QUANTITIES AND QUALITY OF POOP AND PEE IN SCHOOL SANITATION FACILITIES

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

This report aims to provide scientific support to design engineers, technology developers, regulators, and decision makers on the development and installation of new sanitation technologies and improve faecal sludge management of rural school communities by quantifying the volumes and/or mass of urine and faeces generated, quality of faecal-origin products produced at schools through characterisation of the physico-chemical, mechanical and thermal properties.

The final report includes summarised results from the characterisation of faecal matter and effluent from on-site sanitation systems, approximated values of faecal matter and urine generated at each school and design guidelines for the characterisation of faecal sludge from school sanitation facilities – samples were collected in 1 L containers from mobile toilets, septic tank systems and VIP latrines in rural schools of Umbumbulu within the Umlazi district. The analysed parameters include (i) the chemical and physico-chemical properties such as COD, calorimetry, water activity, solids analysis (i.e. total solids (TS), total suspended solids (TSS), total dissolved solids (TDS) and volatile solids), electric conductivity and pH; and nutrient properties, i.e. total nitrogen, total phosphate, and total potassium; (ii) mechanical properties such as density, particle size analysis and yield stress, and (iii) thermal properties such as heat capacity and thermal conductivity. The analysis was done according to standard operating procedures developed at the WASH R&D Centre and according to the methods book for faecal sludge analysis by Velkushanova et al. (2021). The analysis was done in two different categories, i.e. liquid fraction (effluent from septic tanks, VIP latrines and mobile toilets) and solid fraction (sludge from septic tanks and sludge from mobile toilets). Chemical oxygen demand ranged from 10,61-19,49 g/L for liquid samples and for solid samples it ranged from 72,62-242,07 g/L. The nutrient properties were investigated to assess the potential of sludge use in the agricultural sector. The nutrient properties for liquid fraction ranged from 554-1720 mg/L, 85,33-535 and 207-775 mg/L for total nitrogen, total phosphate, and total potassium respectively, while for solid fraction had total nitrogen ranging from 2,72-9,65 g/L and total potassium and total phosphorus at 0,76-3,31 g/L and 0,64-2,24 g/L, respectively. The faecal samples were also evaluated for thermal properties, with thermal conductivity from 0,534-0,588 $Wm.K^{-1}$ and the calorific values ranging from 15 to 27 $MJ.kg^{-1}$ dry solids mobile toilet sludge had higher energy content compared to the VIP and septic tank sludge. The statistical analysis was conducted using Kruskal Wallis to test the significance of the dataset a non-parametric, this test compares the means between three or more distinct/independent groups. The statistical analysis test demonstrated that for liquid samples there is no significance difference between the school sanitation systems and the phosphorus and ammonium ($p>0,05$) however for other nutrient properties such as potassium and nitrogen a significance difference between the on-site sanitation facilities was observed ($p>0,001$)

while for solid fraction (sludge samples) the statistical analysis showed that onsite sanitation systems were significantly different ($P < 0.001$).

The purpose for the quantification of faecal matter is to be able to size the school sanitation infrastructure. This data was collected through conducting the questionnaires from the school learners. On the questionnaire study, consent to ask the learners to participate in the questionnaires was obtained from both the parents and learners, school principals and governing bodies, Department of Basic Education (KwaZulu-Natal) and the Umlazi District Manager. The study revealed high urination values for all schools compared to defaecation, which is supported by evidence that the learners mostly use school on-site sanitation facilities for urination rather defaecation. Sixty-two percent of the learners indicated to use the onsite sanitation facilities for urination only while 36.7% indicated to use the sanitation facilities for both urination and defaecation. Overall 61.5% of learners indicated to not defaecate in school onsite sanitation facilities while 32.1% indicated to defaecate at least once a day. While there are areas of concern regarding cleanliness, smell, and safety in the school sanitation systems, there are also areas of strength and positive perception. The design guideline focusses on the provision of emptying options for school on-site sanitation facilities in rural communities and potential treatment methods of the faecal and effluent accumulation in rural school communities.

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ACRONYMS & ABBREVIATIONS

Acronym	Definition
CNS	Carbon Nitrogen and Sulphur
COD	Chemical Oxygen Demand
DBE	Department of Basic Education
DO	Dissolved Oxygen
EC	Electric Conductivity
FS	Faecal Sludge
FSM	Faecal Sludge Management
NEIMS	National Education Infrastructural Management Systems
SA	South Africa
SDG	Sustainable Development Goals
StatsSA	Statistic South Africa
TDS	Total Dissolved Solids
TS	Total Solids
TSS	Total Suspended Solids
UN	United Nations
VIDP	Ventilated Improved Double Pit
VIP	Ventilated Improved Pit Latrine
VS	Volatile Solids
WHO	World Health Organisation

CHAPTER 1: INTRODUCTION

1.1 CONTEXT

The World Health Organization (WHO, 2022) outline that 6.1 billion people worldwide used at least a basic sanitation service, and 1.6 billion people use toilets or latrines where excreta were safely disposed of in situ. However, 494 million people are still defecating in open spaces such as in street gutters, behind bushes, or into open bodies of water (WHO, 2022), and more than 1.7 billion people still lack access to basic sanitation facilities like private toilets or latrines (WHO, 2022). In response to this, the United Nations (UN) has put forward a target where sustainable development goal (SDG) 6 seeks to ensure the availability and sustainable management of water and sanitation for all, with a particular target to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations (United Nation, 2019).

In South Africa (SA), the proportion of households with access to piped or tap water in their dwellings, off-site or on-site by province increased from 84,4% in 2002 to 98,5% in 2020 and the proportion of households with access to better sanitation increased from 61,7% in 2002 to 83,2% in 2020 (StatsSA, 2020). However, the provision of safe school sanitation in rural areas has been overlooked, the incidents of learners falling into pit latrines in sanitation facilities and drowning in schools demonstrate that these incidents are connected to the lack of proper management of these sanitation infrastructures, restricted technical options for rural schools which are mostly latrine toilets, and user behaviour challenges (Matthews, 2016; Section27.org.za, 2020).

Sanitation facilities at rural schools have not changed much over the years, despite how the world has changed and how industries have adapted to the best technological and innovative trends. There is an urgent need for a new sanitation facility model in rural schools that will question established practices and consider how technology is disrupting society. This model should include technologies that can securely collect and treat human waste, sanitary towels, and wipes on-site. Since SA is a water-scarce and energy-insufficient nation and this model should require the least support for external water and energy supply, and lastly should therefore not require connection to the sewage system.

Part 1 of report focusses on the characterisation of the faecal sludges and effluent produced in the day-to-day production of contemporary school sanitation facilities, as it is effluent essential for the design of such sanitation technologies. Part 1 of the report also focusses on the approximation of faecal masses and urine volumes.

Part 2 of this report is a design guideline which aims to assist and support design engineers technology developers, regulators and decision makers on the development and installation of new sanitation technologies and improved faecal sludge management (FSM) in rural school. The design guideline will focus on (i) emptying options for each school on-site sanitation facilities and (iii) possible treatment options of the faecal sludge accumulated in the school on-site sanitation facilities.

1.2 PROJECT AIMS

Aims

To provide scientific support for the design of school sanitation facilities by quantifying the volumes and/or mass of urine and faeces generated, quality of faecal-origin products produced at schools, and including innovative approaches in school sanitation infrastructure design to deal with current servicing challenges.

Objectives

- To quantify the mass and / or volume of urine and faeces and faecal sludge generated in rural schools.
- To characterise the chemical and physico-chemical, thermal and mechanical properties, of urine, faeces and faecal sludge generated in rural schools.
- To provide observational data related to servicing and hygiene practice challenges associated with current rural school sanitation facilities.
- Develop a design guideline (collection and treatment matrix) for rural school sanitation infrastructure based on information gathered.

CHAPTER 2: THEORETICAL BACKGROUND

2.1 RURAL SCHOOLS SANITATION FACILITIES

The sanitation facilities at the school encompass pit toilets, enviro loo, mobile toilets, ventilated improved pit (VIP) toilets, flush toilet municipal, and flush toilets with septic tanks. In rural areas, the prevalent sanitation facilities are pit toilets, VIP toilets, and flush toilets with septic tanks. According to the 2021 National Education Infrastructure Management System (NEIMS) report, as shown in **Table 2.1**, South African schools have a total of 5,771 pit toilets, 7,611 VIP toilets, 3,103 flush toilet septic tanks, and 202 mobile toilets distributed nationwide. In KwaZulu-Natal schools specifically, there are 1,272 pit toilets, 2,372 VIP toilets, 505 flush toilet septic tanks, and 63 mobile toilets (NEIMS, 2021).

Table 2.1: Sanitation facilities in schools across South Africa (NEIMS, 2020)

Province	Number of sites	Pit	Enviro Loo	VIP	Flush toilet Septic Tank	Mobile	Chemicals
Eastern Cape	5291	1616	139	2773	254	8	4
Free State	1084	127	30	116	131	5	1
Gauteng	2073	0	13	26	154	101	7
KwaZulu-Natal	5803	1272	200	2358	550	63	65
Limpopo	3833	2226	1359	1395	685	1	3
North West	1469	145	44	307	494	16	7
Northern Cape	544	0	41	82	141	5	1
Mpumalanga	1716	385	129	545	482	0	0
Western Cape	1454	0	0	9	212	3	0
Total	**23267**	**5771**	**1956**	**7611**	**3103**	**202**	**88**

Due to lack of water and unavailability of sewer networks, the pit latrine toilets and septic tank systems are the most common on-site sanitation facilities that the schools make use of. The mobile and chemical toilets are used due to (i) lack of infrastructure as rural areas often face challenges in terms of infrastructure development, including sewage systems. Mobile and chemical toilets provide a quicker and more feasible solution in areas where establishing permanent sanitation infrastructure may be difficult, (ii) limited water supply , many rural areas, there may be constraints on the availability of water. Chemical toilets, which require less water for flushing compared to traditional flush toilets, can be a more practical choice in such situations and (iii) in emergency situations such as natural disasters or sudden increases in population (e.g. influx of refugees), mobile toilets can be quickly deployed to address urgent sanitation needs. The flush toilet septic tank facilities basically are connected to an infiltration system, e.g. soakway and require emptying less frequently (can vary to once every six months). Septic Tank pumping is often done once a year, this is to remove solids that build up in the system (WHO, 1992; Pradhan et al., 2011; Tilley et al., 2014). The school ventilated improved pit (SVIP) latrine toilets can be divided into two categories single pit VIP and ventilated improved double pit (VIDP) latrine, both of these are permanent structures and are well suited for any situation. In single pit, each cubicle sits over its own fully lined pit and each pit soakaway has a vent pipe (Deverill & Still., 1998). In ventilated Improved double pit (VIDP) latrine each cubicle is placed over two pits that share the cubicles on the left and on the right. Only one of these pits is used at one time, when it is full the pedestal or seat is moved over to the other pit (Deverill & Still., 1998). Mobile toilets are container-based sanitation facilities that consist of a seat on top and an easily sealable bucket beneath to contain urine and faeces, in some cases, urine is diverted to a separate container. Adding a disinfectant is required to reduce odour and kill pathogens.

2.2 APPROXIMATION OF ON-SITE SANITATION FILLING RATES

Quantifying the filling rates of onsite sanitation systems is crucial for effective management and planning. Several methods can be employed to understand these rates.

2.2.1 Monitoring and Record-Keeping:

Conduct routine inspections of onsite sanitation systems to visually assess the filling levels. This can involve checking septic tanks, pit latrines, or other systems for their current status, (Smith et al., 2019). Keep detailed maintenance logs that record pumping or emptying activities, repairs, and any other relevant information (Johnson, 2020).

2.2.2 GIS and Remote Sensing:

The use of GIS technology to map and analyse the spatial distribution of onsite sanitation systems, can help in identifying areas with higher filling rates and aid in planning interventions, (Jones et al., 2018). Remote sensing technologies can be employed to monitor changes in land use and detect potential issues with onsite sanitation systems (Brown & White, 2021).

2.2.3 Community Interviews and Surveys:

This includes engaging with the community to gather information on the perceived filling rates of onsite sanitation systems. Local knowledge can complement technical assessments, (Brown et al., 2018). Community interviews and surveys serve as a participatory and inclusive method for quantifying filling rates, providing a holistic understanding of onsite sanitation system dynamics by incorporating the valuable perspectives of the end-users. This approach enhances the effectiveness of sanitation interventions and promotes community-led sustainable practices (Brown et al., 2018).

2.3 CHARACTERISATION

The characterisation of the properties found in onsite-sanitation facilities includes a wide range of properties and can be divided into (i) Chemical and physicochemical; (ii) mechanical (iii) thermal properties and (iv) biological properties.

2.3.1 CHEMICAL AND PHYSICO-CHEMICAL PROPERTIES

The chemical properties refer to the characteristics of materials that change as a result of chemical processes, such as oxidation state and whether the material is combustible, corrosive, radioactive, acidic or basic. The chemical properties include nutrient content; pH and conductivity. Physico-chemical properties are influenced by both the physical and chemical processes and are essentially defined by the interaction of components within a material (i.e. faecal sludge, faeces and /or urine). The Physico-chemical properties include solids and moisture content and water activity.

2.3.1.1 pH and Conductivity

Faecal sludge typically has a pH that ranges from slightly acidic to slightly alkaline. The pH of faecal sludge can be influenced by factors such as the diet of the organisms producing the waste, the presence of urine, and the presence of other organic and inorganic materials. Generally, the pH of faecal sludge can range from around 6 to 8. The conductivity of faecal sludge can vary depending on the concentration of dissolved ions and solids in the sludge. Conductivity measures the ability of a solution to conduct electricity and is influenced by the presence of dissolved salts, minerals, and other ions. These parameter are important as they can influence the selection and performance of treatment methods, so they are often measured and monitored as part of treatment processes. Additionally, regulatory standards may dictate acceptable pH and conductivity levels for treated organic matter before it can be discharged or reused. **Table 2.2** illustrates pH of faecal matter from different on-site sanitation facilities.

Table 2.2: Illustrating pH of faecal matter from different on-site sanitation facilities

pH	On-site sanitation	References
6.5-8.0	Septic Tanks	Ingalinella et al., 2002; Cofie et al., 2006; Al-Sa'ed and Hithnawi, 2006
6.03-8,14	Pit latrines	Junglen et al., 2020; Ward et al., 2021
7.6-7.7	Wet & dry VIP	Strande et al., 2014
5.5-7	Urine	Rose et al., 2015; Guan et al., 2020

The pH measurement is critical for understanding acid-base chemistry, alkalinity, neutralization, biological stabilization, precipitation, coagulation, disinfection, and corrosion control processes in water (Strande et al., 2014). As illustrated in Table 2.2, pH of FS from the septic tank and pit latrines is reported to be in similar range of 6.03 to 8.0. The wet and dry VIP were found to be in the range of 7,6-7,7 respectively (Strande et al., 2014). A pH outside of the 6-9 range suggests a disturbance in the biological process, which will prevent anaerobic digestion and methane formation. This could be due to the presence of hazardous compounds, and a significant rise in organic loading. The pH of the urine has been reported to range from 5.5 to 7 (Rose et al., 2015; Guan et al., 2020) while the faecal pH ranges from 5.3 to 7.5 (Rose et al., 2015).

