact on resource recovery and final disposal;
- Electrochemical properties had the strongest correlation to FS dewatering rate, and solid properties on FS dewaterability;
- FS characteristics that were strongly correlated to dewatering could explain observed differences in dewatering between different types of FS;
- Future research is needed to develop predictive models of sludge characteristics on dewatering, based on a fundamental understanding of FS dewatering mechanisms.

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Table 1. Country, type of sludge (FS = faecal sludge, WWS = wastewater sludge), technology, name of sample category and *n* = number of samples analysed in this study.

Country	**Type of sludge**	**Technology**	**Name of sample category**	***n***
Vietnam	FS	Septic tank of households	Septic_VN	10
Vietnam	FS	Septic tank of public pay-for-use toilets	Public_Septic_VN	4
Uganda	FS	Septic tank	Septic_UG	13
Uganda	FS	Unlined pit latrine	Unlined_UG	5
Uganda	FS	Lined pit latrine	Lined_UG	16
Japan	FS	Lined pit latrine	Lined_JP	16
Japan	FS	*Johkasou* tank	Johkasou_JP	9
Switzerland	WWS	Primary sedimentation tank	Primary_CH	6
Switzerland	WWS	Aeration tank	Activated_CH	6
Switzerland	WWS	Anaerobic digester	Digested_CH	6

Table 2. Descriptive statistics (med.=median, S.D.=standard deviation) of physical and chemical characteristics of all FS sample categories.

	n		**pH**	**EC**	**TS**	**TVS**	**COD**	**NH_4-N**	**CST**	**%TS_{final}**
Name of sample category			-	mS/cm	%	%TS	g/L	mg/L	sec/(g TS/L)	%TS
Septic_VN	10	Mean	7.7	2.3	2.1	73.2	24.9	184	23	11
		Med.	7.8	2.0	1.8	75.5	22.1	183	22	12
		S.D.	0.5	1.3	1.3	6.1	14.2	77	9	2
Public_septic_VN	4	Mean	7.4	5.6	3.2	56.5	33.9	598	11	13
		Med.	7.7	3.7	1.7	56.0	17.3	379	13	13
		S.D.	1.1	5.6	4.2	12.8	45.8	691	4	7
Septic_UG	13	Mean	7.4	5.7	2.0	50.9	16.3	579	28	18
		Med.	7.7	4.9	1.8	57.0	13.8	626	27	14
		S.D.	0.7	5.9	1.6	18.9	13.6	548	18	13
Septic tank values from literature[1]	-	Range of mean values	-	2.4-5.0	0.8-4.0	55-71	8.2-37.7	150-600	3-21	-
Lined_UG	16	Mean	7.8	14.6	2.2	54.0	21.6	1654	49	20
		Med.	7.8	13.6	1.7	56.0	20.8	1498	56	17
		S.D.	0.2	7.7	1.0	12.0	8.9	848	22	9
Lined_JP	16	Mean	7.4	12.6	1.1	60.6	10.9	1417	63	18
		Med.	7.3	12.4	1.1	63.0	9.8	1290	44	19
		S.D.	0.6	2.5	0.3	17.9	4.5	362	57	6
Lined pit values from literature[2]		Range of mean values	-	18.1	0.9-5.2	57-64	34.0-65.5	1418-2100	-	-
Unlined_UG	5	Mean	7.8	12.1	17.9	43.2	117.6	3175	10	30
		Med.	7.8	12.0	14.8	52.0	127.2	3110	9	30
		S.D.	0.2	3.7	9.5	15.1	40.8	839	4	10
Johkasou_JP	9	Mean	7.0	2.2	1.0	74.0	13.2	239	66	9
		Med.	7.1	1.7	1.0	77.0	12.6	178	30	8
		S.D.	0.4	2.0	0.4	13.4	6.6	193	93	3

Legend: Septic_UG = septic tank Uganda; Septic_VN = septic tank of households Vietnam; Public_septic VN = septic tank of public pay-for-use toilets Vietnam; Lined_UG = lined pit latrine Uganda; Lined_JP = lined pit latrine Japan; Unlined_UG = unlined pit latrine Uganda; Johkasou_JP = *johkasou* tank Japan.

