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Composition and Characteristics of Faecal Sludge from Various Onsite Pit Technologies and User Categories in Dar es Salaam, Tanzania

***RUHINDA, EF; MGANA, SM; MBULIGWE, SE; MAHENGE, A**

Department of Civil and Environmental Engineering, School of Civil Engineering and Environmental Studies, Ardhi University, P.O.BOX 35176, Tanzania

Corresponding Author Email: frontruh@yahoo.co.uk
**ORCID: 0009-0002-4045-8983*
**Tel: +255718678808*

Co-authors Email: smmgana@gmail.com; steve.em@gmail.com; anesimahenge@gmail.com

ABSTRACT: This study investigates the composition and characteristics of faecal sludge (FS) from different pit technologies (cesspits, pit latrines, septic tanks) and user categories (commercial, industrial, institutional, and residential) in Dar es Salaam, Tanzania, with a view for informed treatment and resource recovery strategies. FS samples exhibited varying concentrations of pH, electrical conductivity (EC), total solids (TS), and volatile solids (VS), COD and nutrients. pH values ranged from 2.83 to 8.41, with no statistically significant differences based on pit technology type or user category. However, the extremely low pH observed in samples from industrial pits suggests possible disposal of industrial chemicals in these sanitation systems. EC levels were notably higher in pit latrines and residential areas, likely due to waste disposal practices in homes, with concentrations 3-5 times above regulatory limits, raising concerns about their impact on treatment effectiveness and re-use potential. TS and VS concentrations also varied, with cesspits showing the highest TS levels and pit latrines exhibiting higher VS, indicating fresher sludge and potential for biogas production, as reflected by a VS/TS ratio ranging from 53.32% to 70.42%. Nutrient analysis revealed elevated levels of phosphate, nitrate and ammonia, particularly in pit latrines and residential pits, highlighting both resource recovery opportunities and challenges for treatment processes. While FS generally fell into the dilute category (TS < 3%), the high concentrations of other parameters underscore the need for a larger treatment footprint per unit volume of FS. The VS/TS ratio suggests that FS is not fully stabilized, indicating potential for further degradation and resource recovery. Additionally, the characteristics of FS suggest potential opportunities for deriving fertilizer and solid fuel. However, ensuring the hygiene of the sludge is crucial for its safe use, particularly in agricultural applications, and further studies are needed to confirm its sanitation.

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Faecal sludge is a significant sanitation challenge on a global scale, especially in areas with low incomes where on-site sanitation systems are prevalent. The management of faecal sludge relies heavily on understanding its features, which encompass both physical and chemical characteristics. The emptying, treatment, and resource recovery and reuse of faecal sludge are contingent upon its inherent characteristics. Faecal sludge is formed by a mixture of excreta, water, and other waste materials that are intentionally or unintentionally disposed of in latrine pits (Ahmed *et al*., 2019; Velkushanova *et al*., 2021). The characteristics of faecal sludge in containment systems are affected by various factors, including demographic, environmental,

**Corresponding Author Email: frontruh@yahoo.co.uk*
**ORCID: 0009-0002-4045-8983*
**Tel: +255718678808*

and technical considerations. Environmental considerations encompass variables such as oxygen levels, moisture content, climate conditions, inflow and infiltration rates, and soil properties. In addition, there are additional variables to consider, such as technical issues like the design of the containment system like degree of lining, and presence of overflow and the type and quality of construction (Bassan *et al*., 2013; Strande *et al*., 2018). The moisture content of the systems, sludge age, organic matter content, hydraulic retention duration and non-biodegradable fraction are all elements that affect the nature of moisture content. These parameters were discussed by (Englund *et al*., 2020; Strande *et al*., 2018). Demographic factors, such as cultural differences, dwelling styles, and land use patterns, user population size and income level can have an indirect impact on the characteristics of faecal sludge. For instance, septic tanks are more prevalent in higher socioeconomic areas, while pit latrines are more prevalent in economically disadvantaged areas. However, the extent of their influence on its properties is still a subject of controversy (Semiyaga *et al*., 2015; Strande *et al*., 2018). According to (Wagner *et al*., 1958), urban pit latrines exhibit higher rates of usage and more frequent emptying in comparison to rural ones. This can be attributed to factors such as population density, increased household usage and frequency. Factors like anaerobic conditions, temperature, total moisture and inhibitory compounds also play a role in the biological degradation of faecal sludge (Bakare *et al*., 2012; Bourgault, 2019; Byrne *et al*., 2017). Various elements can modify the content of faecal sludge. In poor and middle-income countries, containment systems are frequently employed to dispose of additional household waste in latrines (Ahmed *et al*., 2018). The approach has an impact on the storage capacity of containment pits, inhibits sludge biodegradation, and affects the process of emptying the pits, consequently compromising environmental sustainability (Zuma *et al*., 2015). Other chemicals can infiltrate containment pit through deliberate application of cleaning agents or adding pit additives to sink the sludge, however their efficacy has not been experimentally validated (Grolle *et al*., 2018). In such, different pit technologies like septic tanks and pit latrines are influenced differently by these factors (Bakare *et al*., 2012; Byrne *et al*., 2017). The moisture content in sludge is influenced by infiltration, a net inflow and outflow of moisture influenced by factors like soil type, lining type, topography, and groundwater level. High water table in containment systems can induce buoyancy in faecal sludge fractions, increasing the water content of the sludge (Doglas *et al*., 2021). Water entering the latrine pits is determined by flush mechanisms, greywater diversion and water resource availability.