Conductivity is the measurement of ions in a solution. The ion concentration is significant because high salt concentrations, such as in stabilisation ponds, can hinder biological activity (Velkushanova et al., 2021). As illustrated in Table 2.2, the electrical conductivity (EC) values for pit samples were documented to vary between 6.78 and 29.30 mS/cm, and septic tank samples, including those from lined and unlined pit latrines, exhibited EC values ranging from 8.90 to 20.60 mS/cm (Junglen et al., 2020). Additionally, Gold et al. (2018) reported EC values of 12-13.6 mS/cm for both lined and unlined pit latrines. In a separate study, Ward et al. (2021) indicated an EC value of 14.5 mS/cm for pit latrine samples **Table 2.3** illustrates conductivity of faecal matter from various onsite-sanitation facilities.

Table 2.3: Conductivity of faecal matter from various onsite-sanitation facilities

Conductivity	On-site sanitation	References
8.90 to 20.60 mS/cm	Septic tanks	Junglen et al., 2020
12-13.6 mS/cm	Pit latrines	Gold et al., 2018
14.5 mS/cm	Pit latrines	Ward et al., 2021

2.3.2 Solids Content

Solids refer to the matter that is suspended or dissolved in water, wastewater, or faecal sludge. Solids impact physical, biological, and chemical treatment wastewater treatment processes and are a key parameter for compliance with regulatory wastewater discharge limits (SOP, 2016). For example, solids concentration informs the suitable emptying methods for on-site sanitation facilities and determines the design of faecal sludge FS treatment technologies (Strande et al., 2014; Velkushanva et al., 2021) such as the loading rate of technologies such as the drying beds to understand the drying and dewatering properties (Velkushanova et al., 2021).

The total solids (TS) are quantified as the material remaining after 24 hours of drying in an oven at 103-105°C. Volatile solids (VS) are the fraction that is ignited and burned off at a temperature of 500°. The total suspended solids (TSS), the potion of solids retained by a filter paper, and total dissolved solids (TDS) is the portion that passes through the filter of 2.0µm or smaller (SOP, 2016; Strande et al., 2014; Velkushanova et al., 2021). The ratio of VS to TS is used as an indicator of the relative amount of organic matter and the biochemical stability of FS. Solids that settle within a suspension after a specific amount of time (i.e. in an Imhoff cone after 30 to 60 minutes), is reported as the sludge volume index (SVI), and is used for designing settling tanks (Strande et al., 2014; SOP, 2016).

2.3.3 Organic Matter – Chemical Oxygen Demand (COD)

Organic matter indicates the level of material (such as faecal sludge, faeces, and/ or urine) stabilisation, biodegradation capability for biological treatment, and influence on recipient habitats. Chemical oxygen demand is the amount of dissolved oxygen that must be present in water to oxidize chemical organic materials. The COD is also defined as the quantity of an oxidant (such as dichromate in acid solution) that reacts with the sample, oxidising it chemically (Strande et al., 2014; Velkushanova et al., 2021). The total COD is a measure of the organic material in a sample and the degree of stabilisation. other methods to estimate the amount of organic matter in the sludge include CNS analysis, VS analysis and TOC analysis. **Table 2.4** illustrates the literature-reported values of COD for urine, faeces, and faecal sludge.

Table 2.4: Chemical oxygen demand

	Chemical Oxygen Demand (g/L)	**References**
Urine	8-17	Rose et al., 2015
	10	Udert et al., 2006
Faeces	1380-1450	Lopez-Zavala et al., 2002; Buckley et al., 2008
Faecal Sludge (Septic tank)	1 200-7 800	Strauss (2004)

2.3.4 Calorific values

The calorific value of a material is the quantity of heat produced by combustion. The energy content/density within the solid fuels are described in form of a calorific value (MJ kg^{-1} dry solids) which is ultimately the heat that is generated during the process of combustion of a specific mass of dry fuel (Gold et al., 2018). **Table 2.5** shows literature reported calorific values of both faeces and faecal sludge.

Table 2.5: Calorific values of faeces and faecal sludge

	Calorific values (MJ kg^{-1} dry solids)	References
Faeces	11 and 18	Onabanjo et al., 2016;
	25	Muspratt et al., 2014
	20-25	Chikava and Velkushanova, 2014
	15.1-25.1	Wierdsma *et al*., 2014
Faecal sludge	14	Zuma et al., 2015
	18	Septien et al., 2018
	2-25	Velkushanova, 2014;

2.3.5 Water Activity

Water activity (aw) is a measurement of the energy status of the water in a system. The value indicates how tightly wound structurally or chemically within a substance. It is the relative humidity of air in equilibrium with a sample in a sealed measurement chamber. Several studies have reported on the water activity of faecal sludge from different locations. For example, Dorea et al. (2018) measured the water activity of faecal sludge from pit latrines in Haiti and found values ranging from 0.91 to 0.98. Awuah et al. (2015) measured the water activity of faecal sludge from septic tanks in Ghana and found values ranging from 0.94 to 0.98. **Table 2.6** illustrate water activity from different on-site sanitation systems.

Table 2.6: Water activity of faecal sludge from different on-site sanitation systems

Water activity	On-site sanitation system	References
0.95-0.99	Septic tanks	Strande et al., 2014
0.94-0.98	Septic Tank	Awuah et al., 2015
0.98-0.99	Septic Tank with Leachfield	Foppen et al., 2008
0.91-0.98	Pit Latrines	Dorea et al., 2018
0.95-0.99	Pit Latrines	Strande et al., 2014

2.3.6 Nutrient Content

The excreta is rich in nutrients that are derived from food consumption. The urine has high nutrient content, with about 80-90% of total nitrogen; 50-60% of total phosphorus, and 50-80% of total potassium found in excreta (Schouw et al., 2002; Jönsson et al., 2005; Vinnerås et al., 2006; Spångberg et al., 2014; Viskari et al., 2018). The faeces are known to be high in carbon content and it is low in nutrient content with about 10-20% of nitrogen, 20-50% of phosphorus, and 10-20% potassium (Schouw et al., 2002; Jönsson et al., 2005; Vinnerås et al., 2006; Rose et *al*., 2015). The properties of FS are complex and differ from one on-site sanitation facility to the next, such that researchers have reported different values of certain properties of FS based on the sanitation facilities and locations. Organic and inorganic nutrients can be found in faecal sludge. Nutrients must be monitored for NH_3 inhibition, enough nutrients for biological processes, and the potential for agricultural valorisation as compost or fertiliser (Velkushanova et al., 2021). The total nitrogen in FS is present in different forms such as ammonium/ ammonia, nitrate, and other organic forms of nitrogen (Strande et al., 2014). The total phosphorus in FS is present information of phosphate, the acid or base form of orthophosphoric acid. **Table 2.7** illustrates the nutrient properties of urine, faeces, and faecal sludge.

Table 2.7 nutrient properties of urine, faeces, and faecal sludge

	Total Nitrogen	**Total Phosphate**	**Total Potassium**	**References**
Urine	80-90%	50-65%	50-80%	Schouw et al., 2002; Jönsson et al., 2005; Vinnerås et al., 2006; Lapid et al., 2008
Faeces	10-20%	20-50%	10-20%	Spångberg et al., 2014; Viskari et al., 2018; Rose et al., 2015
Faecal sludge	**Total Nitrogen (mg/L)**	**Total Phosphate (mg/L)**		
Septic Tank	190 to 300		-	Koné and Strauss, 2004
	640.40 ±148.40	139.97±139.0		Fanyin-Martin et al., 2017
Pit latrine		521.0±201.5	-	Fanyin-Martin et al., 2017

2.3.7 Thermal Properties

The thermal properties assess the drying, combusting, and heating potential of sludges and therefore the design of combustion treatment facilities and devices, and the application of faecal sludge as a biofuel. Thermal conductivity is the ability of a material to conduct heat and is important for the assessment and understanding of faecal sludge end-use processes such as combustion and composting. Heat capacity is the quantity of heat energy required to change the temperature of an object by a given amount. Table 2.8 illustrate Thermal conductivity and heat capacity reported literature values for faeces and faecal sludge.

Table 2.8: Energy content for faecal material

	Thermal Conductivity (W m.K^{-1})	
Faeces	0.44	Pandarum et al., 2019
	0.55	Hanson et al., 2000, Bart-Plange et al., 2009
Faecal sludge	0.48-0.55	Zuma et al., 2015
	0.09-0.79	Zuma *et al*., 2015; Velkushanova, 2014;
	Heat capacity (kJ/kg.°C)	
Faeces	3,200-4,200	Makununika, 2016
Faecal Sludge	707-4,773	Zuma *et al*., 2015; Velkushanova, 2014;

2.3.8 Mechanical Properties

The mechanical properties of faecal sludge and faeces are significant for the design and sizing of onsite sanitation systems and offsite treatment facilities, as well as collection and transport alternatives. The mechanical analysis encompassed density, particle size distribution, water activity, and rheology/ shear stress which provide data on the material's viscosity which therefore indicates if the material is stiff, can be pumped, or can flow.

2.3.8.1 Yield stress

Yield stress is the minimum amount of stress required to initiate flow or deformation in a material. For faecal sludge, yield stress indicates the minimum force needed to initiate flow or movement of the sludge. It is essential for identifying the minimum shear stress required to initiate flow. This is evaluated using an Anton Paar MCR72 rheometer.

2.3.8.2 Density

Density is a measure of mass per unit volume. It is used as a measure of wetness, volumetric water content, and porosity. Factors that influence the measurement include; organic content, porosity, and material structure. **Table 2.9** illustrate density values of faecal sludge from different on-site sanitation facilities.

Table 2.9: Density values of faecal sludge from different on-site sanitation systems

Density	On-site sanitation systems	References
1000-1200	Septic Tank with Leachfield	Mihelcic et al., 2011
950-1,050	Septic tank	Strande et al., 2014
1000-1200	Septic Tank	Kunwar, 2016

2.3.8.3 Particle size distribution

The particle size distribution of faecal sludge refers to the range of particle sizes present in the sludge. It encompasses a spectrum of particle sizes, including large solids, suspended solids, and dissolved solids. The distribution of particles can significantly impact the behaviour, treatment, and disposal of faecal sludge in sanitation systems. Understanding the particle size distribution is crucial for designing effective treatment processes, assessing the performance of sanitation systems, and determining appropriate disposal or re-use methods (Strande et al., 2014; Tilley et al., 2014) . The particle size distribution can vary widely depending on factors such as the source of the faecal sludge (e.g. pit latrines, septic tanks), the composition of the waste, and any treatment processes it has undergone. Analysing the particle size distribution helps determine the efficiency of treatment processes in removing solids and contaminants. D10, D50, and D90 are percentiles describing the particle size distribution on a volume basis: D50 is the median particle diameter, 10% of the sample is smaller than D10, and 90% of the sample is smaller than D90 (Ward et al., 2023).

2.4 FAECAL SLUDGE EMPTYING OPTIONS

Emptying refers to the discharging/ evacuation of faecal sludge in on-site sanitation facilities. Transport is the physical moving the faecal sludge from the sanitation facility to the treatment plant or to a disposal site (Medland et al., 2016). The emptying of FS from septic tanks or latrines is done through the use of manual and mechanised techniques that may rely upon hand tools, vacuum trucks, pumping systems, or mechanical augers. The emptying method employed are based on the (i) type of onsite sanitation system, (ii) accessibility of the site, (iii) the type of equipment owned by the service provider, and (iv) the level of expertise, (Strande et al., 2014). The characterisation of faecal sludge is important so the emptiers can be aware of the potential challenges that may come along with emptying and transportation. The important properties are mostly inclined by water content, the FS age, the existence of non-biodegradable material and the organic materials.

2.4.1 Styles of emptying

The styles / systems of collection of FS include:

(i) Manual emptying ;

(ii) Manually operated mechanical emptying

(iii) Fully mechanised emptying

2.4.1.1 Manual emptying

Manual emptying is done using purpose built hand tools including buckets, long handle rakes, spades and corers are used dig and pull out FS. The workers do not necessarily enter the containment structure themselves. This method is effective in dealing with thick, difficult to pump FS and FS containing solid waste. The operation and maintenance required in manuals emptying is cleaning of tools and equipment after use and protection from corrosion. Tools can and equipment can be manufactured and repaired locally, **Table 2.10** illustrates the benefits and challenges of manual emptying FS.

Table 2.10: Benefits and challenges with manual emptying of FS

Benefits of Manual emptying	Challenges of manual emptying
• use of simple tools and manual work is very sustainable; • (ii) low cost; • (iii) Provides a source of income for local people and • (iv) ability to remove thick FS.	• it is slow; • it is socially unacceptable in some contexts; • it results in stigmatisation of workers; and • is a potentially serious health risks to workers and community

2.4.2 Manual Operated Mechanical emptying

The septic tanks and pit latrines can be serviced faster, safer and more efficiently by using newly developed innovations in human powered mechanical devices. The manually operated mechanical devices include (i) gulper and (ii) diaphragm pump (Mikhael et al., 2014). The gulper is regularly utilised for FS emptying and is mostly applicable to liquid FS and is used in areas where access is difficult, for example, restricted roads. **Table 2.11** illustrates the benefits and constraints of manual operated mechanical emptying devices (Gulper and diaphragm pump).

Table 2.11: Benefits and constraints of manual operated mechanical emptying devices

	Gulper	Diaphragm pump
Benefits	• Low capital cost; • Simple transportation; • Simple creation and fixes are done locally.	• Simple design with • Relatively few moving parts and • Effective at quickly pumping low viscosity FS
Constraints	• Manual operation requires physical effort; • Not suitable for continuous or high-volume pumping; • May not be suitable for high-viscosity substance.	• Requires periodic maintenance for diaphragm replacement; • Limited suction lift capability; • Sensitive to abrasive or solid particles in the fluid
References	Mikhael et al., 2014	Mikhael et al., 2014

2.4.3 Fully mechanised emptying

The mechanised emptying methods include vacuum trucks, motorised diaphragm pump, trash pump, pit screw auger and so many other devices that are still under development. **Table 2.12** illustrates the benefits and constraints of fully mechanised emptying devices.

Table 2.12: Benefits and constraints of fully mechanised emptying devices.

	Vacuum Trucks pump	Motorised Diaphragm Pump	Gobbler
Benefits	• Suitable for removing low-viscosity sludge • Ideal for transporting large quantities of sludge over long distances.	• it is simple to use, • low cost and • it is easily transportable	• Suitable for pumping FS with high viscosity.
Constraints	• Difficulty to maintain in low-income contexts due to specialized parts, • High cost and • Some tankers are not suitable with thick FS	• Clogging easily when pumping FS with a high solid waste content	• Heavy • Fixed length therefore cannot empty pits of different depths
References	Mikhael et al., 2014	O'Riordan 2009; Mikhael et al., 2014	Still et al., 2012; Still et al., 2013

2.5 FAECAL SLUDGE TREATMENT OPTIONS

Faecal sludge (FS) treatment refers to the processing that changes the physical, chemical and biological characteristics or composition of FS so that it is of a quality fitting for the intended reuse or disposal (Blockley, 2005; Strande et al., 2014. The treatment of FS assists to prevent possible risks to public health and the environment (Tsida, 2020). Technologies have been developed globally with the aim of treating FS, producing value end-product while promoting the livelihood of thousands of people using on-site sanitation facilities. The recommended treatment options of faecal that can be considered for rural schools are:

- Drying Beds _ Planted and unplanted drying beds
- Biogas Digesters _ Anaerobic Digesters
- Composting
- Vermicomposting
- Solar drying
- Pyrolysis for biochar recovery
- Constructed Wetlands
- Composting Toilets

These faecal sludge treatment methods are applicable for rural schools because they are cost-effective, environmentally friendly, additionally, they take into consideration the specific challenges and constraints often associated with rural environments, providing sustainable solutions for faecal sludge management in schools. Implementing these methods can improve sanitation and hygiene conditions, enhance environmental sustainability, and provide educational opportunities for learners. **Table 2.13** illustrates the appropriateness of each faecal sludge treatment method for application in rural schools.