[1,2] Range of mean values from the literature and unpublished data from Sandec/Eawag: [12-14, 25, 45-48].

Figure 1. 75% confidence interval of the bootstrapped median of dewatering (CST) for FS and wastewater sludge. Legend: Septic_VN = septic tank of households Vietnam; Septic_UG = septic tank Uganda; Lined_UG = lined pit latrine Uganda; Lined_JP = lined pit latrine Japan; Johkasou_JP = *johkasou* tank Japan; Activated_CH = wastewater aeration tank Switzerland; Digested_CH = wastewater anaerobic digester Switzerland; Primary_CH = wastewater primary sedimentation tank Switzerland.

Figure 2. 75% confidence interval of the bootstrapped median dewaterability (%TS_{final}) of FS and wastewater sludge. Legend: Septic_VN = septic tank of households Vietnam; Septic_UG = septic tank Uganda; Lined_UG = lined pit latrine Uganda; Lined_JP = lined pit latrine Japan; Johkasou_JP = *johkasou* tank Japan; Activated_CH = wastewater aeration tank Switzerland; Digested_CH = wastewater anaerobic digester Switzerland; Primary_CH = wastewater primary sedimentation tank Switzerland.

Figure 3. Relative Importance of correlation of FS characteristics to the dewatering rate (as CST (sec/(g TS/L)), calculated by bootstrapping multiple regression analysis. The figure shows bootstrapping median and 95% confidence interval, (+) and (-) indicate the direction of influence by each characteristic.

Figure 4. Relative Importance of correlation of FS characteristics to the dewaterability (as %TS_{final}), calculated by bootstrapping multiple regression analysis. The figure shows bootstrapping median and 95% confidence interval, (+) and (-) indicate the direction of influence by each characteristic.

Figure 5. 75% confidence interval of the bootstrapped median of NH_4-N (left), EC (center) and surface charge (right) for septic tank and lined pit latrine FS.

Figure 6. 75% confidence interval of the bootstrapped median of sand content (left), TVS (center) and COD (right) for septic tank and lined pit latrine FS.