Diverse sources of faecal sludge, such as public toilets, restaurants, hotels, schools, hospitals, offices, stores, shopping centers, places of worship, and industrial sites, display distinct usage patterns that can impact the characteristics of the sludge. It is essential to distinguish between different forms of sludge since they have distinct features and this is critical for planning how to handle them. It is crucial to understand the qualities such as redox conditions, stabilization level, biomass, nutrients, particle size, salts, ions, and extracellular polymeric substances in order to effectively prepare for its treatment. Furthermore, there is a significant potential for resources recovery from faecal sludge. Existing studies have primarily focused on recovering energy (Andersson *et al*., 2016; Andriessen *et al*., 2019; Krueger *et al*., 2020), nutrients, and organic matter (Hashemi and Han, 2019; Nikiema and Cofie, 2014; Timmer and Visker, 1998). Additionally, faecal sludge can be used for rearing black soldier fly larvae and plants (Lalander *et al*., 2013; Tokwaro *et al*., 2023). The specific attributes of interest differ depending on the intended application. For instance, when using a substance as a fuel, it is important to evaluate its water content and calorific value (Diener *et al*., 2014; Muspratt *et al*., 2014). When applying soil amendments, it is important to take into account the existence of pathogens and heavy metals.

Therefore, the objective of this paper is to investigate the Composition and Characteristics of Faecal Sludge (FS) collected from cesspits, pit latrines, septic tanks, commercial, industrial, institutional, and residential sources in Dar es Salaam City, Tanzania with a view for informed treatment and resource recovery.

MATERIAL AND METHODS

The case study area and faecal sludge management: This study was conducted in Dar es Salaam, Tanzania, the country's largest and most populous commercial city. According to the 2022 census, Dar es Salaam has a population of approximately 5.4 million people. The city experiences an average annual rainfall of 1,150 mm and an average temperature of 27.3°C. A significant proportion of households in Dar es Salaam rely on onsite sanitation facilities such as pit latrines, septic tanks, and cesspits. However, more than half of the faecal sludge (FS) generated is not properly managed, posing a risk of environmental contamination. Approximately 2,000 m^3 of FS per day is collected by vacuum trucks and co-treated at two wastewater treatment plants in the city.

Sample acquisition: The study involved the collection of samples from vacuum trucks transporting fecal sludge (FS) to treatment facilities. A total of 93 trucks were selected for analysis. For two months, 1-liter samples of FS were collected during each unloading process. The sludge was sourced from various locations, including residential, commercial, institutional, and industrial areas. Commercial sources specifically included market and public latrines. The data gathered emphasized the classification of pits, septic tanks, and cesspits, as well as the origin of the sludge—whether it was from a commercial, industrial, institutional, or residential source. In this context, a cesspit refers to a single chamber connected to latrines via plumbing, functioning as both a septic tank and a soak-away pit. This design is common in the city, where a single pit serves the dual purpose, unlike the typical setup of separate perforated pits for wastewater to soak into the ground.

Sample preparation for analysis: The analysis involved preparatory processes like homogenization, dilution, and filtration. Non-fecal entities were removed before homogenization, and the liquid and slurry sludge samples were mixed to ensure homogeneity. Dilution was conducted to bring the sample concentration within the measurement range, as the feacal sludge contains high concentrations of the measured parameters. Dilution was done in three replicates at a 1:10 sludge: water ratio, with the sample vigorously agitated before each dilution.

Physicochemical parameters analyzed: The physicochemical parameters analyzed in the FS samples were pH, Salinity, Electrical Conductivity (EC), total solids (TS), Volatile Solids (VS), Nitrate (NO_3^-), Ammonia (NH_4^-), Phosphate (PO_4^-), COD (total and dissolved).

Analysis of pH, Salinity and Electrical Conductivity: The pH, electric conductivity, and salinity measurements were conducted using a calibrated pH meter, HANNA Combo model number HI 98129 (Hach Co. and Hach, 1992).

Analysis of Total Solids (TS) and Volatile solids (VS): The Gravimetric method was used to measure Total Solids (TS) in faecal sludge samples. The sample was mixed, weighed, and dried in an oven at 103-105°C for 24 hours. The weight gain corresponded to the cumulative solids present. The total solids content was determined by measuring the weight of the crucible and residues. The volatile solids were also determined by combusting dried samples in a muffle furnace at 550°C for 3 hours. The mass of volatile solids was represented by the volatilized mass during the combustion process.

Analysis of total and particulate Chemical Oxygen Demand (COD_p and COD_t): The chemical oxygen demand of each FS sample was analyzed using the Reactor Digestion technique. The total Chemical Oxygen Demand (COD) was distinguished from Particulate COD by filtering the sample. A solution containing potassium dichromate and concentrated sulfuric acid was produced, and 2.5 mL of the FS sample was introduced into a test tube containing potent oxidizing agents. The mixture was mixed in a fume chamber, heated in an oven at 150ºC for 2 hours, and then cooled to room temperature. COD was measured in mg/L using a Spectrophotometer at a wavelength of 600 nm.

Analysis of nutrient content of the feacal sludge: The study analyzed nutrients in FS samples, including Organic Phosphorous (org-P), Ortho-Phosphate (ortho-PO_4^{-3}), Nitrate-nitrogen (NO_3^-), and Ammonia-Nitrogen (NH_4-N). The nitrate concentration was measured using the Cadmium reduction technique and examined using a spectrophotometer (HACH DR/2010). The ammonia concentration was assessed using the Nesslerization Method and analyzed using a spectrophotometer (HACH DR/2010). The phosphate concentration was measured using the Ascorbic acid technique, Phos Ver3 reagent, and analyzed using a spectrophotometer (HACH DR/2010). The analytical method follows a standard method for water and wastewater examination.