Table 2.13: FS treatment method suitability for rural schools

Treatment Technology	Suitability
Composting	• Composting is a simple and low-tech treatment method that can be implemented in rural areas without the need for complex infrastructure. • The materials required for composting are often locally available, making it a cost-effective.
Biogas Digesters (Anaerobic Digestion)	• Biogas digesters utilise anaerobic digestion to break down organic matter in faecal sludge, producing biogas and a nutrient-rich effluent. • Biogas digesters provide dual benefits of waste treatment and energy production. They can generate biogas for cooking or lighting, benefiting rural schools by reducing energy costs and promoting sustainable practices
Drying Beds	• Drying are low-cost method for sludge dewatering. • They are simple to operate and require minimal energy inputs. • They require minimal infrastructure and can be suitable for climates with adequate sunlight. • Drying beds can be constructed using locally available materials, reducing costs for rural schools. • Dried sludge can be safely disposed of or used as a soil conditioner.
Vermi-composting	• Nutrient-rich compost production; • Reduction of organic waste volume; • Natural decomposition with minimal odour • Environmentally sustainable; • Pathogen reduction through microbial activity; • Cost-effective waste management solution.
Deep Row Entrenchment	• Simple and low-cost FS disposal method and lower transport costs; • Minimal overhead and infrastructure required; • Minimal skills required for daily operation
Solar drying	• Relies on renewable solar energy, reducing reliance on non-renewable energy sources such as electricity. • Have lower operating costs compared to mechanical drying methods. • Reduces greenhouse gas emissions and environmental pollution associated with conventional treatment method

Treatment Technology	Suitability
	• Effectively deactivates pathogens present in faecal sludge through exposure to high temperatures
Pyrolysis	• Effective pathogen reduction • Fast treatment time • High reduction of sludge volume • Production of char
Constructed Wetlands	• Make use of natural processes to treat wastewater by filtering it through soil, plants, and microorganisms. • They are low-cost and low-maintenance compared to conventional treatment systems. • They provide habitat for wildlife, and can be integrated into the landscape. • Constructed Wetlands promote biological treatment, nutrient removal.
Composting Toilets	• Composting toilets convert faecal matter into compost through aerobic decomposition. • Composting toilets require minimal water usage and can operate without connection to sewage systems, making them ideal for remote school locations • Composting toilets produce compost that can be used to enrich soil in school gardens or landscaping projects.
References	Mata-Alvarez, J. 2011; Vymazal, 2011; Strande et al., 2014, EPA., 2019

2.6 LIQUID FRACTION TREATMENT MECHANISMS

Treating the liquid fraction of faecal sludge, which includes urine and wastewater, is crucial for several reasons.

1. Public Health: Untreated liquid fraction of faecal sludge can contain pathogens, such as viruses, bacteria, and parasites, which can cause the spread of diseases, especially when they come in contact with humans or the environment. Treating the liquid fraction of faecal sludge reduces the risk of spreading disease transmission and infections caused by pathogens present in the sludge and protects public health (Strande et al., 2014; Tchobanoglous et al., 2014).
2. Environmental Protection: The untreated liquid fraction of faecal sludge can contain high levels of nutrients, such as nitrogen and phosphorus, which can lead to the eutrophication of water bodies and cause harm to aquatic ecosystems. Treatment of the liquid fraction of faecal sludge can remove or reduce these nutrients and prevent environmental degradation (Hossain & Islam 2017). And it reduces the environmental pollution caused by the discharge of untreated wastewater into water bodies, which can have serious health implications for both humans and animals (Strande et al., 2014)

3. Resource Recovery: The liquid fraction of faecal sludge can contain valuable resources, such as nitrogen and phosphorus, which can be recovered and reused as fertilizers in agriculture. Treating the liquid fraction of faecal sludge can help recover these resources and reduce the reliance on chemical fertilizers ,(Schaub-Jones, 2010; Strande et al., 2014).

2.6.1 Effluent (liquid fraction) treatment

Effluent from on-site sanitation systems, such as septic tanks or pit latrines, typically contains high concentrations of organic matter, nutrients, pathogens, and suspended solids. Constructed wetlands, activated sludge and waste stabilization ponds can be effective in reducing these contaminants to levels that are safe for discharge or reuse. These treatment methods are suitable for rural areas because they are simple, cost-effective, and can be adapted to local conditions and resources. They provide effective ways to manage and treat effluent resulting from faecal sludge while promoting sustainability and environmental protection.

(i) Constructed wetlands

Constructed wetlands are engineered systems that mimic natural wetlands to treat wastewater and stormwater. These systems use plants, soil, and microbes to remove pollutants from water before it is discharged to the environment. Constructed wetlands have become an increasingly popular option for water treatment because they are relatively low-cost and environmentally friendly. Constructed wetlands are be suitable for rural areas because they are low-cost, low-maintenance, and use natural processes to treat wastewater. They can be constructed using locally available materials and vegetation. Constructed wetlands can be designed to fit the local landscape and can treat effluent to meet regulatory standards (Vymazal, J., 2010)

(ii) Activated sludge process

In the activated sludge process, wastewater is aerated and mixed with a microbial culture (activated sludge) in a treatment tank. The microbial culture metabolises organic matter in the wastewater, reducing its concentration.

(iii) Waste stabilisation ponds

Waste stabilization ponds are shallow, man-made ponds where wastewater is held for an extended period of time. The ponds are designed to facilitate natural biological and physical processes that remove contaminants from the wastewater (Mara, 2004). **Table 2.14** illustrate benefits and constraints of the effluent treatment mechanism.

Table 2.14: Benefits and constraints of effluent treatment mechanism

Treatment mechanism	Benefits	Constraints
Constructed wetlands	• Cost effective • Environmental benefits • Efficient pollutant removal • Low energy consumption	• Climate and geographical limitations • Large space requirement • Long term sustainability
Activated Sludge	• Effective removal of organic matter, • Relatively compact footprint compared to other treatment methods. • Can handle high variations in influent flow and load	• Requires mechanical aeration equipment, which consumes energy. • Requires skilled operation and maintenance to ensure proper process control and performance.
Waste Stabilisation Ponds	• Low energy requirements. • Can be cost-effective to construct and operate • Provides additional benefits such as habitat for wildlife and aesthetic value	• Requires a large land area • May require pre-treatment to remove large solids or settleable materials.

References: Hammer, 1989; Kadlec & Knight 1996; Randall, & Sen, 1996; Kivaisi, 2001; Cooper et al., 2010; Summerscales & Lee, 2012; . Metcalf & Eddy, 2013; Zhang et al., 2018; Vymazal, J. 2018

2.7 IDEAL PERFORMANCE CRITERIA FOR FAECAL SLUDGE TREATMENT METHODS

Faecal sludge treatment is a critical process that involves the removal of pathogens, pollutants, and other contaminants from human waste before disposal or reuse. The ideal performance criteria for faecal sludge treatment methods can vary depending on factors such as the location, regulations, and specific objectives of the treatment. Faecal sludge treatment methods are critical in ensuring the safety of the environment and public health. The performance of these methods is evaluated based on different criteria to ensure that they meet the desired standards. Here are the ideal performance criteria for faecal sludge treatment methods:

- **Pathogen reduction**: The primary objective of faecal sludge treatment is to reduce the concentration of pathogens to a level that is safe for human contact and the environment. The ideal performance criteria for pathogen reduction is a minimum of 4 log reduction of helminth eggs and E. coli. This criterion is based on the World Health Organization (WHO) guidelines for safe reuse of wastewater, excreta, and greywater (WHO, 2006).
- **Nutrient recovery**: Faecal sludge contains essential nutrients such as nitrogen, phosphorus, and potassium that can be recovered and reused as fertilizer. The ideal performance criteria

for nutrient recovery is the ability to recover at least 50% of the total nitrogen and phosphorus content of the faecal sludge (Strande et al., 2014).

- **Energy recovery**: Faecal sludge treatment methods should be designed to recover energy in the form of biogas or other forms of renewable energy. The ideal performance criteria for energy recovery is the ability to generate at least 0.3 m^3 of biogas per kg of total solids in the faecal sludge (Eawag, 2017).
- **Odour control:** Faecal sludge treatment methods should be designed to control odours that may arise during the treatment process. The ideal performance criteria for odour control is the ability to reduce the odour emission by at least 80% (Tchobanoglous et al., 2014).
- **Robustness and reliability**: Faecal sludge treatment methods should be designed to be robust and reliable, even under adverse conditions. The ideal performance criteria for robustness and reliability is the ability to maintain a stable operation and achieve the desired treatment outcomes with minimal maintenance and intervention (Tilley et al., 2014).
- **Cost-effectiveness**: Faecal sludge treatment methods should be cost-effective to ensure their affordability and sustainability. The ideal performance criteria for cost-effectiveness is the ability to achieve the desired treatment outcomes at a reasonable cost that is affordable for the end-users (Blackett et al., 2015).
- **Operational Efficiency:** Faecal sludge treatment methods should be designed to operate efficiently and effectively without requiring a significant amount of resources or manpower. The ideal performance criteria for operational efficiency would depend on the size of the treatment plant and the available resources, but a high level of automation and minimal maintenance requirements are generally desirable.
- **Scalability**: Faecal sludge treatment methods should be designed to scale up or down depending on the needs of the community. The ideal performance criteria for scalability would depend on the size of the community and the expected growth rate, but a flexible design that can easily be expanded or downsized is generally desirable.
- **Environmental Impact:** Faecal sludge treatment methods should be designed to minimize their environmental impact. The ideal performance criteria for environmental impact would depend on the specific objectives of the treatment and the local regulations, but a low carbon footprint and minimal discharge of pollutants are generally desirable.

Overall, the ideal performance criteria for faecal sludge treatment methods should prioritize the removal of pathogens and pollutants while minimizing the environmental impact and operational costs. The specific performance criteria would depend on the local regulations and objectives of the treatment, but a high level of efficiency, scalability, and flexibility are generally desirable. Table 2.15 below illustrates some ideal performance criteria for certain FS treatment technology.

Table 2.15: Ideal performance criteria for FS treatment method

Parameters	Unplanted drying bed	Planted drying beds	Biogas Digesters (Anaerobic Digestion)	Pyrolysis for Biochar Recovery	Composting	Deep row entrenchment	Constructed Wetlands	Composting toilets
TS (% dry mass)	2-10%	2-10%	3-20%	70%	20-30%	5-25%	3-8%	60-90%
VS (%)	50-60%	~ 50%	60-80%	60-70%	60-70%	~ 50-60%	-	30-70%
TSS (mg/L)	1000-1500	500-1000	2000-8000	1000-5000	2000-6000	1000-2000	100-500	-
COD (mg/L)	-	-	5000-15000	500-1500	2,000-4000	3000-5000	50-300	-
C:N	20:1-30:1	20:1-30:1	25:1 to 30:1	20:1-30:1	25:1	20:1 -30:1	-	25:1-35:1
Total Nitrogen (mg/L)	500-3000	500-3000	1000-5000	500-3000	500-3000	500-3000	5-20	5-15
Total Potassium (mg/L)	200-1000	200-1000	200-1000	200-1000	200-1000	200-1000	10-50	10-30
Total Phosphorus	200-1000	200-1000	200-1000	200-1000	200-1000	200-1000	3-20	3-15
Ammonia	100-1000	100-1000	100-1000	100-1000	100-1000	100-1000	1-10	2-20
pH	6-7.5	6-7.5	6.5-7.5	6-7.5	6-7.5	6-7.5	6.5-8	5.5-8.5

References: Mihelcic et al., 2011; Karanth et al., 2013; Strande et al., 2014; Tilley et al., 2014; Fidjeland, J., & Jönsson, H. 2015; Strauss et al., 2017; Gensch et al., 2018; Gajurel et al., 2018; Lungali, 2019; Yacob et al., 2018; Krueger et al., 2020.

CHAPTER 3: MATERIALS AND METHODS

3.1 INTRODUCTION

This Chapter focuses on the experimental procedures for the characterisation and quantification of faecal sludge in rural school on-site sanitation facilities. it is further divided into 2 sections where section 1 focuses on the methods towards for the quantification and/or accumulation of urine and faeces in rural school onsite sanitation facilities and section 2 focuses on the materials and methods for characterisation of excreta and faecal sludges. The selected on-site sanitation facilities were the ventilated pit latrines (VIP) toilets, septic tanks, i.e. flush toilet with septic tanks and mobile toilets were selected as the on-site sanitation facilities for this study based on the fact that majority of rural schools make use of these facilities at the KwaZulu-Natal (KZN) province,

Area of study : This study was conducted at Durban, KwaZulu-Natal, South Africa, at the rural areas called Umbumbulu which fall under the Durban Metropolitan. The schools at which the faecal samples were collected and questionnaires were conducted will remain anonymous in this study and will be referred to as School 1, school 2, etc.

3.2 QUANTIFICATION – DATA COLLECTION THROUGH QUESTIONNAIRES

3.2.1 SAMPLE SIZE

The sample size analysis was conducted through the Chi-Square test for the independent association of two categorical variables. The null hypothesis (H_0) tested was that there will be no independent association between the two categorical variables. It was assumed that the most complex contingency table for the Chi-Square test should have a 4x3 structure resulting in (4-1)(3-1) = 6 degrees of freedom (df). In the application of the Chi-Square test, sample sizes usually detect effect sizes between 0.1-0.5 with 0.1 considered small and desirable, 0.3 (medium) and 0.5 (large). The aim was to estimate a sample size that will be capable of detecting small effect sizes. Given the α=0.05 and df = 6 and using GPower 3.1.9.7 sample size calculation software, it is estimated that a minimum sample size of 979 will be required to detect small effect sizes of at least 0.16 about 98% of the time (have 98% power of test) with 95%confidence. There are 8 schools involved and of different population sizes. Hence proportional sampling method was used as shown in Table 3.1.

Table 3.1: Proportional Sampling methods to conduct questionnaires in each school

Schools	School Population	Required Population percentage %	Sample
1	779	19%	182
2	320	8%	75
3	239	6%	56
4	1 800	43%	420
5	441	11%	103
6	378	9%	88
7	147	4%	34
8	96	2%	22
Total		**100%**	**979**

A questionnaire was developed to gather information on the use of school toilets by the learners. The questionnaires also focuses on the factors that will lead their use or not use of school toilets such as liquid intake and food consumption before and during school hours. Prior to conducting the questionnaire with the learners, a parent consent form and learner assent was given to the learners to complete, Appendix A illustrate questionnaires for both learners and care takers.

3.2.2 Approximation of urine volumes and faecal mass

The variations exist in urine and faecal mass production rates due to factors such as age, gender, activity level, and hydration status. Therefore, the calculated volume are an approximation and not an exact measurement. The urine volume and faeces mass were calculated using the following assumed data and equations.

