DEEP ROW ENTRENCHMENT OF FAECAL SLUDGE IN SMALL TOWNS IN UGANDA

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LIST OF ABBREVIATIONS AND ACRONYMS

BOD_5	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DEFAST	Decentralized Faecal Sludge Treatment
DRE	Deep Row Entrenchment
FS	Faecal Sludge
ft	Feet
FSTPs	Faecal Sludge Treatment Plants
l	Litres
m	Metres
m^3	Cubic metres
N_2	Nitrogen
NO_2	Nitrite
NO_3	Nitrate
O & M	Operation and Maintenance
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
US	United States
VIP	Ventilated Improved Pit Latrine
VSS	Volatile Suspended Solids
WASH	Water Sanitation and Hygiene

ABSTRACT

Deep Row Entrenchment (DRE) is an innovative concept utilized in faecal sludge management, as both a disposal and reuse mechanism. While this idea has been tested in a handful of countries such as South Africa, India, and Benin, its utilization in Africa remains relatively limited, despite its numerous advantages, including its cost-effectiveness in terms of implementation, operation, and maintenance. Moreover, it offers a viable interim solution for locations lacking faecal sludge treatment facilities. It is for these reasons that Water for People, Uganda, decided to pilot this concept in two emerging small towns, Kamwenge and Kole. These towns boast thriving pit emptying businesses but lacked functioning treatment facilities. The primary objective of this pilot was to assess the potential of DRE as an interim solution for faecal sludge disposal and reuse in these towns.

Sites to pilot these projects were selected in collaboration with the district and towns officials, such as, the District Health Inspectors, District Water Officers, District Environmental Officers and Town Mayors basing on several factors highlighted in literature including good soil permeability, flat surface, distance from surface water, ground water depth, etc. Site set up was then done which included site clearing, excavation of trenches and fencing. Warning signs were also put up. Acquisition of faecal sludge (FS) was done in collaboration with already existing pit emptiers within the towns who delivered the faecal material to the site for burial. Faecal sludge was collected from residential and commercial buildings (like schools and offices). No industrial or toxic sludges were deposited in the trenches. The pit emptying mechanism used by the pit emptiers was the Gulper IV and sludge was transported in barrels on a pickup truck to the site. Sludge was dumped into the trenches leaving an allowance of 0.3m for backfill. After each dump, sludge was left to de-water for 2 to 3 days and then backfilling was done to prevent exposure to air and vectors. This process would then be repeated for a new layer of sludge. Following final backfill, an allowance of 3 months was given for decomposition of the sludge after which eucalyptus trees were planted on the trenches. Site monitoring was done monthly to ensure that pit emptiers were practicing safe discharge and standard operating procedures at these sites.

Analysis of faecal sludge characteristics was done for fresh faecal sludge samples as received at site and for buried FS samples intermittently to monitor stabilization of the sludge over project period. Test parameters included; moisture content, total solids (TS), biological oxygen demand (BOD_5), chemical oxygen demand (COD), nitrogen, phosphorus, and potassium. Results on the fresh FS revealed the values of TSS, COD, phosphorus, potassium, and total nitrogen (TN) to be high, and therefore sludge was concluded to be of mid - high strength. In addition, results revealed no risk of nitrate and nitrite contamination of ground water as no concentrations of these were found in the fresh FS. Entrenched sludge samples of 6-months, 9-months and 14-months were found to have undergone stabilization with significant reductions in COD and BOD_5. Reduction in moisture content, total solids and nutrient content was also realized. The results also revealed minimal risk of health infection from helminth eggs as the viable count was reported to have reduced from 322 to 1 within six months.

Among the challenges encountered during project execution include;- vandalization at the sites which hindered data collection on tree growth characteristics, considerable distances to the sites which hindered frequent site monitoring and high transport costs incurred by the pit emptiers. With this pilot, an understanding was gained of the aspects of DRE discussed in previous studies, such as, site selection, faecal sludge stabilization in the trenches, and operation and maintenance of the site.