Analysis of sludge Volume Index (SVI): It is used to describe the settling characteristics of sludge; it's also a process control parameter to determine the recycle rate of sludge. It is simply defined as the volume (in ml) occupied by 1 gram of sludge after settling for around 30-60 minutes. The concentration of sludge sample with a total suspended solids (TSS) was measured by filling a 1L graduated cylinder with a sludge sample and allow the sample to settle. After 30min of settling, read the volume occupied by the sludge from the graduated cylinder. The SVI with the measured concentration of the sample was calculated using equation 1.

$$SVI = \frac{\mathrm{SV30}}{XtSS} \quad (1)$$

Data analysis: The study analyzed FS sludge sources, including pit types like pit latrines, septic tanks, and cesspits, and source types like domestic, institutional, commercial, and industrial. Pearson correlation analysis and ANOVA were used to observe relationships among parameters. Statistical significance was set at P≤0.05. Data was converted from an Excel sheet to CSV files using Microsoft Excel 2016 program, and correlations were performed using Python programming.

RESULTS AND DISCUSSION

pH, Electro conductivity (EC) and Salinity: The average pH concentrations were 7.44±1.00, 6.99±1.47, and 7.42±1.00 for pit latrines, septic tanks, and cesspits, respectively. The pH concentrations of the pits in commercial, industrial, institutional, and residential sites were measured to be 7.21±0.94, 6.84±1.44, 6.94±1.40, and 7.51±0.94, respectively. The pH concentrations exhibited considerable variation, ranging from a low of 2.83 to a maximum of 8.41. The statistical analysis indicated that the pH values in faecal sludge were not significantly affected by the type of pit or the source type. The electrical conductivity (EC) exhibited significant variation among different pits and sources. The average EC concentrations were 5859.10±2999.39, 3317.36±1744.19, and 4388.7±1764.83 for samples obtained from pit latrines, septic tanks, and cesspits, respectively. The conductivity measurements for samples collected from pits in commercial, industrial, institutional, and residential places are as follows: 4139.98±1855.03, 3415.38±1947.91, 3844.21±1759.69, and 4803.65±2594.62 µS/cm. The salinity concentrations for samples from pit latrines, septic tanks, and cesspits were 3.22±1.77, 1.75±0.98, and 2.34±0.99 ppt, respectively. The samples collected from pits in commercial, industrial, institutional, and residential places had concentrations of 2.21±1.06, 1.80±1.09, 2.05±0.99, and 2.60±1.52 ppt respectively. The pH levels of faecal sludge differed among different types of pits, such as pit latrines, septic tanks, and cesspits, as well as among different sources, including residential, commercial, institutional, and industrial sources. However, the variation in all physical parameters was not statistically significant ($P \geq 0.05$), which is consistent with previous studies (Nzouebet *et al*., 2019). The variations in pH levels found in a few cases, which deviate significantly from the typical pH ranges for faecal sludge, can be attributed to the variable use of sanitation facilities rather than factors related to design and the environmental conditions as observed in (Cofie *et al*., 2006; Ingallinella *et al*., 2002; Nzouebet *et al*., 2019). This study observes several samples with pH levels drastically below the normal range of FS, as low as (2.83), which were discovered to come from pits located in industrial locations. This can be linked to the inclination to release chemical waste into FS containment pits. The introduction of sludge with extreme pH levels could have adverse effects on the biological processes of bacteria in treatment plants. The study observed a worrisome increase in electroconductivity levels, which serves as a surrogate indicator of total dissolved salts. The concentration of EC was found to be higher in samples collected from pit latrines compared to other types of pits. Additionally, samples taken from pits located in residential areas exhibited higher concentrations than those from other sources. This can be attributed to the practice of disposing other types of waste with high dissolved solids in the latrines in the use of pit additives, such as salts which is more prevalent pit latrines and homes than other places. Certain homes include chemical additions, such as salt, into their toilet systems, resulting in increased electrical conductivity and salinity (Grolle *et al*., 2018). This observation indicates the possibility of FS electrical conductivity being affected by these factors. The current concentrations are approximately 3-5 times higher than the regulatory limit. The EC concentration is a matter of concern in treatment processes, since the technologies used may encounter challenges in reducing the EC concentration to levels within the regulation limits set by the EPA and Tanzanian faecal sludge disposal standard (FTZS 3173), which is 1500 µS/cm. Higher EC and salinity in a product sludge or effluent will have a negative impact on the soil structure, water holding capacity, and water availability for plants when using FS effluent for irrigation.

Total Solids (TS), Volatile Solids (VS) and VS/TS ratio: The study reveals variations in the average concentrations of total solids (TS) among different types of pits. The mean total solids (TS) concentrations for pit latrines, septic tanks, and cesspits were 19.89±17.06, 8.05±8.16 and 22.92±53.84 g/L respectively. Samples from cesspits exhibited higher levels of TS compared to other pits. The average concentration of volatile solids (VS) varied depending on the type of pit type, with samples collected from pit latrines exhibiting higher quantities of VS. The average VS concentrations were 12.36±10.42, 5.77±6.06 and 11.184±16 mg/L for pit latrine, septic tank and soak way pits respectively. Statistical analysis showed no significant influence of the type of pit on the amounts of TS and VS in faecal sludge. The mean values of VS/TS ratios were 64.57±18.38, 53.32±26.54 and 59.74±15.48 for samples obtained from pit latrines, septic tanks and cesspits respectively. Samples from pit latrines exhibited a greater volatile solid to total solids ratio.