Table 3.2: constant variables and frequency

Parameters	**Data**
Urine Volume (mL)	60 mL / visit to the toilet /Learner
Stool Mass (g)	230 g / visit to the toilet /Learner
FREQUENCY	
Urination frequency	Extracted from the questionnaires (ranging from 1-4 times per day during school hours)
Defaecation Frequency	Extracted from questionnaires (ranging from 0-2 per day during school hours)

3.2.2.1 Total urine volume and stool mass per learner per day

The estimated total urine volume produced by each learner per visit to the school toilet was estimated to be 60 ml during school hours. This estimate can vary based on factors such as age, gender. The estimated stool mass produced by each leaner per visit to the toilet was estimated to be 230 g for all the learners. The frequency was collected from the data provided by learners in the questionnaires.

$$\frac{\text{Total Urine Volume}}{\text{learner.day}} = \text{Urine volume} \times \text{frequency per day} \quad \textbf{(1)}$$

$$\frac{\text{Total stool mass}}{\text{learner.day}} = \text{Stool mass} \times \text{frequency per day} \quad \textbf{(2)}$$

3.2.2.2 Learner Population:

The learner population was provided by each school and is presented in Table 3.1

3.2.2.3 Multiply Total Urine Volume / stool mass by the total number of learners:

By multiplying the estimated total urine volume per learner per day or stoll mass per learner per day by the total number of learners during school hours, this gave an approximation of the total urine and faeces output for all learners combined for a day.

$$\frac{\text{School Total Urine Volume}}{\text{day}} = \frac{\text{Total Urine Volume}}{\text{learner.day}} \times \text{School population} \quad \textbf{(3)}$$

$$\frac{\text{School Total faecal mass}}{\text{day}} = \frac{\text{Total stool mass}}{\text{learner.day}} \times \text{School population} \quad \textbf{(4)}$$

3.3 CHARACTERISATION

3.3.1 SAMPLING METHODS

The sampling of faecal sludge and effluent were collected in different schools around the Umlazi district in the eThekwini municipality. The faecal matter samples were collected in different schools from different on-site sanitation facilities available including mobile toilets, septic tanks, and ventilated pit latrines toilets. Table 3.3 illustrates the type of samples collected in each toilet facility. A 1 litre sample was collected on each toilet facility using a sampling tool for septic tanks and VIP and a scoop in mobile toilets. The mobile toilets are said to be emptied every end of the week, while septic tank systems and pit latrines are not emptied as frequently.The samples were transported to the WASH R&D sanitation laboratory and kept in a cold room at 4° C for further analysis.

Table 3.3: Background on school sampling and school information

No. School	Sample collected	On-site sanitation
4	- Faecal Sludge - Effluent	Septic Tank
1	- Faecal Sludge - Effluent	VIP latrines
2	- Faecal sludge - Effluent	Mobile Toilets
2	- Effluent	Septic tanks

3.3.2 NALYSIS

The analysis was carried out according to the WASH R&D Centre standard operating procedures and through the methods for analysis book by Velkushanova et al., 2021. The analysis was carried out in the WASH R&D Centre sanitation laboratory. The samples were analysed for a physico-chemical analysis; mechanical analysis; and thermal analysis. Table 3.4 illustrates different parameters analysed under each type of analysis.

Table 3.4: Parameters analysed under each type of analysis

Chemical and Physico-Chemical Analysis	Mechanical Analysis	Nutrient Analysis	Thermal Analysis
• pH and Electric Conductivity • Total COD • Solids (TSS; TS, TDS, VS) • Water Activity • Calorific Content	• Density • Particle size Distribution • Rheology/ shear stress	• Total Nitrogen • Total Phosphate • Total Potassium • Ammonium	Thermal Conductivity Heat capacity

3.3.3 Chemical and Physico-chemical properties

3.3.3.1 pH and Electrical Conductivity (Ec)

- The pH and Ec were measured using a pH meter probe.

3.3.3.2 Total Chemical Oxygen Demand (COD)

The Chemical Oxygen Demand was analysed on all samples and was measured for all the collected samples. The sample is digested for two (2) hours in a strongly acidic dichromate solution, using silver sulphate as a catalyst and mercuric sulphate as a masking agent to prevent chloride interference. The dichromate is partially reduced by the oxidizable material present in the sample. The excess dichromate is titrated with ammonium iron (II) sulphate and the COD value is calculated from the amount of dichromate.

The half reaction for the reduction of dichromate is:

$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3-} + 7H_2O$

The remaining dichromate is titrated with a standard ammonium iron(II) sulphate solution:

$Cr_2O_7^{2-} + 6Fe^{2+} + 14H^+ \rightarrow 6Fe^{3+} + 7H_2O + 2Cr^{3+}$

The equivalence point is indicated by the sharp colour change from blue-green to reddish-brown as the Ferroin indicator undergoes reduction from iron (III) to the iron (II) complex.

3.3.3.3 Solids and Moisture content

Three samples of 10 g each were used to analyse the moisture content of the faecal sludge samples in triplicate. The samples were placed in an oven (*Gallenkamp)* at 105°C and dried for 24 hours. The mass evaporating and remaining represent the moisture content and total solids respectively. The samples remaining were then placed in a furnace (*Furnace E160*) at 550°C for 2 hours, after which the mass was measured. The mass loss on ignition was taken to be the volatile solids, and therefore the difference in mass from before and after being put in the furnace was measured. Moisture content and volatile solids was calculated using the following equations:

$$\boldsymbol{MC} = \frac{\boldsymbol{m_{crucible}} + \boldsymbol{m_{faeces}} - \boldsymbol{m_{exit\ oven}}}{\boldsymbol{m_{faeces}}} \qquad \textbf{(5)}$$

Where:

MC = Moisture Content

$m_{crucible}$ = mass of a crucible

m_{faeces} = mass of faeces

$m_{exit\ oven}$ = mass of crucible & feaces after drying in the oven

$$VS = \frac{m_{exit\,oven} - m_{exit\,furnace}}{m_{faeces}} \qquad (6)$$

Where:

VS = Volatile solids

m_{faeces} = mass of faeces

$m_{exit\ furnace}$ = mass of faeces & crucible exiting the furnace

$m_{exit\ oven}$ = mass of faeces & crucible exiting the oven

3.3.3.4 Nutrient analysis

The nutrient analysis was conducted through the chemical testing of total nitrogen, total phosphate, total potassium and total ammonium. The nitrogen, phosphorus and potassium contents (NPK) and ammonium were measured for all the collected samples using the Spectroquant Method Cell Test.

3.3.3.5 Water Activity

The water activity for faeces and faecal sludge samples was measured and the temperature was constant ambient temperature and at 24°C. An *AquaLab* Tuneable Diode Laser (TDL) water activity meter was employed to characterize the binding of moisture with the dry matter within the faecal sludge. Figure 3.1 displays the water activity meter used in the laboratory. The water activity was analysed in triplicates, using subsamples from the main sample. The time for each sample analysis was 20 minutes for each analysis. The analysis followed the procedure stipulated by the WASH R&D CENTRE – UKZN laboratory SOP and Velkushanova et al. (2021).

Figure 3.1: ***TDL Water activity Mater***

3.3.3.6 Calorimetry

The energy content in faecal samples was also analysed using the oxygen bomb calorimeter. calorimetry is basically the science of measuring quantities of heat, as distinct from temperature. The oxygen bomb calorimeter is the standard instrument for measuring calorific values of combustible samples. For this study the calorific values were determined for faecal solid samples, i.e. faecal sludge samples. Figure 3.2 illustrates the Anton Parr 6200 calorimeter.

Figure 3.2: Calorimetry

3.3.4 Thermal properties

3.3.4.1 Thermal conductivity and heat capacity

The *C-Therm TCi* Thermal Conductivity Analyser was used for this study. It has an accuracy of 5% and a precision of 1%, and is able to measure substances of temperatures between -50°C and 200°C. It can also measure a wide range of thermal conductivities, varying from 0 to 120 W/m.K, see Figure 3.3 below. Samples of 1.88 mL were placed in the sampling sensor, as indicated by the standard operating procedure. *C-Therm TCi* 2.3 software was used, and the thermal conductivity was directly measured. The software has the ability to take multiple measurements on a single sample and samples were analysed in triplica.

Figure 3.3: C-Therm TCi Thermal Conductivity Analyser

3.3.5 Mechanical analysis

The mechanical analysis encompassed density, particle size distribution, and shear yield stress.

3.3.5.1 *Density:*

The bulk density is determined by oven-drying a known volume of sample and the mass of the dry sample measured. The analysis followed the procedure stipulated from the WASH R&D CENTRE – UKZN laboratory SOP and Velkushanova et al. (2021).

3.3.5.2 *Particle size distribution*

The *Malvern Mastersizer 3000* measures the size of particles contained within a sample. The purpose of the unit is to transmit red laser light and blue light through a sample and then use its detectors to generate data about the light scattering pattern caused by particles in the sample, which can be interpreted by the Mastersizer software to provide accurate particle size information. Figure 3.4 illustrates the particle size analyser.

Figure 3.4: ***Master size 3000 Particle analyser***

3.3.5.3 *Yield Stress using rheometer*

Rheological measurements provide information on a material's visco-elastic behaviour. The visco-elastic characteristics of the faecal sludge and faeces were thus determined using an Anton Paar MCR72 rotational rheometer. The rheometer system includes a measuring system ST59-2V-44.3/120 , Anton Paar software (Version 1.24584) and building materials cell (BMC90). For this study, the cup and vane arrangement was chosen because it is most suited for viscous materials containing solid particles (such as faecal sludge), and it also reduces the influence of wall slip throughout the tests. **Figure 3.5** illustrates a picture of the rheometer.

Figure 3.5: Rheometer

3.4 STATISTICAL ANALYSIS

Kruskal Wallis test was used to test the significance of the dataset a non-parametric Kruskal Wallis test was conducted, this test compares the means between three or more distinct/independent groups. The independent groups in this case are the three onsite sanitation facilities, i.e. mobile toilets, ventilated improved pit latrine and septic tanks. The Kruskal Wallis test was selected based on the fact that it does not assume normality in the data and is much less sensitive to outliers.

3.5 DESIGN GUIDELINE

The design guideline will focus on the sizing of the rural school sanitation infrastructure based on the faecal and liquid (urine and /or effluent) accumulation; (ii) emptying options suitable for the type of sludge in those onsite sanitation facilities and (iii) suitable treatment options for the type of faecal sludges in those on-site sanitation facilities based on the characterisation of FS properties found in onsite-sanitation facilities includes a wide range of properties and can be divided into (i) Physico-chemical; (ii) mechanical (iii) thermal properties and (iv) biological properties.

CHAPTER 4: RESULTS AND DISCUSSION

The results section is divided into two parts; where section 1 is the approximation of urine volumes and faecal stool mass from data from the questionnaires conducted in school and section 2 is the characterisation of faecal matter from school on-site sanitation facilities. Section 2 is further divided into 2 parts where part 1 is the results on liquids fraction which is the results of the analysis of effluent from septic tanks, mobile toilet and VIP latrine toilets and part 2 is the results on analysis of solid fraction, i.e. sludge. The liquid samples were analysed for physico-chemical nutrient properties, while the solid samples were analysed for a wide variety of properties, including physico-chemical analysis, mechanical analysis, nutrient content, and thermal properties. The analysed parameters are expected to vary from one containment system to the next based on (i) different diets by the contributing users; (ii) age; (iii) type of containment system and (iv) frequency of emptying of each system.

4.1 SECTION 1 : APPROXIMATION OF URINE VOLUMES AND FAECAL MASS

4.1.1 Participants

Table 4.1: Age and Gender across the schools

Sanitation systems	Pit latrines; (N=205)	Septic tanks (N=669)	Mobile toilets (N=186)	p-value	Overall (N=1060)
Gender				<0.001	
Female	79 (39.5%)	371 (55.8%)	107 (57.5%)	Chisq.	557 (53.0%)
Male	121 (60.5%)	294 (44.2%)	79 (42.5%)		494 (47.0%)

The questionnaires were completed by leaners in schools with different on-site sanitation systems. Overall 53% of the learners that participated in the questionnaires were females and 47% were the males.

4.1.2 Faecal Mass and urine volumes approximation

Table 4.2: Urine volume and faecal mass approximation results

School	School Population	Total school Urine volume/Day (L//day)	Total school Urine volume/ Week (L//Week)	Total school faecal mass/ day (kg/day)	Total school faecal mass/ week (kg/week)
1	779	113,00	565,01	70,06	350,27
2	320	43,76	218,79	30,59	152,94
3	239	39,38	196,92	12,83	64,14
4	800	236,04	1180,20	140,11	700,57
5	441	70,27	351,36	44,40	222,01
6	378	102,45	512,24	118,41	592,03
7	147	34,49	172,46	22,69	113,47
8	96	31,57	157,88	29,60	148,01

Table 4.2 Illustrates the urine volume and faecal mass approximation results. From the results it was found that urine volume output is higher than the faecal mass output for all the schools regardless of the type of on-site sanitation system being used in the school. One of the primary factors contributing to higher urination output is the hydration practices among learners.

This is supported by the fact that a large majority of learners at 83% reported consuming sufficient fluids (water, juice, tea, etc.) before and throughout the school hours, as illustrated in Figure 4.1. as stated above, fluids intake directly affect the urine output and adequate hydration is essential for maintaining overall health and cognitive function. The disparities between urination and defecation output could be a result of unhygienic and inadequacy of the sanitation facilities within schools. Figure 4.2 depicts some of the factors that may lead to the less use of school sanitation facilities for defaecation. This information further suggests that learners may feel more comfortable using sanitation facilities at school for urination only compared to defaecation due to factors such as privacy concerns, cleanliness of facilities, bad odour, safety issues and availability of toilet supplies such as the toilet paper and some students may prefer to use sanitation facilities at home or may feel uncomfortable using school facilities for defaecation due to personal reasons. Again the low faecal mass may indicate that the current sizing and design of school toilets are adequate for the student population's needs. If students are exhibiting low faecal output during school hours, it may suggests that the existing toilet facilities are effectively accommodating their restroom needs without experiencing overcrowding or congestion.

4.1.3 Contributing factors

(i) Fluids and food intake before and during school hours

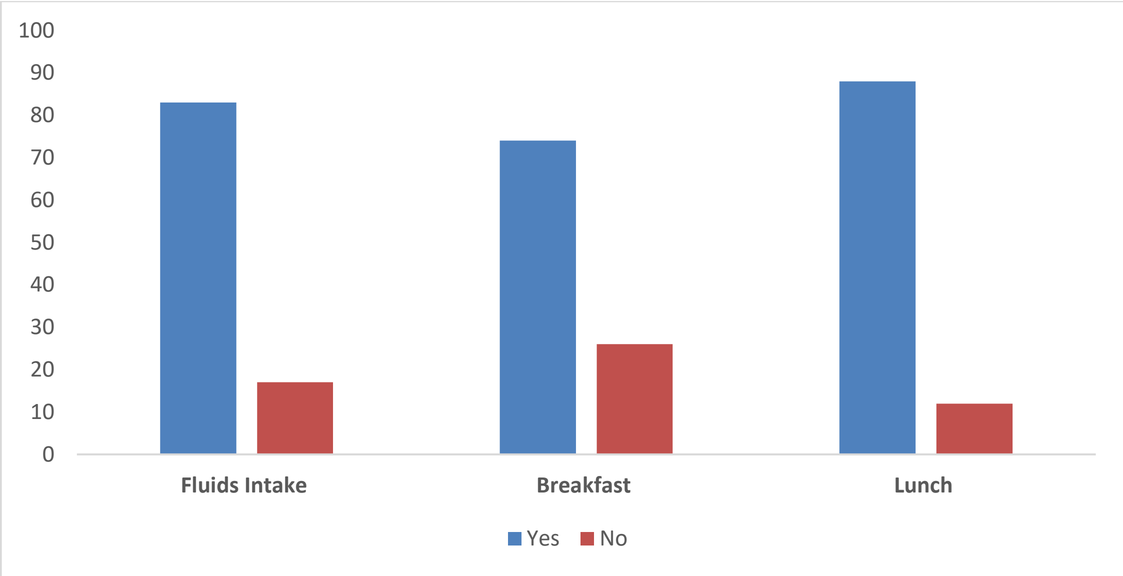

Figure 4.1: Results on fluids and food intake before and during school hours

Figure 4.1 illustrate outcomes on fluids and food intake of leaners before coming to school (i.e. breakfast) and during school hours (lunch). It was found that 83% of learners do take fluids whether water, juice, milk or any other beverages. The fluid intake directly impacts urine output as their bodies process and eliminate excess fluids through urine production. 74% of learners indicated to eat breakfast before coming to school and 88% indicated to eat lunch during school hours, though their diet was not inquired, the food intake, particularly the consumption of dietary fibre-rich foods like fruits and vegetables, influences faecal mass. Fiber adds bulk to stool, promotes regular bowel movements, and contributes to the formation of faecal matter.