Figure 1

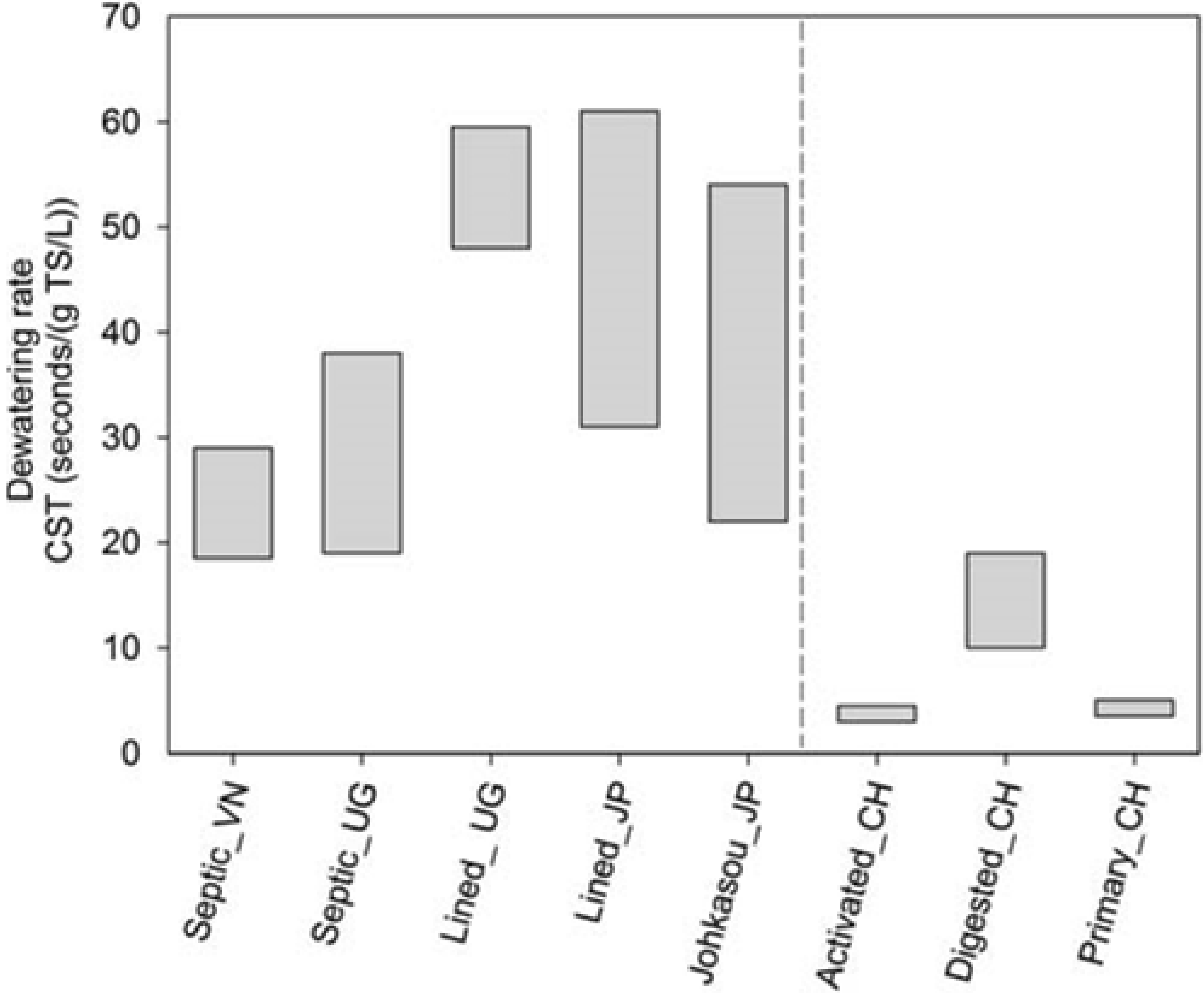

Dewatering rate
CST (seconds/(g TS/L))
70
60
50
40
30
20
10
0
Septic_VN
Septic_UG
Lined_ UG
Lined_JP
Johkasou_JP
Activated_CH
Digested_CH
Primary_CH