1.0 INTRODUCTION

1.1 Background

Faecal sludge is partly digested excreta that comes from on-site sanitation systems, for example, pit latrines, septic tanks and dry toilets. Management of faecal sludge is an issue in developing countries where affordable sanitation facilities are not accessible (Singh et al., 2017). As the urbanization in developing countries increases, the growing population in urban areas increases the waste production, that is, the faecal sludge production. By 2030, 5 billion people are expected to be served by on-site sanitation systems, which contribute a great amount of faecal sludge in need of treatment (World Health Organization, 2006).

Sludge is utilized for agricultural practices in many countries, and the burial of faeces and other household waste as a soil management system appears to have been used as early as the period 5000 BC-1450 AD by inhabitants of the Amazon Basin, where the technique produced a deep nutrient and organism rich soil which continues to have the capacity to support intensive agriculture and a high population density (David Still et al., 2012). The concept of DRE is not new, but the addition of deep-rooted, nutrient-demanding trees, such as hybrid poplar, to utilize the nutrients is a new improvement (University of Maryland, 2021).

Deep Row Entrenchment (DRE) of sewage sludge has been presented as a feasible option by the United States Environmental Protection Agency (US EPA) since at least 1975 (Partners in Development, 2022). DRE is a unique biosolids beneficial reuse system that combines short-rotation hybrid poplar production and the deep row application of biosolids to reclaim mine spoils, other drastically disturbed soils, or marginal soils, solving the problems associated with surface application of biosolids while providing environmental benefits and a positive cash flow. DRE is not subsidized but actually produces business income. DRE solves many of the pollution and odor problems associated with conventional surface application of biosolids, but DRE is not well understood by regulators, environmentalists, and others (University of Maryland, 2021).

Researchers at the University of Maryland pioneered the DRE of wastewater treatment plant secondary sludge in the early 1980s because of an increase in the production of sludge estimated to exceed 1.2 million wet tons per annum, increasing cost of sludge disposal and reduced option for the disposal of sludge. This technique has also been used in North America and Australia, therefore, the application of wastewater treatment plant sludge in the plantation forest industries can be a well-known practice (Babatunde, 2014).

DRE has been piloted in several other countries across the world including Malaysia, India, South Africa, and Benin as an interim or longer-term solution. Across these four countries, DRE was chosen because of its low cost, and the simplicity of its design. In South Africa and Benin it was also chosen for its potential to provide opportunities for sludge reuse as soil conditioner in agroforestry. In Malaysia and India, DRE was introduced as an interim solution to dispose of waste while awaiting the construction of faecal sludge and wastewater treatment facilities. In both countries, disposal of untreated sludge in deep trenches was not perceived as a desirable long-term strategy because of possible ground and surface water pollution through leaching (Simone Soeters et al., 2021).

In Malaysia, DRE was introduced in 1994 by the Indah Water Konsortium (IWK), a government-owned company. A total of 26 trenching sites were created across the country, but almost all have now been phased out as Faecal Sludge Treatment Plants (FSTPs) and sewerage services have taken their place. In India, DRE is currently being used in the state of Odisha, with 84 trenching sites servicing 114 towns. The DRE sites are owned and operated by the local municipalities, with Ernst & Young providing technical support to towns transitioning towards FSTPs (Simone Soeters et al., 2021).

1.2 Statement of the Problem

In many of the small towns, the challenge of faecal sludge treatment is still eminent and is partly caused by; non-functionality or non-availability of the treatment plants and the distances between the treatment plants and the customers served. Pit emptiers in these towns will almost always opt for dumping options that allow them to achieve the most profit and therefore for towns with weak regulation, many turn to illegal dumping of the faecal sludge in the environment or charging high pit emptying fees. Additionally, customers such as schools and health care facilities with high volumes of sludge and the advantage of huge pieces of land, will opt for unsafe burial in a bid to reduce on the costs of emptying. This poses a potential threat to the environment, affecting both soil and water quality in the long run. While addressing the challenges of non-functional plants and long transport distances may take time, interim solutions like ensuring safe burial conditions for faecal sludge in these small towns are crucial.

1.3 General Objective

To investigate the potential of deep row entrenchment as an interim solution for safe faecal sludge disposal and reuse in small towns which do not have functional faecal sludge treatment plants.