(ii) School On-site sanitation systems conditions

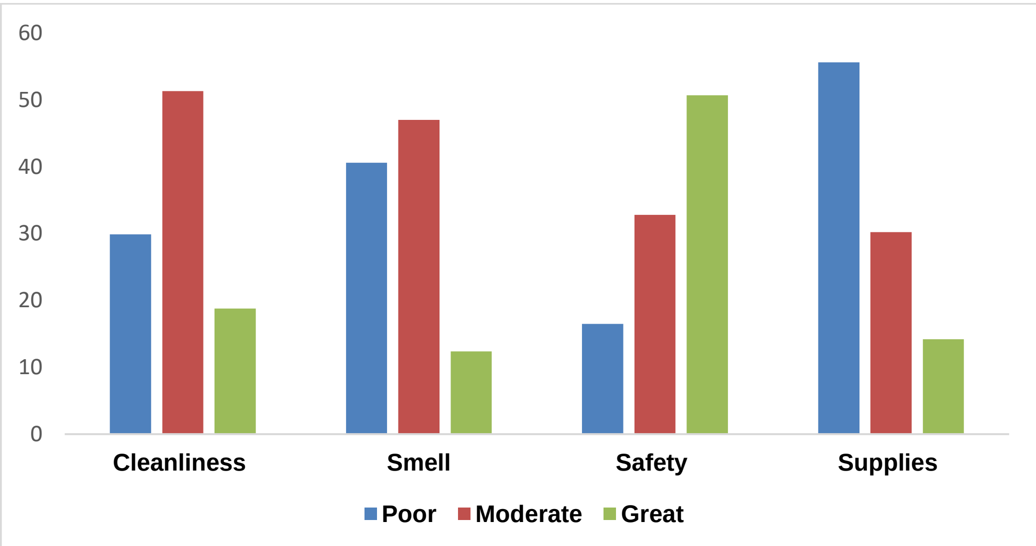

Figure 4.2: Results on the conditions of school on-site sanitation facilities

Figure 4.2 are findings from learners about their school sanitation systems that provide valuable insights into the cleanliness, smell, safety aspects and provision of sanitation supplies into these facilities. About 30% of the learners indicated that the sanitation facilities are poor when it comes to cleanliness, this indicates that a significant portion of students perceive the cleanliness of the sanitation systems to be unsatisfactory. Poor cleanliness levels may result from inadequate maintenance, lack of regular cleaning schedules, or insufficient hygiene practices among users. About half of the learners indicated a moderate rating which suggests that the sanitation systems are neither exceptionally clean nor notably dirty. However, there is room for improvement to enhance cleanliness standards and ensure a hygienic environment for students. A small portion of about 18% learners indicated an effective sanitation management practices, regular cleaning routines.

A large proportion of learners (41%) expressed dissatisfaction with the smell of the sanitation systems indicates a significant issue that needs to be addressed. Foul odours may stem from inadequate ventilation, improper waste disposal practices, or hygiene-related issues. 47% leaners gave a moderate ratings which suggest that while some students may not find the smell intolerable, there is still room for improvement in addressing Odor-related concerns

A notable percentage of learners (17%) rated the safety of sanitation systems as poor and this raises concerns about potential hazards or risks associated with these facilities. Safety issues may include slippery floors, broken fixtures, inadequate lighting, or insufficient security measures.

A significant majority (56%) of learners rated the provision of sanitation supplies as poor indicating a notable deficiency in the availability or accessibility of essential resources within the school sanitation systems like toilet paper. Insufficient provision of supplies like toilet paper can lead to discomfort, inconvenience, and potential hygiene-related issues for learners.

4.1.4 School toilet use

Table 4.3: School on-site sanitation facility usage

Toilets use	Pit latrines (N=205)	Septic tanks (N=669)	Mobile toilets (N=186)	p-value	Overall (N=1060)
No	0 (0.0%)	11 (1.6%)	2 (1.1%)	Chisq.	13 (1.2%)
Yes	198 (100.0%)	655 (98.3%)	184 (98.9%)		1037 (98.8%)
Urination and or defaecation				<0.001	
No use	0 (0.0%)	11 (1.6%)	2 (1.1%)	Chisq.	13 (1.2%)
Urination only	70 (34.1%)	462 (69.3%)	125 (67.2%)		657 (62.1%)
Urination/Defaecation	135 (65.9%)	194 (29.1%)	59 (31.7%)		388 (36.7%)

Table 4.3 illustrate the findings of the toilets use by learners in different schools across different on-site sanitation facilities. The toilet use by the learners influences the volumes of urine and faecal matter accumulation and therefore affects the filling rate of the on-site sanitation facility and emptying cycles. 98.8% of the learners indicated that they do use the school on-site sanitation

facilities provided, while only 1.2% indicated that they do not use the provided sanitation facilities at school.

The majority of learners (62,1%) reported using school toilets solely for urination. This finding suggests a prevalent preference among students to limit their school sanitation system for urination, possibly due to factors such as hygiene concerns, privacy considerations, or cultural norms. Students may feel more comfortable using the school sanitation systems for urination only and may seek alternative facilities for defecation.

A significant minority of leaners (36,7%) report using school toilets for both urination and defecation. This indicates that a considerable portion of students are comfortable using school facilities for all restroom needs. Factors influencing this choice may include convenience, accessibility, and perceptions of cleanliness and safety within the school sanitation systems.

Overall the findings highlight variations in hygiene practices and comfort levels among learners regarding use of school sanitation facilities. Learners who limit their use of these school sanitation systems to urination only may have specific preferences or concerns regarding cleanliness and privacy, while those comfortable using the restroom for all needs may prioritise convenience and accessibility. The learners usage patterns may reflect perceptions of sanitation facility conditions, including cleanliness, smell, and safety. School sanitation facilities that are well-maintained, adequately stocked, and hygienic are more likely to encourage students to use them for all needs, while poorly maintained facilities may deter learners from using them for defaecation

4.2 SECTION 2: CHARACTERISATION RESULTS

This section is divided into two parts where Part A demonstrate characterisation results for liquid fraction and Part B solid fraction characterisation results.

Part A: Characterisation results for liquid fraction

(i) Physico-chemical properties of liquid fraction

Parameters	Mobile toilets	Septic Tank	VIP latrine toilets
pH	7,80	7,11	8,74
EC(mS/cm)	11,88	4,23	36,70
Chemical Oxygen Demand (g/L)	12,51	10,61	19,49
Total Solids (mg/L)	0.035	0,015	0,016
Volatile solids (mg/L)	0,371	0,609	0,088
Total Suspended solids (mg/L)	0,474	0,264	0,136
Total Dissolved solids (mg/L)	0,483	0,177	0,463

(i) pH and EC

The effluent for VIP latrine toilets have the highest pH level, indicating alkaline conditions, whereas mobile toilets have a relatively neutral pH, and the septic tank falls in between. The alkalinity of VIP latrine toilets may be attributed to the presence of lime or other alkaline additives used for odour control and waste treatment. The VIP pH effluent is generally within an acceptable range for the effluent to be discharged into the environment without causing harm to the surrounding ecosystem. It is still important to properly treat and dispose of the effluent from VIP toilets to avoid contamination of nearby water sources and to ensure the safety and health of people who may come into contact with it. Mobile toilets and septic tanks generally have lower pH levels, which may be influenced by factors such as the composition of waste and microbial activity within the systems. Mobile toilets pH is within the range reported by Skorecki et al. (2016); Rose et al. (2015) and Guan et al. (2020). The pH of septic tanks is in the range of the reported septic tank FS, (Cofie et al., 2006 and Al-Sa'ed et al., 2006). VIP latrine toilets exhibit the highest electrical conductivity, indicating higher concentrations of dissolved ions and salts in the faecal sludge which could be a result of using of additives like lime or other chemicals, as well as the accumulation of dissolved solids from waste decomposition. Mobile toilets have moderate electrical conductivity, while the septic tank shows the lowest EC among the three systems.

(ii) Chemical Oxygen demand

The mobile toilets effluent exhibit COD value of 12.51 g/L which suggests a moderate level of organic pollutants. Mobile toilet effluent may contain a mix of organic waste, detergents, and other contaminants associated with human activity. The septic tank effluent exhibit COD value of 10.61 g/L which indicates a moderate level of organic pollutants as well. The wastewater from septic tanks contains human waste, toilet paper, and other organic materials. While septic tanks help in primary treatment, they still require periodic maintenance and may need further treatment before discharge. The VIP latrine toilets effluent exhibit COD value of 19.49 g/L which suggests a higher concentration of organic pollutants compared to mobile toilets and septic tanks. This could be due to factors such as longer retention times, higher usage rates, or different waste compositions in VIP latrines.

(iii) Solids Concentration

The total solids concentration in the effluent from mobile toilets suggests that the wastewater contains relatively few suspended or dissolved solids. This might be due to the nature of the waste being more liquid and less solid. The septic tank total solids concentration indicates a similar trend of relatively low suspended or dissolved solids as septic tanks usually settle solids before effluent is discharged, which could contribute to the lower total solids concentration. VIP latrines also show a low concentration of total solids, similar to septic tanks and mobile toilets.

The septic tank effluent has a higher concentration of volatile solids compared to mobile toilets and VIP latrines. This suggests a substantial amount of biodegradable organic matter in the wastewater, which may require further treatment to prevent environmental contamination. The relatively high concentration of volatile solids in the effluent from mobile toilets suggests a significant amount of organic matter that can be readily decomposed by microorganisms. This may indicate a higher content of faecal matter or organic compounds in the wasteway. The VIP latrine effluent has the lowest concentration of volatile solids among the three sanitation facilities. This may indicate a lower organic content or a higher degree of decomposition within the system.

The three on-site sanitation system exhibited lower TSS values which indicate better water clarity and less turbidity, which can be beneficial for downstream water bodies and ecosystems, however the TDS values indicate the presence of contaminants such as salts, heavy metals, and dissolved organic compounds, which may affect water quality and ecosystem health. This further suggests that proper treatment and management practices are still essential to mitigate the impact of effluent discharge on surrounding ecosystems and public health.

(iv) Nutrient Concentration

Parameters	Mobile toilets	Septic tanks	VIP latrine toilets
Total Nitrogen (mg/L)	282,50	554	1720
Total Phosphate (mg/L)	85,33	184	535
Total Potassium (mg/L)	775	297	553

The VIP system generally has the highest nutrient content (nitrogen, phosphate, and potassium) in its effluent compared to the mobile toilets and septic tank systems. The mobile toilets exhibit relatively high levels of potassium compared to the other systems. The septic tank system generally shows lower levels of nutrients compared to the VIP system but higher levels compared to the mobile toilets, indicating an intermediate level of nutrient concentration.

All three on-site sanitation systems contain sufficient levels of all three nutrients, making it suitable for agricultural use. However, it may require dilution or proper treatment to avoid nutrient imbalance and potential harm to plants due to excessive nutrient concentration, and high nitrogen content may require careful management to prevent environmental issues such as nitrogen runoff.

Part B: Characterisation results for solid fraction

(i) PHYSICO-CHEMICAL PROPERTIES

PARAMETERS	VIP Latrine Toilets	Mobile toilet	Septic Tanks
pH	8,45	7,27	5,88
EC (mS/cm)	30,58	2,33	30,70
Total Solids (TS) %	8,50	17,42	10,15
Total suspended solids (TSS) (mg/L)	3624,00	1123,89	733,62
Total dissolved solids (TDS) (mg/L)	1422,96	289,42	93,33
Chemical Oxygen Demand(COD) (g/L)	72,62	119,23	242,07
Water Activity (aw)	1,002	1,005	1,021
Calorific Content (MJ/kg)	18,37	23,24	18,90
Total Nitrogen (g/L)	2,83	9,65	2,72
Ammonia (g/L)	2,15	3,44	0,75
Total Potassium (g/L)	0,94	3,31	0,76
Total Phosphorus (g/L)	1,10	2,24	0,64

(a) pH and EC

The VIP latrine faecal sludge have a relatively alkaline pH, which could be attributed to factors such as the composition of the material used in the toilet, the presence of certain additives, or the nature of the waste deposited. VIP toilets often use lime or other alkaline agents to neutralize odours and facilitate decomposition, which can contribute to the alkaline pH of the faecal sludge. The pH of septic tank sludge is slightly acidic, which could result from the decomposition of organic matter by anaerobic bacteria within the tank. Anaerobic digestion processes in septic tanks generate acidic byproducts such as fatty acids, which can lower the pH of the sludge. The pH of mobile toilet sludge is closer to neutral, indicating a balance between acidic and alkaline components. Mobile toilets may have different waste compositions compared to VIP toilets and septic tanks, which could influence the pH of the sludge.

VIP toilets have a relatively high electrical conductivity compared to the other sanitation facilities, the elevated EC could be due to the presence of dissolved salts, organic matter, and other contaminants in the faecal sludge. Factors such as the use of chemicals, additives, and the composition of the waste deposited into VIP toilets can influence the conductivity of the sludge. The electrical conductivity of septic tank sludge is lower compared to VIP toilets but higher than mobile toilets. The lower EC suggests a lower concentration of dissolved ions and salts compared to VIP toilets. The anaerobic digestion process in septic tanks may contribute to the reduction of dissolved solids and ions in the sludge. The lower EC in mobile toilets indicates a lower concentration of dissolved ions and salts in the faecal sludge from mobile toilets. Mobile toilets may experience greater dilution due to the frequent emptying leading to lower EC values.

(b) Solids content

The TS content of faecal sludges was significantly different (P< 0,0001) from one on-site sanitation facility to the other, the mobile toilet sludge which was evidently a fresher faeces (due to weekly emptying of these facilities) exhibited the highest TS% (17,42%), supported by Rose et al. (2015) and Penn et al. (2018). This was followed by septic tank systems with average TS of 10,15% which is higher than the average TS of septic tanks as outlined by Velkushanova et al. (2021) (5%). The higher TS concentration of septic tanks could be a result of the reduced flush water entering the septic tank systems. Lastly, pit latrines exhibited a TS of 8,49% similar to Zuma et al. (2015) and Velkushanova. (2014). The septic tanks and VIP sludge can be classified as slurry sludge and can be easily pumpable using mechanised devices such as a vacuum truck and mobile honey wagon.. Results showed that all types of faecal sludge and faeces obtained from VIPs, MTs and STs illustrated a water activity from 0.95 to 0.99, which is considered high and conducive to microbial growth (Awasthi et al., 2020), comparable to studies by Samal et al. (2022) and, Strande & Brdjanovic (2014).