The mean values of total solids (TS) were 20.81±69.83 g/L for commercial sources, 8.80±15.93 g/L for industrial sources, 14.63±8.76 g/L for institutional sources and 30.37±93.23 g/L for residential sources. The mean concentrations of volatile substances (VS) for commercial, industrial, institutional, and residential sources were 11.71±20.38, 5.32±10.58, 11.85±6.04 and 16.76±44.78 g/L respectively.

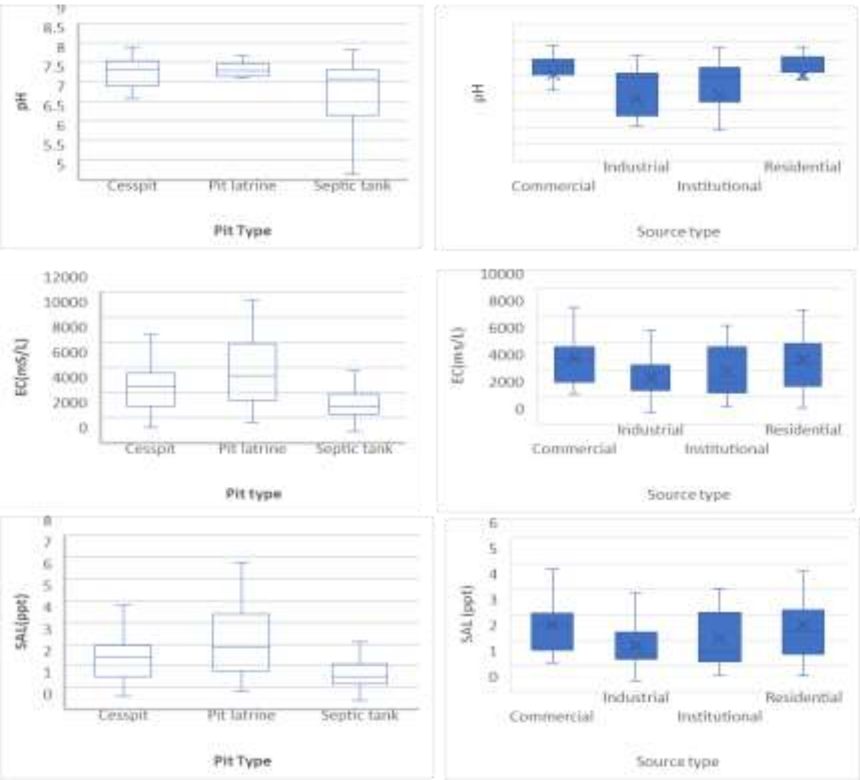

Fig. 1: The variations of pH, EC and Salinity of faecal sludge based on the type of latrines and source of feacal sludge.

Also, the statistical analysis showed no significant influence of the type of pit on the amounts of TS and VS in faecal sludge (P≥0.05). The TS concentrations observed range can be classified as low concentration according to the FS categories (>3%) (Velkushanova *et al.*, 2021) however high as compared to wastewater. The samples of faecal sludge (FS) collected from cesspits and pit latrines had relatively elevated average total solids (TS) levels. This can be partly attributed to the technical aspects of their construction, which facilitate the seepage of liquids while retaining solids. Pit latrines are partially dry systems that produce less moisture compared to wet systems such as septic tanks and cesspits. This is because pit latrines are designed to allow for infiltration of water into ground (Nzouebet *et al.*, 2019). In a similar vein, (Bakare *et al.*, 2012) also reported elevated levels of parameters in pit latrines. The higher concentrations of volatile solids (VS) identified in the pit latrine samples align with the results published in earlier investigations (Bourgault, 2019; Septien *et al., 2018;* Zuma *et al., 2015)*. The higher concentration of volatile solids (VS) in pit latrines compared to other pits can be attributed to increased usage, which in turn increases the likelihood of more frequent emptying with relatively fresh sludge. In this category, the TS is in the form of a runny liquid which can be easily worked with pumps during emptying and treatment. Increased water inputs required to create such a diluted sludge can be attributed to groundwater infiltrations caused by a high-water table. It is obvious that many pits in Dar es Salaam are located in groundwater, as indicated by the known hydrogeology of the area. Dilute sludge treatment often requires larger treatment areas for treatment units that use surface loading techniques.

The pit latrines samples have a greater average ratio of volatile solid to total solid (VS/TS) compared to other types of pits. This indicates that pit latrines are more likely to include fresh faecal sludge (FS) than the other varieties. Septic tanks have a lower ratio of volatile solids (VS) to total solids (TS) because they often take longer before being emptied (Bourgault, 2019; Still *et al.*, 2012) therefore more organics degraded. In addition, FS samples obtained from institutional and residential settings have a higher ratio of volatile solids (VS) to total solids (TS), which may be attributed to more frequent emptying as a result of excessive usage.

The high ratio of volatile solids (VS) to total solids (TS) observed in pit latrines and cesspits, exceeding 60%, shows great potential for energy generation, specifically in the form of biogas. This indicates that they can be considered as a suitable source of biogas feedstock, in terms of VS as recommended by (Sheffler, 2018; Tayler, 2018) where the VS content should exceed 50%. But less suitable as TS content was less than the recommended of 6%.