Figure 2

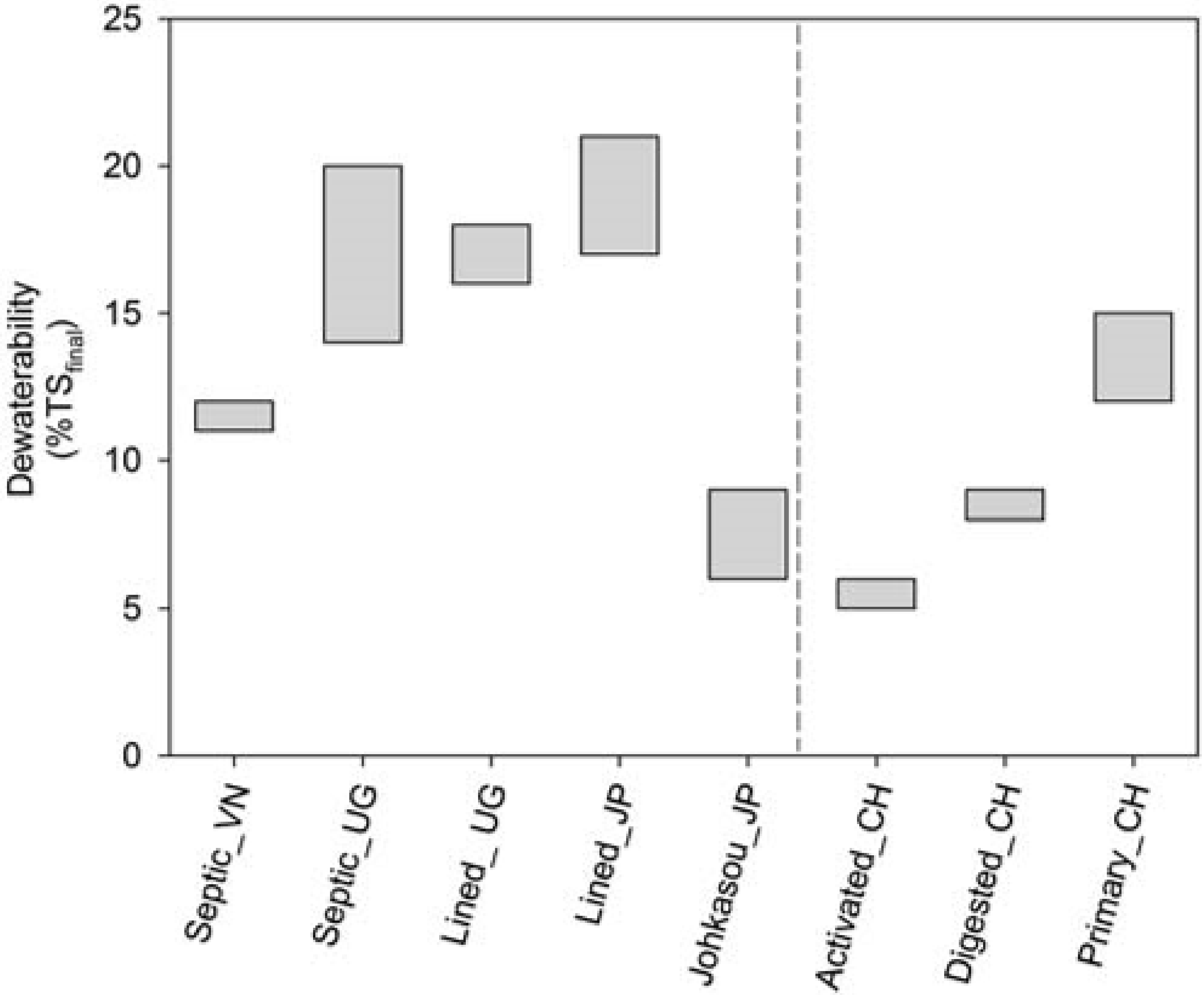

Dewaterability
(%TS_{final})
25
20
15
10
5
0
Septic_VN
Septic_UG
Lined_ UG
Lined_JP
Johkasou_JP
Activated_CH
Digested_CH
Primary_CH