The highest TSS was observed from VIPs at 3,62 (g/L), similar to values reported by Jayathilake et al. (2019) and Junglen et al. (2020). Septic tanks and MTs exhibited a TSS of 733,61(mg/L) and 1123,89 (mg/L) respectively, this was within ranges reported by Koottatep et al. (2005); Junglen et al., (2020); Heinss et al. (1998) and Koné and Strauss (2004). A Similar trend was observed for TDS with VIPs illustrating the highest, followed by mobile toilets and septic tanks, fall findings were supported by Olatunji and Oladepo (2013) and Mbouendeu et al. (2022). In general the faecal sludges from the different on-site sanitation facilities demonstrated low TSS and TDS results which indicate a relatively high water content and a low concentration of organic matter, nutrients, and other contaminants. This can make the faecal sludge easier to handle, transport, and treat, as it may require less dewatering or thickening prior to treatment (Strande and Brdjanovic, 2014). Statistical results revealed that sanitation types were significantly different (P<0,001), for both TDS and TSS.

(c) Chemical Oxygen Demand (COD)

Highest COD was obtained from MTs 242,07 (g/L), followed by STs 119,23 (g/L), and VIPs 72,62 (g/L). Findings are comparable to studies by Elmitwalli et al. (2006); Heinss et al. (1998) Chaggu (2004); Coetzee et al. (2011) and Gaillard (2002). The high COD values from MTs are indicative of their “high strength” and low biodegradation (Rose et al., 2015). High COD of MTs sludge indicates a high concentration of organic matter, which can make the sludge more difficult to treat and require safe disposal methods (Cofie et al., 2006, Barrios-Hernández et al., 2020). Additionally, high COD levels in can lead to increased oxygen demand in the receiving water bodies or soil, potentially causing environmental problems such as eutrophication or oxygen depletion (Bai et al., 2019). To effectively treat and dispose of MTs sludge, which is high in COD, will require more advanced treatment methods such as anaerobic digestion, aerobic composting, or thermal drying. Hence, high-strength sludge is optimal for valorisation purposes, however, may require more pre-treatment prior to safe end-use and disposal. Whereas the opposite was observed from VIPs illustrating a lower strength indicating its lower organic content and a higher level of degradation and potentially making the sludge easier to treat and dispose of (Müller, 2000)

(d) Water Activity

The faecal sludge samples from different school sanitation facilities demonstrated a water activity of 1aw which is comparable to studies conducted by Amoah et al., 2018, Awuah et al., 2020 and Abebrese et al., 2018. This means that the faecal sludge samples can be considered to have high water activity and are more susceptible to microbial growth and decomposition, as the presence of water in faecal sludge provides an environment for microbial growth and metabolism, and the more water available, the higher the potential for microbial activity. Also, the faecal sludge contains a high concentration of organic matter, which can support microbial growth and metabolic activity. Microorganisms such as bacteria, viruses, and protozoa in faecal sludge require water to carry out metabolic processes and reproduce and as they grow and multiply, they consume nutrients and release metabolic by-products, which can further increase the water activity.

(e) Calorific Content

The faecal sludges from different on-site sanitation systems actively demonstrate a high calorific content of indicates that the sludges have a high potential for energy recovery (Septien et al., 2020). Mobile toilets sludge depicted the highest calorific content (23,24 MJ/kg), owing to the large quantity of organic material present in faeces compared to faecal sludge, comparable to (Speece, 2008) who outlined values between 23-29 Mj/kg. This was followed by septic tanks and pit latrines that depicted a calorific value of 18,90 MJ/kg and 18,37 MJ/kg respectively, comparable to studies by Muspratt et al. (2014) (16,2-19,1 MJ/kg). Calorific values for sludges were comparable to the values of coffee husk (16 MJ/kg); firewood (16 MJ/kg); saw dust (20 MJ/kg) and Charcoal (28 MJ/kg),(Diener et al., 2014). To recover energy from high-calorific faecal sludge, a variety of treatment methods can be used, including anaerobic digestion, pyrolysis, thermal drying, or incineration. These processes can generate heat or electricity that can be used for on-site energy needs or fed back into the grid. In addition to energy recovery, high-calorific faecal sludge can also be used as a soil amendment or fertilizer, as it can provide nutrients and organic matter to the soil.

(f) Nutrient properties

Fresher faeces from MTs illustrated the highest nutrient concentration in all parameters (Nitrogen, Ammonia, Potassium, and Phosphorus), indicative of its high strength. Subsequently , the lower nutrient concentration observed in STs, and VIPs can be a consequence of the larger volumes of flush systems entering the STs, diluting the nutrient concentration and a higher retention time faecal sludge is stored in VIPs (Rose, 2015, Rose et al., 2015). Nutrient concentration is essential for the reuse of faecal material as fertilizers, mobile toilets showed significantly larger concentrations of nutrients which could be harmful to the environmental, whereas more digested sludge illustrated concentrations more applicable for safe environmental discharge.

Mobile toilets consistently have higher levels of both total nitrogen and ammonia compared to VIP toilets and septic tanks. VIP toilets and septic tanks generally show similar levels of total nitrogen and ammonia, although the concentrations are slightly higher in VIP toilets. The absence of efficient treatment processes in mobile toilets could contribute to the retention of nitrogenous compounds, leading to higher total nitrogen and ammonia levels. The slight differences in nitrogen concentrations of VIP and septic tanks could be influenced by factors such as additives, microbial activity, and environmental conditions within each system. The correlation between total nitrogen and ammonia levels suggests that a significant portion of the nitrogen in the faecal sludge exists in the form of ammonia, which is consistent across the sanitation facilities

(ii) MECHANICAL PROPERTIES

On-site Sanitation Type	Density (g/cm³)	Shear Yield Stress (Pa)	PSA DV (50 μm)	DV(10 μm)	DV(90 μm)
Mobile Toilets	1,039	46,032	38,93	2,88	486,75
Septic Tanks	1,047	349,901	82,93	9,16	632,75
Pit Latrines	1,026	22,753	118,40	10,24	791,66

The densest faecal material was observed in fresh faeces from MTs, (1,047 g/cm^3), followed by VIP and ST sludge at am 1,039 g/cm^3 and 1,026 g/cm^3 respectively. All density values were within reported ranges outlined by Penn et al. (2018). Shear yield stress was used to determine the shear force needed for the initial flow to move. Aged faecal sludge from Septic tanks required the highest yield stress needed to initiate flow at 349,90 Pa, this was followed by Pit Latrines and fresh faeces. Results were within ranges reported by Mercer et al. (2021) and (Septien et al., 2018). PSA for Dv (50μm) was 82,93; 38,93 and 118,40 for septic tanks, mobile toilets, and pit latrines respectively. This explains that particle size was greatest from septic tank sludge. Overall PSA depicted a range of 0,76-3500 μm; 0,594-500 μm and 0,675-3500 μm, for VIPs, MTs, STs.

(iii) THERMAL PROPERTIES

Sample name	Thermal Conductivities	Heat Capacity (J/kg/K)
VIP latrine toilets	0,59	3248,00
Mobile toilet	0,52	3416,24
Septic Tanks	0,57	3227.75

(a) Thermal Conductivity and heat capacity.

Thermal conductivity from all sanitation systems showed minimal variation which ranged between 0,51-0,58 (W/m.K). Findings for thermal conductivity are similar to those reported by Drechsel et al. (2003); Zuma et al. (2015) and Pandarum et al. (2019). The low thermal conductivity of sludge indicates that the sludge is an undesired characteristic for fuel, as it causes resistance to heat penetration within the solid (Septien et al., 2020). However, this property can also be beneficial in some applications, such as in the use of faecal sludge as a soil conditioner, where a low thermal conductivity can help to insulate the soil and retain moisture, or the use of sludge as a building material as it indicates the sludge has good thermal insulation characteristics. Heating capacity ranged from 3227,75 J/kg/K to 3416,24 across the three sanitation facilities Statistical results revealed that sanitation types were significantly different ($P<0,001$), for both thermal conductivity and heat capacity.

CHAPTER 5: DESIGN GUIDELINES

5.1 SIZING OF SCHOOL SANITATION FACILITIES

The sizing of school sanitation infrastructure in South Africa is critical to ensuring access to safe and adequate sanitation facilities for all learners. The South African Department of Basic Education (DBE) has developed guidelines for the design and construction of school sanitation infrastructure based on the number of learners in a school, the type of facility required, and the available budget. According to the DBE guidelines, the minimum requirement for school sanitation facilities in South Africa is one toilet per 25 learners for girls, and one toilet per 35 learners for boys. The facilities should also include separate urinals for boys and handwashing facilities for all learners. The guidelines also recommend that schools should provide at least one toilet and handwashing facility for learners with disabilities (DBE, 2010).

For appropriate size of sanitation facilities in school communities, it is important to consider the following factors:

- **Number of learners**: The number of learners in a school is the primary determinant of the size of the sanitation infrastructure required. Schools with larger enrolments require more facilities to meet the needs of all learners.

- **Age and gender of learners:** The age and gender of learners can influence the type of facilities required. Younger learners may require smaller and more child-friendly facilities, while older learners may require more private and adult-sized facilities.

- **Type of facility**: The type of facility required will depend on the needs of the school and the available budget. Schools can choose between various options, including flush or pit latrines, waterborne or non-waterborne sanitation systems, and handwashing facilities with or without running water. From the research conducted, it was found that the schools in rural communities mostly make use of pit latrines, septic tank systems and mobile toilets also known as container based sanitation systems.

- **Available space**: The available space on the school premises can influence the size and layout of the sanitation infrastructure. Schools with limited space may need to consider alternative designs, such as multi-story structures or shared facilities.

5.2 FS EMPTYING DESIGN GUIDLINE

The ideal performance criteria for faecal sludge emptying methods can be broadly categorized into three main areas: technical, social, and environmental. Technical criteria focus on the efficiency and effectiveness of the emptying method, while social criteria consider the impact of the method on the community and its acceptability. Environmental criteria focus on the impact of the method on the environment, particularly in terms of public health and water quality.

Technical Criteria:

- **Effectiveness:** The emptying method should be effective in removing the maximum amount of sludge from the pit, leaving it empty or with a minimum of residual sludge. The method should be able to remove sludge from pits of varying depths, widths, and conditions.
- **Efficiency:** The faecal sludge emptying method should be efficient in terms of time, cost, and energy. The method should be able to empty the containment system quickly and without excessive labour or equipment costs. The energy consumption of the method should also be minimal.
- **Safety:** The emptying method should be safe for the workers involved in the process, as well as for the community around the pit. The method should minimize the risk of injury, disease transmission, and environmental contamination.
- **Scalability:** The faecal sludge emptying method should be scalable to meet the needs of the community. The method should be able to handle large volumes of faecal sludge and be adaptable to a range of containment systems.
- **Maintenance:** The faecal sludge emptying method should be easy to maintain. The equipment used should be simple and easy to repair. The method should also be able to operate reliably with minimal maintenance

Social Criteria:

- **Acceptability:** The emptying method should be acceptable to the community, taking into account cultural and religious practices. The method should not cause offense or discomfort to the community, and should be conducted with respect for their dignity and privacy.

- **Accessibility:** The emptying method should be accessible to all members of the community, regardless of their income or location. The method should be affordable and the service provider should be able to reach even the most remote or marginalized communities.

Environmental Criteria:

- **Public health:** The emptying method should not pose a risk to public health, either through direct exposure to faecal sludge or through contamination of water sources. The method should comply with international and national standards for public health and sanitation.
- **Water quality:** The emptying method should not have a negative impact on water quality, either by polluting surface or groundwater sources. The method should prevent the release of untreated faecal sludge into the environment, and ensure proper disposal or treatment.

Economic criteria:

- **Affordability**: It is essential to ensure that faecal sludge emptying services are affordable for both service providers and users. Affordability considerations include the pricing structure, payment mechanisms, subsidies, and financing options to make the service accessible to all income groups.
- **Revenue generation**: Faecal sludge emptying services can generate revenue through service fees, tariffs, or taxes. Establishing appropriate pricing mechanisms helps recover operational costs, maintain service quality and equipment.

Emptying decision Matrix

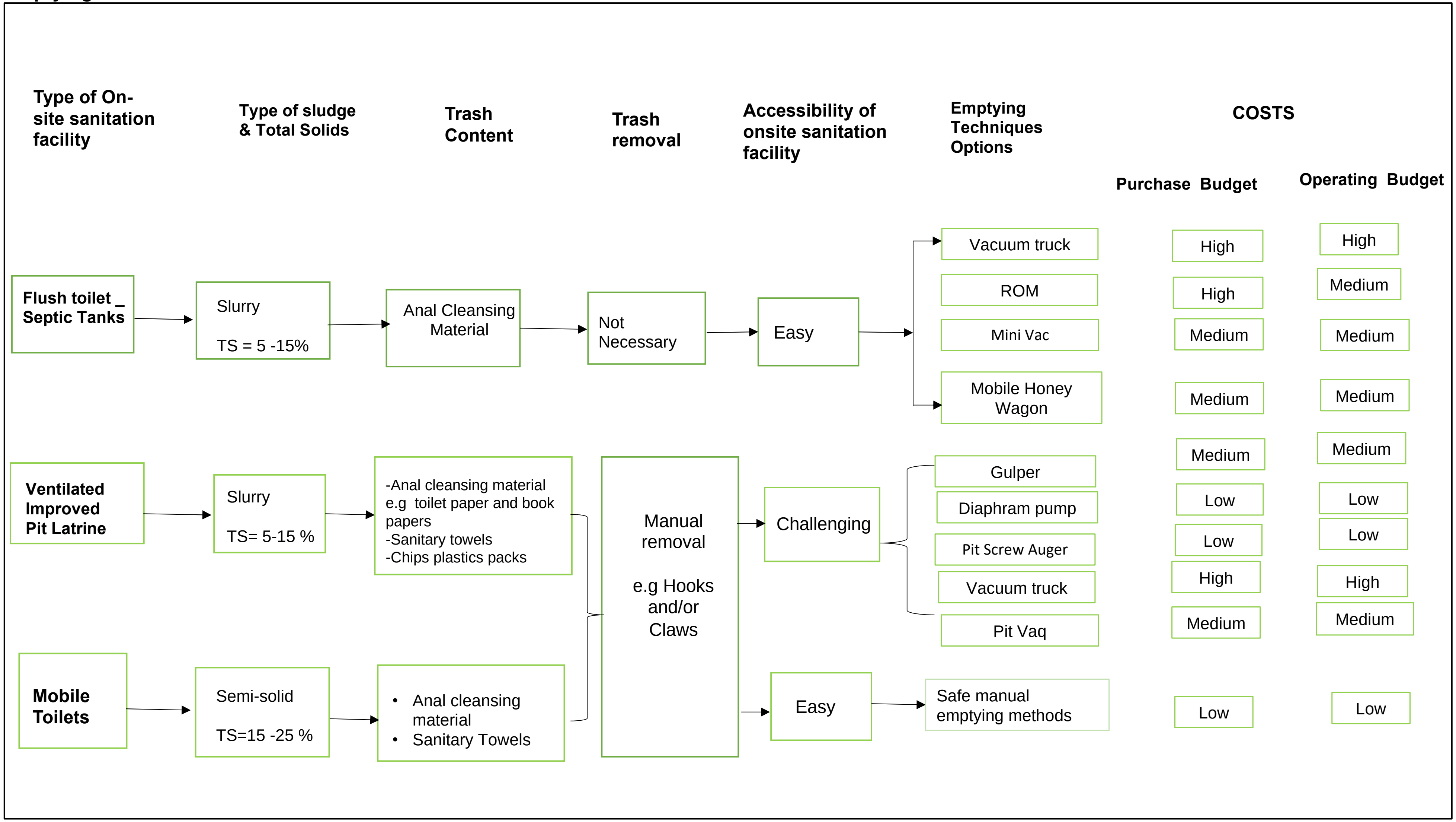

Figure 5.1: Emptying decision matrix

5.3 EMPTYING DECISION MATRIX

Figure 5.1 illustrate FS emptying matrix for rural school on-site sanitation facilities, where the on-site sanitation facilities were ventilated improved pit latrines, septic tanks, and mobile toilets. The emptying matrix was designed based on the characteristics of the faecal sludge (presented in the previous report) within the facilities.