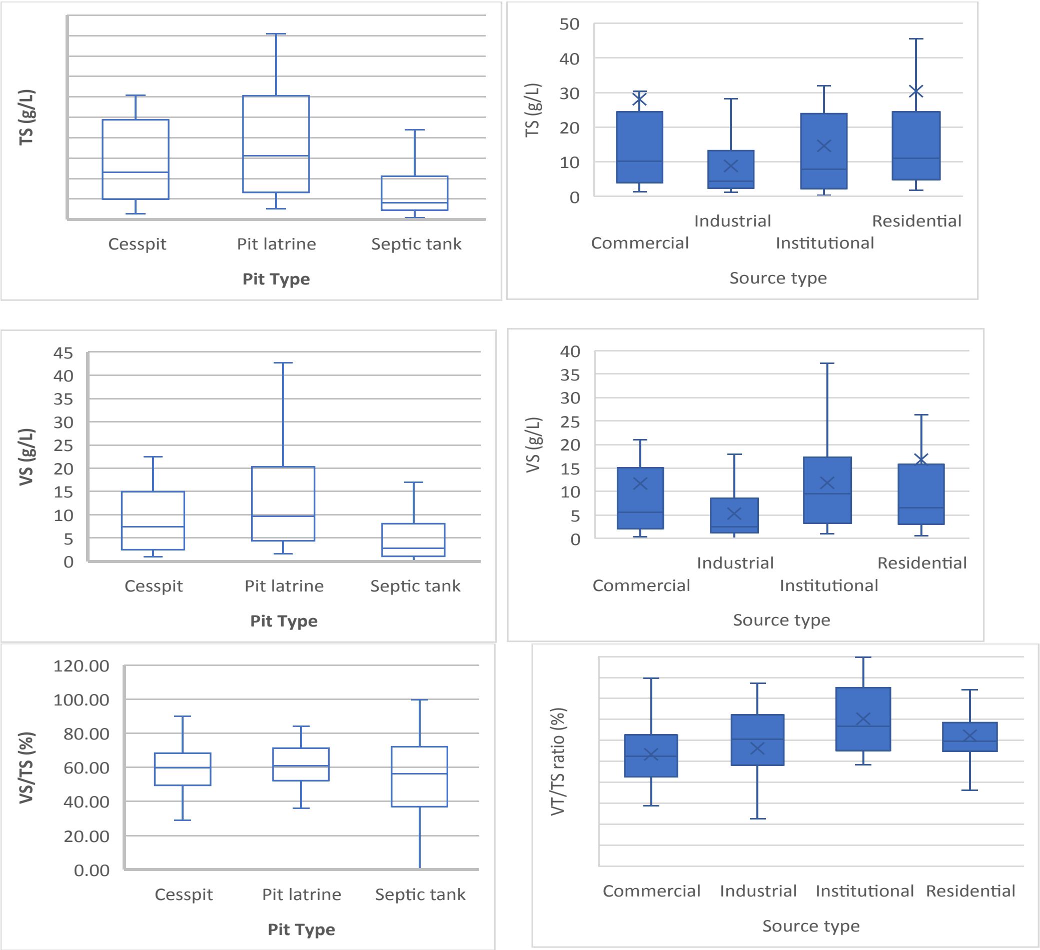

Fig. 2: The variations of TS, VS and VS/TS ratio of faecal sludge based on the type of latrines and source of faecal sludge.

Chemical Oxygen Demand (COD): The samples analyzed for both total chemical oxygen demand (COD_t) and particulate Chemical Oxygen Demand (COD_p). The mean values of total COD_t concentrations varied among different pit classifications, with the average values for pit latrines, septic tanks and cesspits being 15500±20537.81, 8119.38±12296.34 and 6178.69±8214.58 mg/L respectively. Also, the mean concentrations of particulate COD_p in FS were 14342.38±18571.25, 7629.28±12190.36 and 5501.54±7800.63 mg/L for pit latrines, septic tanks and cesspits, respectively. The samples obtained from pit latrines exhibited much greater concentrations of COD_t and COD_p, about twice as much when compared to samples from other types of pits. In terms of source user types, the average COD_t was 8251.28±7059.95, 5196.88±17382.47, 11787.50±5670.15, 10572.53±16628.36 mg/L for samples from commercial, industrial, institutional and residential pit source respectively. Also, particulate COD was 7615.62±6421.82, 4902.63±17171.29, 11310.64±5626.65 and 9779.83 ± 15357.24 mg/L for samples from commercial, industrial, institutional and residential pit source respectively.

The average COD concentration ranges were in agreement with the findings of earlier studies by (Ahmed *et al.*, 2019; Bassan *et al.*, 2013; Nzouebet *et al.*, 2019). There is a slight difference was observed between the fraction of particulate COD_p to total COD_t across various pits types, with the average values of the percentage of COD_p/COD_t ratio being 89.70%, 82.67% and 81.76% for pit latrines, septic tanks and cesspits respectively. And, COD_p/COD_t of 84.78%, 88.95%, 91.61% and 86.63% for commercial, industrial, institutional and residential sources respectively. Also, samples from institutional pits had high COD_p/COD_t ratio than other pits. The majority of FS samples exhibited high values of particulate COD_p in proportion of the total Chemical Oxygen Demand (COD_p/COD_t) suggest that a large component of the COD in faecal sludge is in a colloidal form. In comparison, the samples collected from pit latrines having higher values for COD_p to COD_t can be attributed to the configuration of pit latrines, which facilitates the infiltration of water from the pits into the surrounding soil, as well as the tendency of users to dispose of rubbish in pits as opposed to septic tanks. As a result, there is a greater chance for higher amount of total solids present in pit latrines compared to septic tanks (Bourgault, 2019; Nzouebet *et al*., 2019). There is a scarcity of studies that have compared the chemical oxygen demand of particulate matter (COD_p) to the total chemical oxygen demand (COD_t) for faecal sludge. However, (Myszograj *et al*., 2017) found that the particle COD accounted for 60-80% of the total COD in untreated sewage sludge which is slightly lower than values of FS. This discovery shares similarities with the current situation, but it indicates that the sludge differs depending on its production. High colloidal and particulate compounds are considered to be more complex and biodegrade slowly. They are slowly biodegradable which require extracellular breakdown prior uptake and utilization by microorganisms and in treatment they can be removed by physical-chemical means such as coagulation, flocculation and settling (Strande and Brdjanovic, 2014). The efficacy of methods for treatment is significantly influenced by the proportion of particulate matter. In this scenario, the characteristics of FS may require the separation of solids from liquids during treatment in order to achieve a notable improvement in treatment effectiveness.