Figure 3

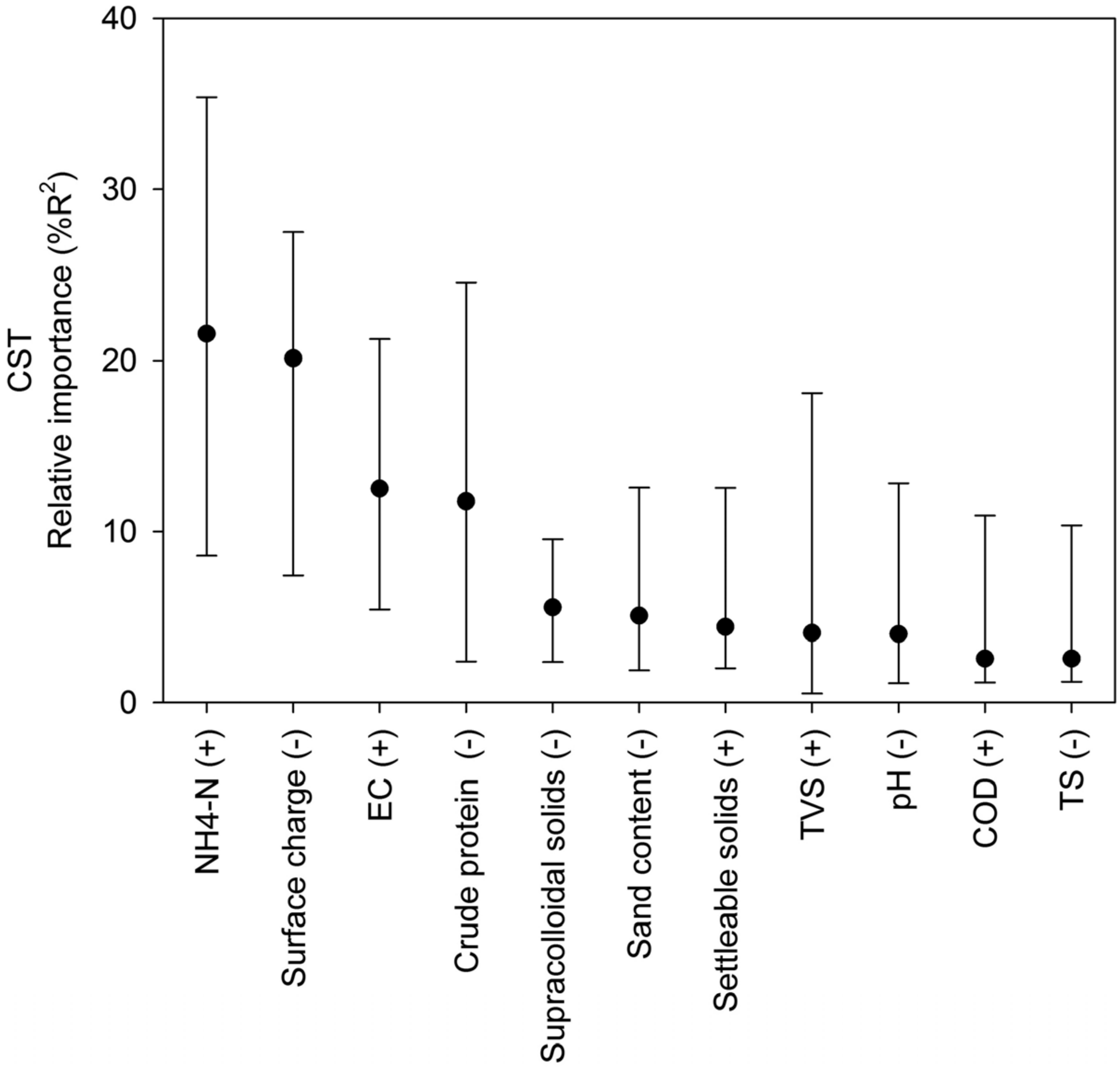

CST
Relative importance (%R²)
40
30
20
10
0
NH4-N (+)
Surface charge (-)
EC (+)
Crude protein (-)
Supracolloidal solids (-)
Sand content (-)
Settleable solids (+)
TVS (+)
pH (-)
COD (+)
TS (-)