5.3.1 Type of sludge

Septic tanks and VIP latrine sludge exhibited total solids at a range between 5-15% which was then classified as a slurry sludge. The mobile toilets exhibited a more solid fresh faecal sludge with total solids ranging between 15-25% and therefore classified as semi-solid

5.3.2 Trash content and trash removal

Trash removal in school toilets is an important aspect of sanitation and hygiene management. Proper trash removal ensures that the sanitation facilities function effectively and prevents blockages and other issues that could cause health hazards.

- Most schools visited did not have waste bins provided in the sanitation facilities for solid waste such as sanitary pads and other non-biodegradable materials.
- For school VIP latrines and mobile toilets the trash content found included the anal cleansing material toilet paper and book papers and the sanitary towels. For this systems it is recommended that manual removal of the trash content be carried out before the emptying takes place. The manual trash removal tools include hooks and claws.
- Septic tanks had little to nothing visibility of trash, all that was observed during the sample collection was small pieces of toilet paper and that was considered negligible.

⇒ The schools should provide separate trash bins for solid waste such as paper, sanitary pads, and other non-biodegradable materials. These bins should be placed in convenient locations within the latrine, and students and staff should be encouraged to use them regularly. The trash should be emptied regularly and disposed of properly in designated waste disposal sites.

⇒ Schools should educate students and staff on proper waste disposal practices to prevent littering and the dumping of trash in the latrine. This education can include posters and signs in the latrine and classroom areas, as well as classroom discussions and awareness campaigns.

5.3.3 Accessibility to the sanitation site

Accessibility in emptying on-site sanitation systems refers to the ease and ability of sanitation workers or service providers to access and safely remove human waste from sanitation facilities. It involves physical access. Overall the sanitation systems were located in a place that is easy to reach by service vehicles or equipment. For all the sanitation systems in all the schools the roads, pathways, and entrances leading to the facility were clear of obstacles and accessible to vehicles.

- The septic tanks and mobile toilets and had easy access to the site and during collection of the faecal content.
- VIP in schools had easy access to the site however a challenging access in terms of collecting the samples, a specialized equipment may be required to open them for emptying as some were sealed with concrete at the back-end.

5.3.4 Emptying technique options

Based on the sludge characteristics for each on-site sanitation system, emptying technologies/devices were recommended.

- For Septic tanks systems have a slurry sludge and therefore the recommended emptying technique mostly are the fully mechanised technologies. These include the vacuum truck, ROM, mini vac and mobile honey wagon.
- The VIP latrines also have a slurry faecal sludge, however due to the challenging access to the emptying area manually operated mechanical devices were recommended. These devices include gulper, pit screw Auger and diaphragm pump. Additionally pit vaq and vacuum truck can be used on these systems as they can easily suck the slurry sludge, however they will need sufficient length of the suction hose.
- Mobile toilets consist of a thicker sludge and therefore require safe manual emptying. Manual emptying involves the use of buckets or shovels to remove the sludge and transport it to a disposal site. This method is labour-intensive and has the potential to pose health risks to workers due to direct contact with faecal matter, however wearing a full PPE is recommended as it will reduce contact with the sludge.

5.4 IDEAL PERFORMANCE CRITERIA FOR FAECAL SLUDGE TREATMENT METHODS

Faecal sludge treatment is a critical process that involves the removal of pathogens, pollutants, and other contaminants from human waste before disposal or reuse. The ideal performance criteria for faecal sludge treatment methods can vary depending on factors such as the location, regulations, and specific objectives of the treatment. Faecal sludge treatment methods are critical in ensuring the safety of the environment and public health. The performance of these methods is evaluated based on different criteria to ensure that they meet the desired standards. Here are the ideal performance criteria for faecal sludge treatment methods:

- **Pathogen reduction**: The primary objective of faecal sludge treatment is to reduce the concentration of pathogens to a level that is safe for human contact and the environment. The ideal performance criteria for pathogen reduction is a minimum of 4 log reduction of helminth eggs and E. coli. This criterion is based on the World Health Organization (WHO) guidelines for safe reuse of wastewater, excreta, and greywater (WHO, 2006).
- **Nutrient recovery**: Faecal sludge contains essential nutrients such as nitrogen, phosphorus, and potassium that can be recovered and reused as fertilizer. The ideal performance criteria for nutrient recovery is the ability to recover at least 50% of the total nitrogen and phosphorus content of the faecal sludge (Strande et al., 2014).
- **Energy recovery**: Faecal sludge treatment methods should be designed to recover energy in the form of biogas or other forms of renewable energy. The ideal performance criteria for energy recovery is the ability to generate at least 0.3 m^3 of biogas per kg of total solids in the faecal sludge (Eawag, 2017).
- **Odour control:** Faecal sludge treatment methods should be designed to control odours that may arise during the treatment process. The ideal performance criteria for odour control is the ability to reduce the odour emission by at least 80% (Tchobanoglous et al., 2014).
- **Robustness and reliability**: Faecal sludge treatment methods should be designed to be robust and reliable, even under adverse conditions. The ideal performance criteria for robustness and reliability is the ability to maintain a stable operation and achieve the desired treatment outcomes with minimal maintenance and intervention (Tilley et al., 2014).
- **Cost-effectiveness**: Faecal sludge treatment methods should be cost-effective to ensure their affordability and sustainability. The ideal performance criteria for cost-effectiveness is the ability to achieve the desired treatment outcomes at a reasonable cost that is affordable for the end-users (Blackett et al., 2015).
- **Operational Efficiency:** Faecal sludge treatment methods should be designed to operate efficiently and effectively without requiring a significant amount of resources or manpower. The ideal performance criteria for operational efficiency would depend on the size of the treatment plant and the available resources, but a high level of automation and minimal maintenance requirements are generally desirable.
- **Scalability**: Faecal sludge treatment methods should be designed to scale up or down depending on the needs of the community. The ideal performance criteria for scalability would depend on the size of the community and the expected growth rate, but a flexible design that can easily be expanded or downsized is generally desirable.
- **Environmental Impact:** Faecal sludge treatment methods should be designed to minimize their environmental impact. The ideal performance criteria for environmental impact would depend on

the specific objectives of the treatment and the local regulations, but a low carbon footprint and minimal discharge of pollutants are generally desirable.

Overall, the ideal performance criteria for faecal sludge treatment methods should prioritize the removal of pathogens and pollutants while minimizing the environmental impact and operational costs. The specific performance criteria would depend on the local regulations and objectives of the treatment, but a high level of efficiency, scalability, and flexibility are generally desirable. Table 5.1 below illustrates some ideal performance criteria for the recommended FS treatment technologies applicable to rural areas.

Table 5.1: **Ideal performance criteria for FS treatment methods**

Parameters	Unplanted drying bed	Planted drying beds	Biogas Digesters (Anaerobic Digestion)	Pyrolysis for Biochar Recovery	Composting	Deep row entrenchment	Constructed Wetlands	Composting toilets
TS (% dry mass)	2-10%	2-10%	3-20%	70%	20-30%	5-25%	3-8%	60-90%
VS (%)	50-60%	~ 50%	60-80%	60-70%	60-70%	~ 50-60%	-	30-70%
TSS (mg/L)	1000-1500	500-1000	2000-8000	1000-5000	2000-6000	1000-2000	100-500	-
COD (mg/L)	-	-	5000-15000	500-1500	2,000-4000	3000-5000	50-300	-
C:N	20:1-30:1	20:1-30:1	25:1 to 30:1	20:1-30:1	25:1	20:1-30:1	-	25:1-35:1
Total Nitrogen (mg/L)	500-3000	500-3000	1000-5000	500-3000	500-3000	500-3000	5-20	5-15
Total Potassium (mg/L)	200-1000	200-1000	200-1000	200-1000	200-1000	200-1000	10-50	10-30
Total Phosphorus	200-1000	200-1000	200-1000	200-1000	200-1000	200-1000	3-20	3-15
Ammonia	100-1000	100-1000	100-1000	100-1000	100-1000	100-1000	1-10	2-20
pH	6-7.5	6-7.5	6.5-7.5	6-7.5	6-7.5	6-7.5	6.5-8	5.5-8.5

References: Mihelcic et al., 2011; Karanth et al., 2013; Strande et al., 2014; Tilley et al., 2014; Fidjeland, J., & Jönsson, H. 2015; Strauss et al., 2017; Gensch et al., 2018; Gajurel et al., 2018; Lungali, 2019; Yacob et al., 2018; Krueger et al., 2020

Table 5.2: Treatment matrix for VIP Pit latrine toilets

Parameters	Legend	Selection criteria	Unplanted drying bed	Planted drying bed.	Anaerobic Digestion	Pyrolysis for Biochar Recovery	Vermi-composting	Composting	Solar Drying	Deep row entrenchment	Constructed Wetlands	Composting Toilets
TS (%total mass)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	2	2	1	1	1	1	1	2	1
VS (%)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	2	1	1	2	2	-	2	1	-
TSS concentration (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	1	1	1	2	2	-	1	1	-
COD (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	1	-	1	1	-	1	1	1
Nutrient Concentrations Nitrogen (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	1	2	-	2	1	-	1	1	1
Nutrient concentration: Ammonia (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	-	2	-	2	2	-	1	1	1
Nutrient Concentration: Potassium (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	1	-	-	2	1	-	1	1	1
Nutrient Concentration: Phosphorus (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	-	-	2	1	-	1	1	1
C: N	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	1	-	1	1	-	1	-	2
pH	0 1 2	Not Suitable Suitable after pre-treatment Suitable	2	2	2	2	2	2	2	2	2	2
Performance dependency			**6/10 60%**	**12/18 66,6%**	**12/16 75%**	**5/8 63%**	**17/20 85%**	**14/20 70%**	**3/4 75%**	**12/20 60%**	**11/18 61%**	**10/16 63%**

Table 5.3: Treatment Matrix for Septic tank systems

Parameters	**Legend**	**Selection criteria**	**Unplanted drying bed**	**Planted drying bed.**	**Biogas Digesters (Anaerobic Digestion)**	**Pyrolysis for Biochar Recovery**	**Vermi-composting**	**Composting**	**Solar Drying**	**Deep row entrenchment**	**Constructed Wetlands**	**Composting Toilets**
TS (%total mass)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	2	2	1	1	1	1	1	1	0
VS (%)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	2	2	2	1	-	2	-	0
TSS concentration (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	2	2	2	2	2	2	-	2	1	-
COD (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	1	-	1	1	-	1	1	-
Nutrient Concentrations Nitrogen (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	1	2	-	2	1	-	1	1	1
Nutrient concentration: Ammonia (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	2	-	2	2	-	2	1	1
Nutrient Concentration: Potassium (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	-	-	-	2	2	-	1	1	1
Nutrient Concentration: Phosphorus (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	-	-	2	1	-	1	1	1
C: N	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	1	-	1	1	-	1	-	1
pH	0 1 2	Not Suitable Suitable after pre-treatment Suitable	2	2	2	2	2	2	2	2	2	2
Performance dependency			**7/10** **70%**	**12/18** **66,6%**	**14/16** **87,5**	**7/8** **87,5%**	**17/20** **85%**	**14/20** **70%**	**3/4** **75%**	**14/20** **70%**	**9/16** **56%**	**7/12** **58%**

Table 5.4: Treatment matrix for mobile toilet faecal sludge

Parameter	Legend	Selection criteria	Unplanted drying bed	Planted drying bed.	Biogas digesters (Anaerobic Digestion)	Pyrolysis for Biochar Recovery	Vermi-composting	Composting	Solar Drying	Deep row entrenchment	Constructed Wetland	Composting Toilets
TS (%total mass)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	2	2	1	1	1	1	1	1	0
VS (%)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	2	1	2	1	-	2	-	-
TSS concentration (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	2	2	2	2	2	2	-	2	1	-
COD (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	1	-	1	1	-	1	1	-
Nutrient Concentrations Nitrogen (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	1	1	-	1	1	-	1	1	
Nutrient concentration: Ammonia (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	-	2	-	1	1	-	1	1	1
Nutrient Concentration: Potassium (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	1	1	-	-	1	1	-	1	1	1
Nutrient Concentration: Phosphorus (mg/L)	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	-	-	1	1	-	1	1	1
C: N	0 1 2	Not Suitable Suitable after pre-treatment Suitable	-	1	1	-	1	1	-	1	-	2
pH	0 1 2	Not Suitable Suitable after pre-treatment Suitable	2	2	2	2	2	2	2	2	2	2
Perfomance dependency			**7/10 70%**	**12/18 66,6%**	**13/16 81,3%**	**6/8 75%**	**13/20 65%**	**12/20 60%**	**3/4 75%**	**13/20 65%**	**9/16 56%**	**7/10 70%**

5.5 FAECAL SLUDGE TREATMENT MATRIX

The specific treatment technologies presented in the treatment pathways (decision matrices) were selected on applicability to sanitation facilities used in rural areas. Treatment technologies selected included physical, thermal and biological and were selected based on their low in cost, easy to operate, low energy requirement and exhibited minimal skill for operation were selected.

Table 5.2 to Table 5.4 provides a decision matrix determining the treatment pathway for faecal sludge from rural school sanitation facilities. The tool is based on the analysed faecal material characteristics from mobile toilets, septic tanks and VIP pit latrines toilets. The scoring ranged from 0-2 where 0 indicates not suitable; 1 suitable after pre-treatment and 2 indicates suitable.

Characteristics of the different faecal material from school on-site sanitation facilities, were compared to optimal performing criteria of treatment technologies, based on literature and case studies. Based on the studied characteristics, aspects to consider for optimal FS treatment involves initially pre-treating the FS. The type of pre-treatment is specific to desired outcomes of the treatment and quality of FS. The mobile toilets sludge exhibited the highest-strength faeces, with high concentrations of chemical and physical properties, followed by septic tanks and pit Latrines that exhibited more stabilised faecal content, and lower chemical concentrations.

5.5.1 PHYSICAL TREATMENT

The physical treatment technologies under analysis for these on-site sanitation facilities include unplanted drying beds (UPDBs), planted drying bed (PDBs), solar drying, deep row entrenchment (DRE), constructed wetlands and urine diversion dry toilets.

For the treatment of VIP, septic tank and mobile toilet sludge the tested parameters suggest that these sludges require a pre-treatment process step before they are loaded into the unplanted drying beds (UPDBs), planted drying bed (PDBs), and for deep row entrenchment (DRE) and solar drying. In some treatment processes this is without altering the pH, TSS or TS as it is within the required specifications.

The treatment efficiency of unplanted drying beds for mobile toilet sludge and septic tanks (70% efficiency) suggests that these beds can effectively remove a significant portion of the solids and pathogens present in the sludge. VIP latrines produce faecal sludge that may have lower solids content and higher liquid content compared to mobile toilets and septic tanks, the slightly lower treatment efficiency (60%) for VIP latrine sludge suggests that unplanted drying beds may be somewhat be less effective in treating sludge from VIP latrines compared to septic tanks and mobile toilets.