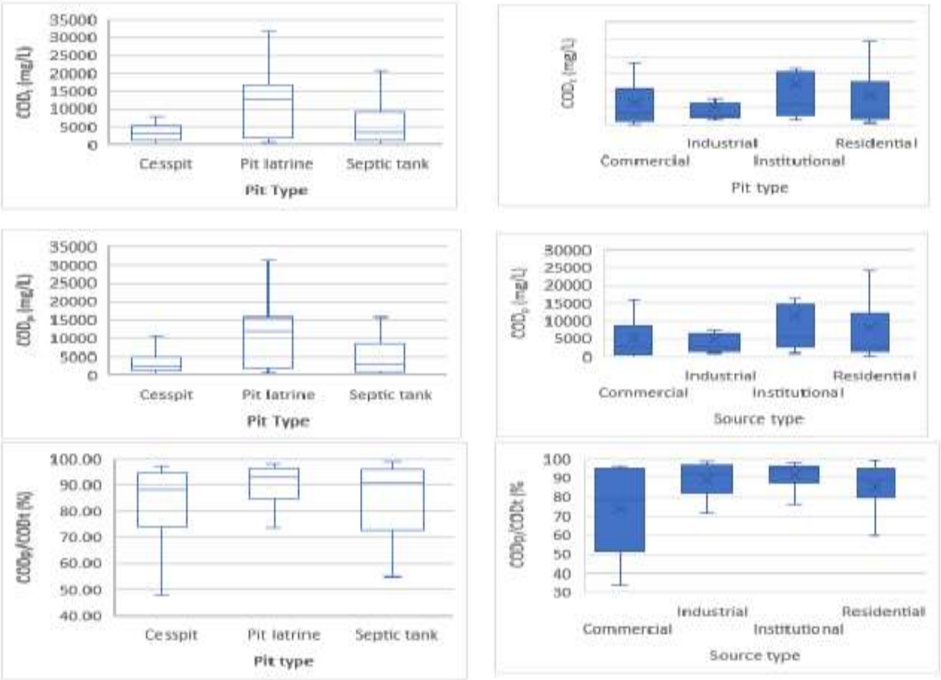

Fig 3. The variations of forms CODt, COD_p and the COD_p/COD_t ratio of faecal sludge samples based on the type of latrines pits and user sources of feacal sludge

Nutrient content of the feacal sludge: The results indicate that the average concentration of organic phosphate (org-P) is higher in pit latrines than in other types of pits, including cesspits and septic tanks. Specifically, ortho-phosphate (PO_4^{3-}) concentrations are slightly elevated in samples from pit latrines, with average concentrations of 3421.36±7280.62 mg/L, compared to 896.01±684.43 mg/L in septic tanks and 1141.82±560.20 mg/L in cesspits. When considering the type of source category, PO_4^{3-} concentrations were 1463.84±612.27 mg/L in commercial pits, 724.23±766.13 mg/L in industrial pits, 1117.36±417.00 mg/L in institutional pits and 2249.02±5368.30 mg/L in residential pits. For organic phosphorus, the average concentrations in pit latrines, septic tanks, and cesspits were 1080.29±1299.95 mg/L, 326.67±206.93 mg/L and 637.07±602.40 mg/L respectively. The concentrations based on source pit type were 512.42±464.68 mg/L for commercial pits, 200±189.88 mg/L for industrial pits, 426±150.49 mg/L for institutional pits, and 811.53±991.74 mg/L for residential pits. Both PO_4^{3-} and organic phosphorus concentrations were highest in pit latrines and residential pits. The organic phosphorus and phosphate concentrations are similar to values observed by (Ahmed *et al*., 2019; Strande *et al*., 2014). Higher concentration for both organic and ortho phosphate in pit latrines and residential pits can be attributed to their uses. Pit latrines are also receiving laundry water which contains dissolved phosphate from detergent uses in home. Regarding ammonia (NH_3) concentrations, the averages were 644.71±1101.72