Figure 4

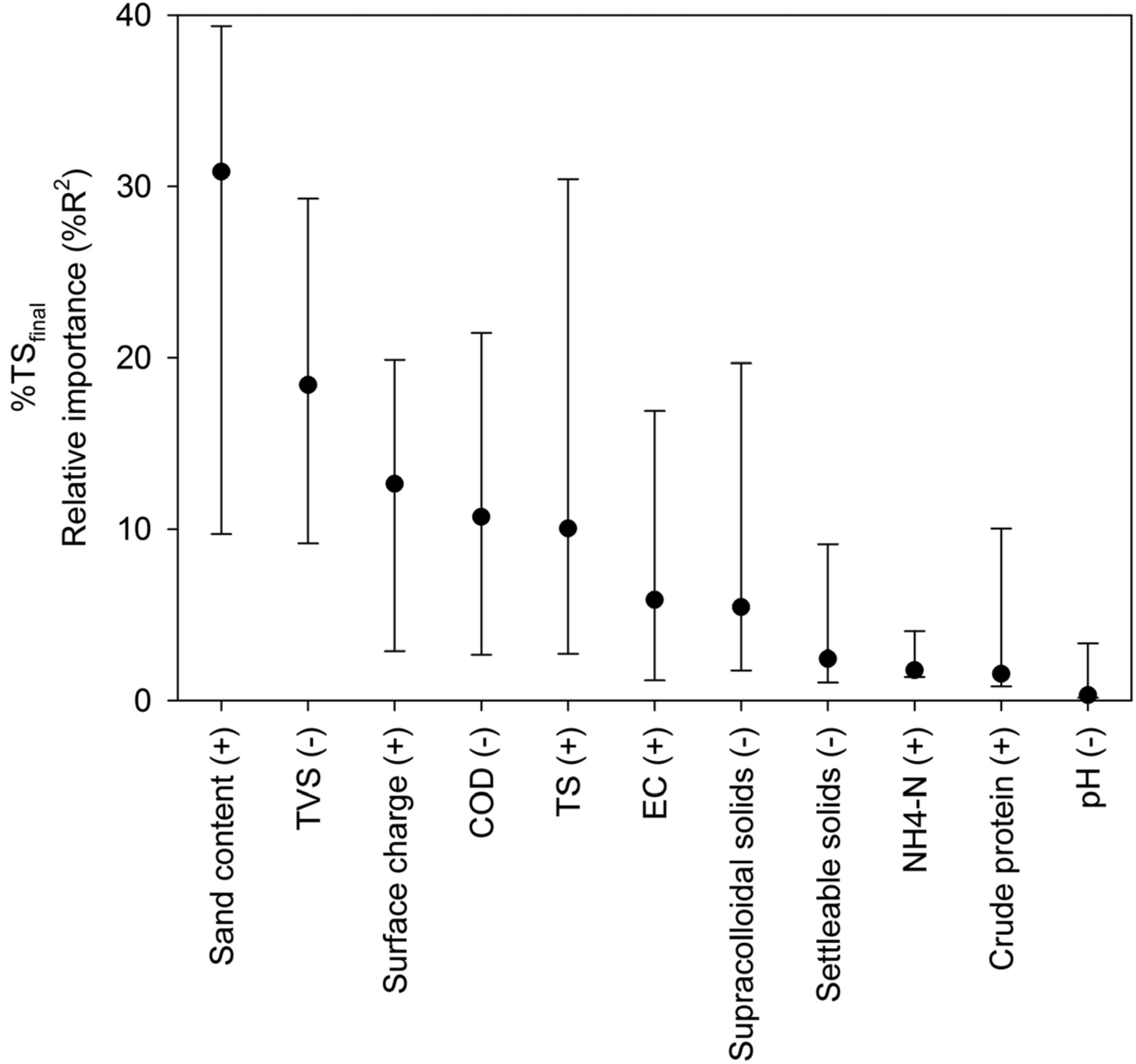

%TS_{final}
Relative importance (%R^2)
0
10
20
30
40
Sand content (+)
TVS (-)
Surface charge (+)
COD (-)
TS (+)
EC (+)
Supracolloidal solids (-)
Settleable solids (-)
NH4-N (+)
Crude protein (+)
pH (-)