The three on-site sanitation systems exhibited same treatment efficiency of 66,6%, however the planted drying beds are well-suited for treating faecal sludge from septic tanks. The solid content of septic tank sludge facilitates the dewatering process, and drying beds can effectively remove pathogens and solids through natural processes. Faecal sludge from mobile toilets typically contains higher solid content, however planted drying beds can effectively treat faecal sludge from mobile toilets, albeit with some limitations. The higher solid content may pose challenges in the dewatering process, and additional pre-treatment measures might be necessary to optimise the efficiency of drying beds. Faecal sludge from VIP latrines have lower solid content and higher liquid content compared to septic tanks, the planted drying beds can still be effective in treating faecal sludge from VIP latrines, although additional considerations may be needed to address the higher liquid content. Performance dependency on drying beds for VIP latrines requires careful attention to design parameters such as bed sizing, drainage, and retention time to ensure efficient dewatering and treatment of the sludge.

Solar drying demonstrates consistent performance across different on-site sanitation systems, achieving a performance dependency of 75% for treating faecal sludge from mobile toilets, VIP latrines, and septic tanks. The effectiveness of solar drying is attributed to its ability to harness solar energy to promote evaporation and decomposition processes, resulting in significant reduction in pathogens and moisture content in the treated sludge. The performance dependency of 75% suggests that solar drying can achieve significant reduction in pathogens and moisture content in the sludge from VIP latrines, septic tanks and mobile toilets making it a sustainable treatment option for decentralised sanitation systems in rural areas.

Deep row entrenchment demonstrates variable performance across different on-site sanitation systems, with slightly higher efficiencies observed for septic tanks compared to mobile toilets and VIP latrines. The performance dependency of 70% indicates that deep row entrenchment can achieve substantial reduction in pathogens and organic matter in the sludge from septic tanks, making it a viable treatment option for decentralised sanitation systems. The performance dependency of 65% for mobile toilets suggests that deep row entrenchment can achieve significant reduction in pathogens and organic matter in the sludge from mobile toilets, making it suitable for environmentally friendly disposal or reuse. The performance dependency of 60% for VIP latrine toilets suggests that while deep row entrenchment can achieve some reduction in pathogens and organic matter in the sludge from VIP latrines, additional measures may be needed to optimize treatment efficiency. The constructed wetlands demonstrate relatively similar performance across different on-site sanitation systems, with slightly higher efficiencies observed for VIP latrines compared to mobile toilets and septic tanks. Constructed wetlands are a viable treatment option for faecal sludge from mobile toilets, septic tanks, and VIP latrines, with relatively consistent performance across different sanitation systems.

5.5.2 THERMAL TREATMENT

The thermal treatment processes considered in this work are pyrolysis for biochar recovery. Pyrolysis demonstrates variable performance across different on-site sanitation systems, with the highest efficiency observed for septic tanks, followed by mobile toilets and VIP latrines. The high performance dependency of 87.5% and 75% for septic tanks and mobile toilets indicate that pyrolysis can achieve substantial reduction in pathogens, organic matter, and other pollutants in the sludge from septic tanks, making it a highly effective treatment option for decentralized sanitation systems. The performance dependency of 63% suggests that while pyrolysis can achieve some reduction in pathogens, organic matter, and other pollutants in the sludge from VIP latrines, its efficiency may be slightly lower compared to septic tanks.

5.5.3 BIOLOGICAL TREATMENT OPTIONS

The biological treatment processes considered in this work include biogas digesters (anaerobic digestion) , composting, vermicomposting, septic tanks and composting toilets.

Anaerobic digestion demonstrates high and relatively consistent performance across different on-site sanitation systems, with the highest efficiency observed for septic tanks, followed by mobile toilets and VIP latrines. The high performance dependency across the on-site sanitation systems indicates that anaerobic digestion can effectively treat faecal sludge from all these systems by breaking down organic matter in the absence of oxygen, producing biogas and a stabilized sludge residue and achieve substantial reduction in pathogens, organic matter, and other pollutants in the sludge.

Both composting and vermin-composting demonstrates relatively similar performance across different on-site sanitation systems, with consistent efficiencies observed for septic tanks and VIP latrines, and slightly lower efficiency for mobile toilets. Overall composting and vermi-composting are viable treatment option for faecal sludge from mobile toilets, septic tanks, and VIP latrines, resulting in the production of compost with consistent and relatively high performance across different sanitation systems.

Composting toilets show variable performance across different on-site sanitation systems, with higher efficiency observed for mobile toilets and VIP latrines compared to septic tanks. composting toilets are a viable treatment option for faecal sludge from mobile toilets, septic tanks, and VIP latrines, with variable performance across different sanitation systems. Proper design and operational practices are crucial for maximising treatment efficiency and achieving satisfactory treatment outcomes.

5.6 TREATMENT MATRIX FOR THE LIQUID FRACTION

Treating the liquid fraction of faecal sludge in on-site sanitation systems is important for protecting public health, conserving natural resources, and reducing the environmental impact of sanitation systems. It also allows for the recovery of valuable nutrients and helps to control odours. Table 5.3 illustrate treatment options for effluent in septic tanks, mobile toilets and school VIP latrine systems.

Table 5.3: effluent treatment methods

	Constructed Wetland	**Activated sludge**	**Waste stabilization Ponds**
Objective	• Reduce TSS& TDS • Nitrification	• Reduce BOD • Reduce pathogens • Nutrient removal • Nitrification	• Solid-Liquid separation • Pathogen reduction
Input	Effluent	Effluent	Effluent & Sludge
Output	Treated Effluent Biomass	Treated Effluent Sludge	Effluent Sludge
Energy requirement	+	+++	+++
Space requirement	++	+	+++
Technical Complexity	++	+++	++
Applicable Level/Scale	+Household ++Neighbourhood ++City	+Neighbourhood ++City	+Neighbourhood ++city

Legend:
+ Low
++ Medium
+++ High

5.6.1 Constructed Wetlands as treatment for effluent

Constructed wetlands for treating effluent from septic tanks typically require moderate to large land areas, depending on factors such as the volume of effluent to be treated, hydraulic loading rates, and treatment objectives. Constructed wetlands generally have low energy requirements since they rely on natural processes such as gravity flow, plant uptake, and microbial activity for treatment.
Constructed wetlands for septic tank effluent treatment can be relatively straightforward in terms of design and operation. However, proper consideration of factors such as hydraulic loading rates, vegetation selection, and soil characteristics is essential to ensure effective treatment.
Constructed wetlands for treating effluent from mobile toilets typically require smaller land areas compared to septic tank effluent treatment, as the volume of effluent is usually lower. However, space requirements still depend on factors such as the number of toilets served and treatment objectives. Similar to septic tank effluent treatment, the energy requirement for constructed wetlands treating effluent from mobile toilets is generally low. Energy is mainly used for pumping effluent to

the wetland if necessary. Constructed wetlands for mobile toilet effluent can be less complex compared to septic tank effluent treatment due to the smaller scale and relatively uniform characteristics of the effluent.

The space requirement for constructed wetlands treating effluent from VIP latrines may vary depending on factors such as the number of latrines served and effluent volume. The space requirement can be similar to or smaller than the space requirement for septic tank effluent treatment. Energy requirements are typically low for constructed wetlands treating effluent from VIP latrines, similar to other types of effluent. Constructed wetlands for VIP latrine effluent treatment may be less complex compared to septic tank effluent treatment, especially if the effluent is relatively well-decomposed and less concentrated.

5.6.2 Activated sludge as treatment for effluent

Activated sludge systems typically require less space compared to constructed wetlands for treating effluent from any source of on-site sanitation system. However, the exact space requirement depends on the volume of effluent. Overall activated sludge systems offer a more compact footprint compared to constructed wetlands but require higher energy inputs due to aeration requirements. The technical complexity of activated sludge systems is higher compared to constructed wetlands, but they offer effective treatment of various types of effluent from septic tanks, mobile toilets, and VIP latrines.

5.6.3 Waste stabilisation ponds

The waste stabilization ponds offer a relatively simple and low-energy treatment option for various types of effluent, including those from septic tanks, mobile toilets, and VIP latrines. However, they generally require larger land areas compared to other treatment methods such as activated sludge systems and constructed wetlands.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

The process of eradicating unsafe sanitation facilities in rural schools is a critical endeavour that requires a comprehensive and multi-faceted approach. Firstly, the discrepancy between low faecal mass and urine volume prompts reflection on learner's sanitation system habits and the underlying factors influencing their preferences. Understanding why a significant portion of learners primarily use the school toilets for urination only calls for deeper exploration into concerns related to cleanliness, privacy, safety and provision of supplies such as toilet paper. Addressing these concerns requires collaborative efforts among school administration, staff, learners, and relevant stakeholders to foster a supportive and inclusive school sanitation environment that accommodates diverse needs and preferences. Secondly, it is time that schools adopt innovative approaches into their on-site sanitation facilities, to combat issues of bad odour and safety issues, approaches that prioritise cleanliness, comfort, and learner's well-being. This may include exploring innovative toilet design solutions that prioritize hygiene, safety, and user comfort.

The results on the characterisation of faecal matter and effluent from school on-site sanitation systems is crucial for enhancing the design and functionality of school sanitation systems. This data further assist is selecting appropriate faecal sludge emptying methods and treatment pathways for beneficiation. Based on the characteristics the faecal sludge from septic tanks, the septic tank sludge was found suitable for emptying with devices such as vacuum truck, ROM and minivac, while VIP sludge is most suitable for emptying with devices such as pit vaq and gulper. The mobile toilets such was recommended for manual safe emptying and vacuum truck. The proper emptying of school sanitation facilities is essential for promoting a clean and healthy learning environment and for the proper functioning of these systems and the prevention of health hazards. It is further recommended that proper handling and disposal of sludge should be done by trained personnel and in compliance with local regulations and environmental standards.

Understanding faecal sludge as a resource rather than a waste is a paradigm shift that recognizes the potential value and opportunities associated with managing human waste. This perspective aligns with the principles of sustainable sanitation and the circular economy. For rural schools, where infrastructure and resources, technical expertise, and socio-economic conditions may be limited, it is essential to choose appropriate faecal sludge treatment methods that are practical, cost-effective, and sustainable. Such treatment methods include composting, biogas digesters, drying beds, septic tanks and deep row entrenchment. In terms of performance efficiency, these treatment methods were found to be viable treatment option for faecal sludge from mobile toilets, septic tanks, and VIP latrines, with variable performance across different sanitation systems and, however proper design and operational practices are crucial for maximising treatment efficiency and achieving satisfactory treatment outcomes.

The importance of treating the liquid fraction of faecal sludge is to reduce the risk of pathogen transmission and ensure public health. Another study by Schaub-Jones (2010) emphasizes the role of treating the liquid fraction of faecal sludge in nutrient recovery. According to the study, the liquid fraction of faecal sludge contains significant amounts of nitrogen and phosphorus, which are essential nutrients for plant growth. Treating the liquid fraction can help recover these nutrients, thereby reducing the dependence on chemical fertilizers and promoting sustainable agriculture. The effluent from each sanitation system exhibits variations in nutrient content. These variations could be attributed to factors such as the composition of waste, the microbial activity within the system, and the treatment processes employed (if any). Understanding the nutrient content of effluent is crucial for assessing its impact on the environment, especially concerning issues like eutrophication in water bodies and soil fertility. Proper treatment and management strategies should be implemented to mitigate any adverse effects associated with the discharge of nutrient-rich effluent into the environment

While the government is still in the process of eradication of VIP pit latrine toilets in rural schools, it is recommended that in their approaches they consider the use of urine diversion dry toilets (UDDTs), as UDDTs are suitable for water-scarce areas and can be used in decentralized systems. Also they separate urine from faeces, reducing odour and promoting easier management of both the faecal waste and urine. These systems are often simple to construct, making them feasible for rural schools. Secondly it is recommended that they consider the septic tanks with leachfields soakway, as these systems are simple and cost effective. Again they are suitable for smaller-scale systems, require less maintenance, and provide on-site treatment with minimal energy requirements. Lastly Septic tanks are suitable treatment mechanism for rural school as it require minimal day-to-day operation and maintenance. Periodic desludging or emptying is necessary to remove accumulated sludge. This low-maintenance characteristic is beneficial in rural areas where access to skilled technicians and maintenance resources may be limited.

Further considerations can be extracted from the South African Sanitation Technology Enterprise Programme (SASTEP) school sanitation project such as a New generator developed by the University of South Florida (USF) in the USA, with funding from the Bill and Melinda Gates Foundation. This innovative sanitation system was commercialised by WEC projects in South Africa and installed in an informal community in Soweto. This systems comes with benefits such as (i) ease of installation, (ii) non-sewered, (iii) rainwater harvesting, (iv) it treats the sludge using an anaerobic digester and further produce biogas; (v) water is recycled for reuse in the system though it can only be used for flushing and not drinking; (vi) it produces waste that is treated and is nutrient rich ideal for crop fertiliser.

APPENDIX A

Quantities of poop and pee in School On-site Sanitation

Instruction: Tick the applicable box and fill in the correct information on the provided space

1. **Identify as?**

   ○ Male

   ○ Female

   ○ Other

   ○ Rather not say

2. **Age**

3. **Do you drink water or juice before and during school hours?**

   ○ Yes

   ○ No

   ○ Sometimes

   ○ Other …………………………..

4. **Do you eat breakfast before school?**

   ○ Yes

   ○ No

   ○ Sometimes

   ○ Other ……………………………
5. **Do you eat during school hours?**

   ○ Yes

   ○ No

   ○ Sometimes

   ○ Other …………………………….
6. **Do you use school toilets?**

   ○ Yes

- ○ No
- ○ Sometimes
- ○ Other

7. What do you use school toilets for?

- ○ Urinating
- ○ Defecating
- ○ Urinating and defecating
- ○ Other

8. How many times <u>a day</u> do you urinate on school toilets?

9. How many times <u>a day</u> do you defecate on school toilets?

10. How many times would you say you urinate on school toilets weekly?

11. How many times would you say you defecate in school toilets weekly?

12. On a scale of 1 to 3, how would you rate the cleanliness of the school toilets

1. Poor	**2. Moderate**	**3. Great**

13. On a scale of 1 to 3, how would you rate the smell of the school toilets

1. Poor	**2. Moderate**	**3. Great**

14. On a scale of 1 to 3, how would you rate the safety of the school toilets

1. Not safe	**2. Moderate**	**3. Very safe**

15. **On a scale of 1 to 3, how would you rate the provision of toilet supplies such as soap, toilet paper**

1. Poor	2. Moderate	3. Great

Questionnaire For Care Takers and/or Cleaners

Quantities of poop and pee in School On-site Sanitation

1. **On a scale of 1 to 3, how would you rate the cleanliness of the school toilets**

1. Poor	2. Moderate	3. Great

2. **On a scale of 1 to 3, how would you rate the smell of the school toilets**

1. Poor	2. Moderate	3. Great

3. **On a scale of 1 to 3, how would you rate the provision of toilet supplies e.g. hand-washing soap, toilet paper**

1. Poor	2. Moderate	3. Great

4. **On a scale of 1 to 3 how would you rate the safety of the school toilets**

1. Not safe	2. Moderate	3. Very safe

5. **On average how many learners you would say use the toilets daily**

Girls:	Boys:

6. **On average how many learners you would say use the toilet for urinating?**

Girls:	Boys:

7. **On average how many leaners you would say use the toilet for defecating?**

Girls:	Boys:

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