mg/L in pit latrines, 169.30±110.27 mg/L in septic tanks, and 235.55±125.26 mg/L in cesspits. Ammonia concentrations in samples from commercial, institutional, industrial, and residential pits were 282.73±148.91 mg/L, 159.26±114.75 mg/L, 210.05±67.75 mg/L, and 429.60±823.13 mg/L respectively. Pit latrines and residential pits exhibited the highest ammonia concentrations among the types and sources examined. The chemical parameters of organic phosphorus, phosphate, nitrate, and ammonium-nitrogen showed variability among pits with similar and dissimilar characteristics. Some differences in concentration values of NO_3- and NH_4-N were observed. The type of pit can affect the balance between nitrate and ammonia, depending on the conditions for oxidation and reduction processes in faecal sludge deamination which are different in different pit types (Harder *et al*., 2019). Nitrogenous compounds' fluctuation may be linked to domestic latrine use practices and ecological factors. The variation in nitrogenous compounds varies across pits, with some receiving only excreta and water, while others receive multiple waste streams, such as food waste from the kitchen, and are used for solid waste disposal, potentially adding more nitrogenous compounds beyond what is contained in human excretions (Bakare *et al*., 2012; Nzouebet *et al*., 2019). Furthermore, (Fidjeland *et al*., 2013) found that variations in pit categories may be due to chemical reactions generating ammonia and nitrate, which are influenced by environmental conditions and retention duration. When it applies to treatment, controlling ammonia-nitrogen is the most challenging aspect in faecal sludge treatment (Ahmed *et al*., 2019). An effective design is required to reduce the observed levels, which are hundreds of times higher than the permitted regulatory limit of Tanzania (5 mg/L), to within that limit. Additionally, there is a notable concentration of dissolved nutrients, particularly phosphate (PO_4^{3-}). In the realm of natural treatment technologies, these systems are generally ineffective at retaining phosphate, resulting in effluents that are high in phosphate content. This characteristic suggests the potential use of faecal sludge (FS) treatment effluent for crop irrigation. Furthermore, implementing effective nutrient retention mechanisms within the treatment process can produce biosolids that are rich in nutrients, thereby facilitating resource recovery. Given the limited efficiency of existing natural treatment methods in removing nutrients from faecal sludge, it is recommended to explore and enhance physical-chemical processes such as coagulation, flocculation, and settling for better nutrient retention. These technologies offer a more effective approach to resource recovery by converting nutrients in faecal sludge into organic fertilizers, given the elevated nutrient levels present in the sludge.

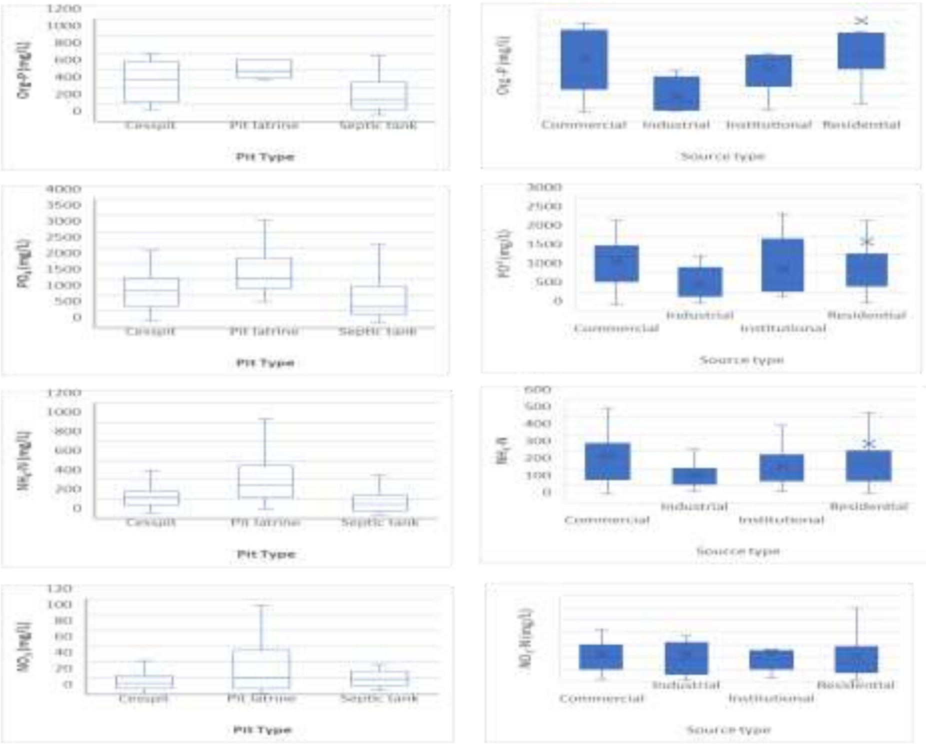

Fig 4. The variation of nutrient content of the faecal sludge based on the type of latrines pit type and sources of feacal sludge

Inter correlation of physical-chemical parameters of faecal sludge: The results in figure 5 demonstrated a strong correlation between electrical conductivity and salinity, with a perfect correlation coefficient of 1.0, consistent across all sample sources. Additionally, a strong correlation was observed between volatile solids (VS) and total solids (TS). Phosphate ions also showed a robust correlation with total solids and volatile solids, both with a correlation coefficient of 0.99. Furthermore, a strong correlation was identified between volatile solids and ammonium nitrogen (NH_4-N), with a coefficient of determination (r^2) of 0.96. Total Chemical Oxygen Demand (COD) was strongly correlated with total solids, evidenced by a correlation coefficient of 0.86, and with phosphate (PO_4^{3-}), which had a correlation coefficient of 0.84. These correlations align closely with findings reported by (Junglen *et al*., 2020). The study highlights a strong correlation between salinity and electrical conductivity, suggesting that dissolved salts are a significant contributing factor. Additionally, the strong positive relationship between total solids and volatile solids suggests that a large proportion of the solids are organic, offering potential for resource recovery, such as biogas production. The strong link between total solids and chemical oxygen demand further indicates the potential for energy generation when biosolids are dried and utilized as solid fuel because of richness in organic content. Moreover, the significant associations between total solids, volatile solids, and key nutrients such as phosphate, ammonium nitrogen, and chemical oxygen demand, particularly in samples from pit latrines, suggest that solid retention during treatment also facilitates the retention of nutritional content in biosolids.