Figure 5

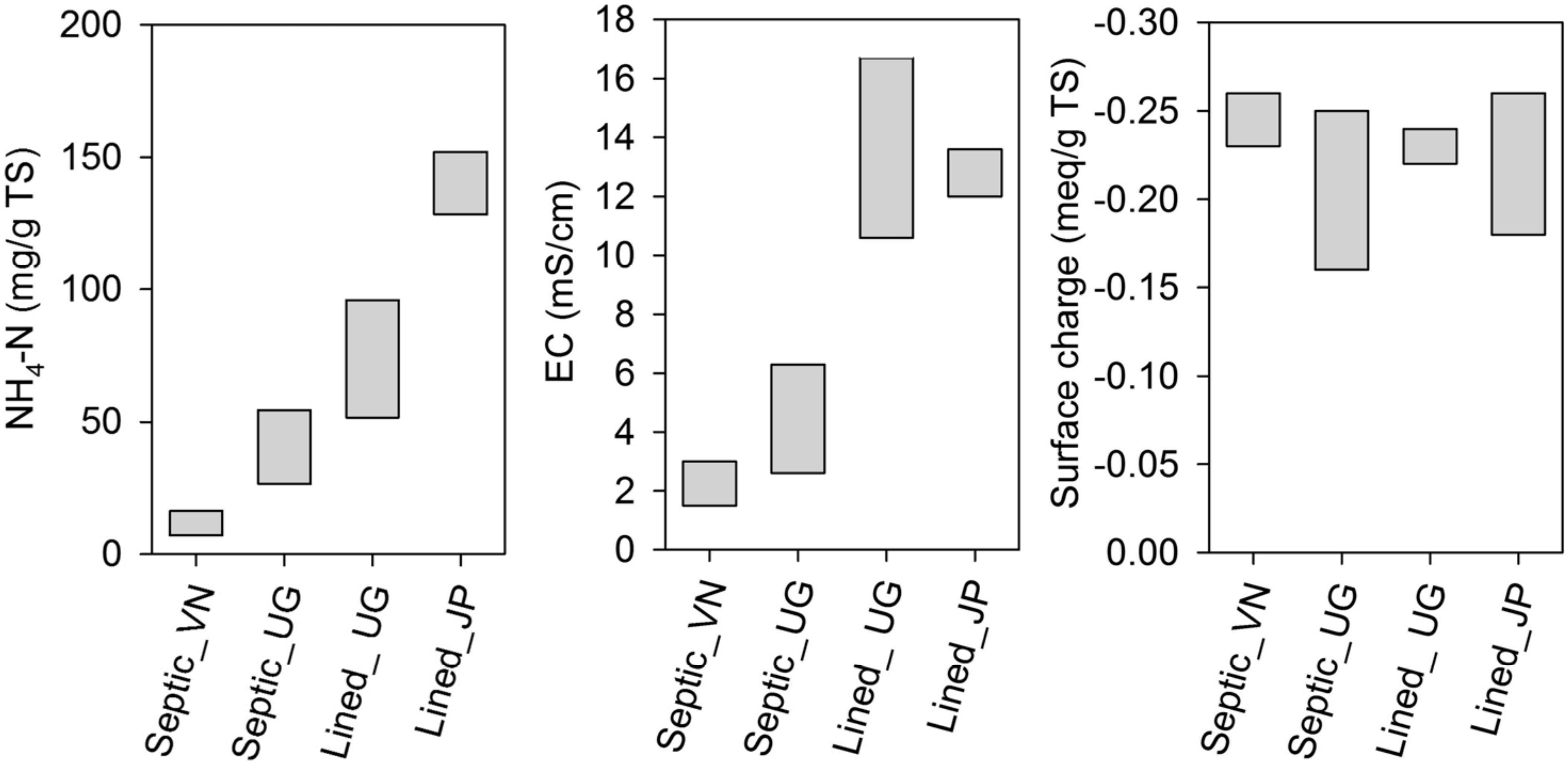
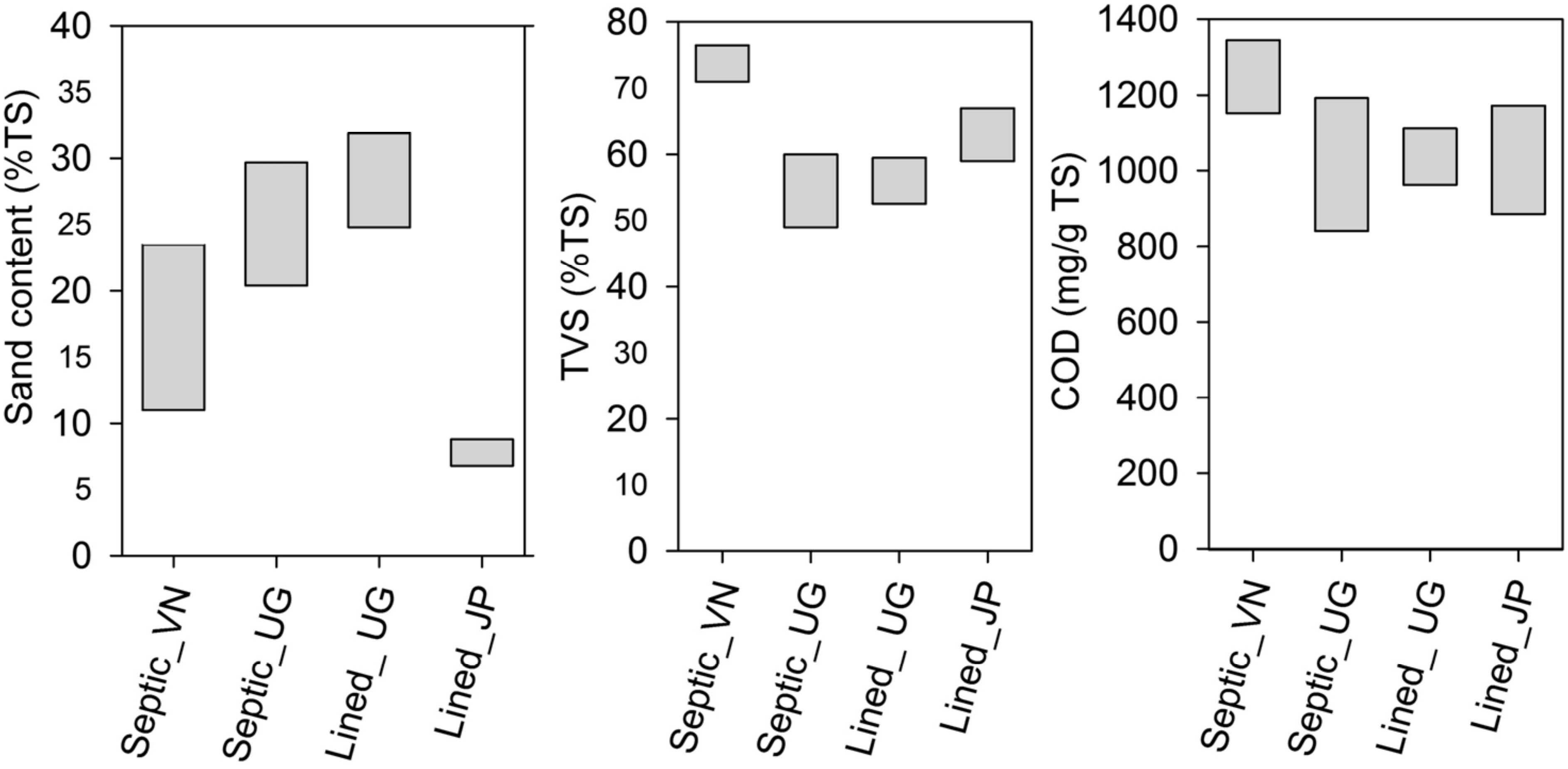

200
150
100
50
0
NH4-N (mg/g TS)
Septic_VN
Septic_UG
Lined_ UG
Lined_JP
18
16
14
12
10
8
6
4
2
0
EC (mS/cm)
Septic_VN
Septic_UG
Lined_ UG
Lined_JP
-0.30
-0.25
-0.20
-0.15
-0.10
-0.05
0.00
Surface charge (meq/g TS)
Septic_VN
Septic_UG
Lined_ UG
Lined_JP

Figure 6


Sand content (%TS)
40
35
30
25
20
15
10
5
0
Septic_VN
Septic_UG
Lined_ UG
Lined_JP
TVS (%TS)
80
70
60
50
40
30
20
10
0
Septic_VN
Septic_UG
Lined_ UG
Lined_JP
COD (mg/g TS)
1400
1200
1000
800
600
400
200
0
Septic_VN
Septic_UG
Lined_ UG
Lined_JP