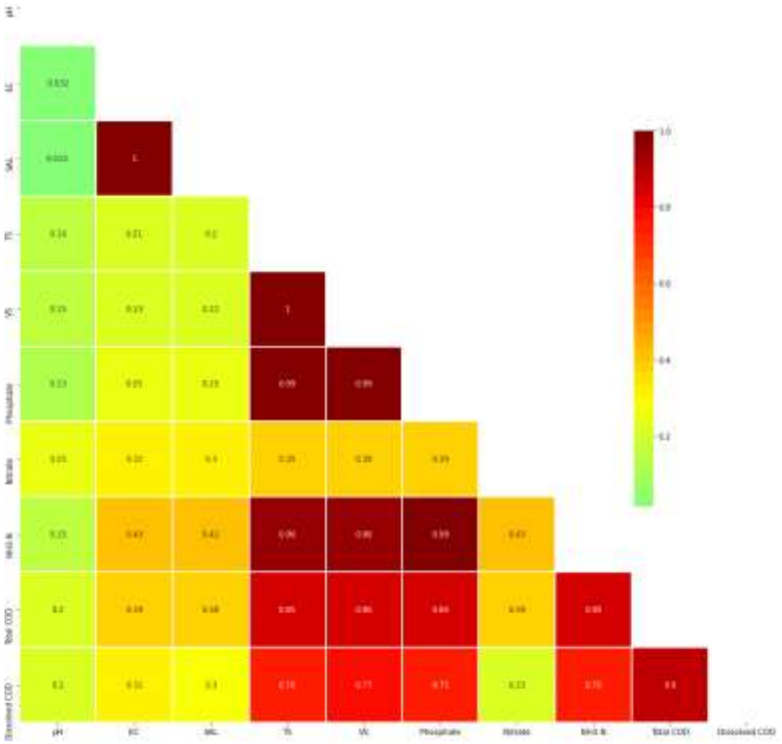

Fig 5. Cross correlation matrix (Pearson test, 95 % confidence level) showing relationship of physical and chemical parameters of faecal sludge samples

Sludge volume index (SVI): The study revealed that the settling characteristics of faecal sludge varied depending on the type of pit, as detailed in Tables 1 and 2. The sludge volume indices (SVIs) for samples from pit latrines, septic tanks, and cesspits were 11.15, 31.11, and 28.68 mL/gTSS, respectively. Septic tank samples exhibited better settling behavior, while samples from other pit types demonstrated inadequate settling. The SVI values also differed based on the source type, with institutional samples displaying satisfactory settling behavior, while those from commercial, industrial, and residential sources showed poor settling. These findings are consistent with the recommended SVI range of $30 < SVI < 80$ mL/gTSS (Gold *et al*., 2018). Sludge settleability tests indicated lower SVI values in samples from pit latrines and cesspits compared to septic tanks, suggesting that the sludge's ability to settle and dewater is influenced by factors such as solid concentration and stabilization level (Velkushanova *et al*., 2021; Ward *et al*., 2019).

The sludge in septic tanks is more stabilized due to the longer retention time of solids before emptying in septic tanks, in contrast to other pit types. The reduced settleability observed in commercial, industrial, and residential pits is likely due to the frequent emptying of these pits. Partial decomposition of pit latrine sludge contributes to poor sedimentation, as elevated levels of extracellular polymeric substances (EPS) in partially digested sludge hinder settleability. EPS's strong electrical charge and water-binding capacity further complicate sludge dewatering (Ward *et al*., 2019). Determining the maximum limits of settlement is crucial for developing effective treatment strategies (Junglen *et al*., 2020).It was also found that sludge samples from institutional sources had SVIs within the acceptable range of $30 < SVI < 80$ mL/gTSS, as recommended by (Gold *et al*., 2018). The frequent need for pit emptying, especially in commercial, industrial, and residential settings, is primarily due to high usage rates and groundwater intrusion. Previous studies by (Cairncross *et al*., 2014; Chaggu *et al*., 2002) have shown that the sludge in Dar es Salaam requires stabilization treatment before settling due to its partially digested state and poor settleability, necessitating larger footprint of settling facilities per unit volume of FS treated.

Table 1. Sludge volume index of faecal sludge samples based on different latrine pit types

Pit type	**Average Settled volume (mL)**	**TSS (g/L)**	**SVI_{30} (mL/gTSS)**
Pit latrine	65	5.83	11.15
Septic tank	70	2.25	31.11
Cesspit	100	3.49	28.68

Table 2. Sludge volume index of faecal sludge samples based on different source types

Pit type	**Average Settled volume (mL)**	**TSS (g/L)**	**SVI_{30} (mL/gTSS)**
Commercial	8	2.398	3.34
Institutional	78	5.01	32.53
Industrial	50.34	7.12	7.02
Residential	110	21.76	5.06

Conclusion: Faecal sludge (FS) characteristics vary among different pit types and usage contexts, including commercial, industrial, institutional, and residential sources. These variations are not statistically significant, but can be attributed to the design and usage patterns of onsite sanitation facilities. The design may accommodate uses beyond their original intent, and user behavior can lead to diverse usage patterns. The study hypothesized that the different uses of these facilities could result in significant variations in FS characteristics, potentially posing challenges to treatment plants. However, the differences were not statistically significant. Some samples from industrial premises showed extremely low pH levels, which is atypical for FS and could pose a risk to treatment processes. The assessed characteristics of FS were more concentrated than typical wastewater, suggesting the need for separate treatment rather than co-treatment. The characteristics also suggest potential opportunities for resource recovery, such as biogas production, fertilizer, and solid fuel. However, hygiene is crucial for safe use, and further studies are needed to ensure sanitation for safe agricultural application.

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