1.4 Specific Objectives

1) To select suitable sites to set up deep row entrenchment pilot projects in Kole and Kamwenge districts.
2) To monitor the stabilization of faecal sludge buried in the trenches over project period.
3) To assess effect of faecal sludge on water quality.
4) To assess the effect of the buried faecal sludge on tree growth.

1.5 Research Questions

1) What are the main considerations for a site to qualify for deep row entrenchment?
2) Which parameters need to be tested in monitoring the stabilization of the faecal sludge?
3) Which parameters need to be tested in assessing pollution of water points downstream?
4) Which tree species is the best to grow on the trenches and which characteristics will be monitored to analyze tree growth?

1.6 Scope

This pilot project centered on deep row entrenchment as a faecal sludge disposal and reuse method in Kole and Kamwenge town councils. The experiments were carried out over a two-year period, spanning from January 2022 to October 2023.

1.7 Relevance of the Study

In many of the small towns, the challenge of faecal sludge treatment is still eminent and is caused by two main issues; non-functionality or non-availability of the treatment plants available and the distances between the treatment plants and the customers served. Pit emptiers in these towns will almost always opt for dumping options that allow them achieve the most profit and therefore for towns with weak regulation, many turn to illegal dumping of the faecal sludge in the environment.

Additionally, for customers such as schools and health care facilities with high volumes of sludge emptied, have the advantage of huge pieces of land and are located further away from the treatment plant, in a bid to reduce on the costs of emptying will opt for unsafe burial. This can be detriment to the environment (soil and water) in the long run.

While the challenge of non-functionality/non-availability and the long haulage distances not likely to be solved now, there is need to ensure safe burial conditions for the FS in these small towns.

The amount of safely managed sludge effectively treated and disposed of correctly would increase particularly in rural and peri-urban areas.

Additionally, there is an opportunity for the use of sludge as a soil conditioner in agro-forestry which helps to mitigate the effect of climate change.

2.0 LITERATURE REVIEW

2.1 Demographics of the Study Areas

This study was conducted as a pilot project in the districts of Kole and Kamwenge, where Water For People operates in collaboration with the local governments. The organization engages in annual sanitation reviews and provides capacity-building initiatives, including technical and business training for masons and pit emptying operators.

In Kamwenge town council in 2020, an analysis of faecal sludge management in the town revealed the following practices: -

- On-site burial
- Covering and abandoning pits when full
- Lack of a designated faecal sludge treatment facility in the entire district
- Disposal and treatment of faecal sludge occurring at lagoons in Fort Portal
- Absence of monitoring mechanisms to ensure safe disposal and treatment
- Uncommon or undocumented faecal sludge reuse

In Kole town council, capacity building efforts for pit emptying operators highlighted the need for a local faecal sludge disposal site. The closest site was a Decentralized Faecal Sludge Treatment (DEFAST) site located on Lira road, which was inconveniently distant and costly for the pit emptiers.

2.1.1 Demographics of Kamwenge District

Kamwenge District is in the central-eastern part of the Western Region of Uganda. The district has two counties with eight sub-counties, one town council and a population of 317,000 people of which 88 % have access to safe water. The district covers an area of approximately 2,304 square kilometers. Of this, 64.1 square kilometers (2.6%) is covered by open water. It is predominantly a rural district with some of the worst poverty levels in the country. The annual population growth rate from 1991-2002 stands at 3.3% per annum compared to the national average of 3.4% per annum. Land in Kamwenge district is predominantly used for agriculture both animal and crop husbandry. 85% of households, that is, 75,679 out of 89,068 households in the district are engaged in subsistence agriculture (Kamwenge DDP, 2016). Of every ten households in Kamwenge, eight have a functioning, clean and safe latrine (Nandini Kochar, 2019). Most households have standard latrines with a pit and some have solid floor/upper structure and a roof. These pit latrines are usually constructed using local materials, mud, reeds, grass for thatching, poles for slab and superstructure (Lieven Peeters, et al., 2011).

Latrine type	No of households	% of households
No latrine	1	0.13%
Pit + upperstructure	42	5.41%
Pit + upperstructure + roof	731	94%
Pit only	3	0.39%
Grand Total	777	100%

Table 1: *Type and conditions of the latrines of the households surveyed (Lieven Peeters, et al., 2011)*

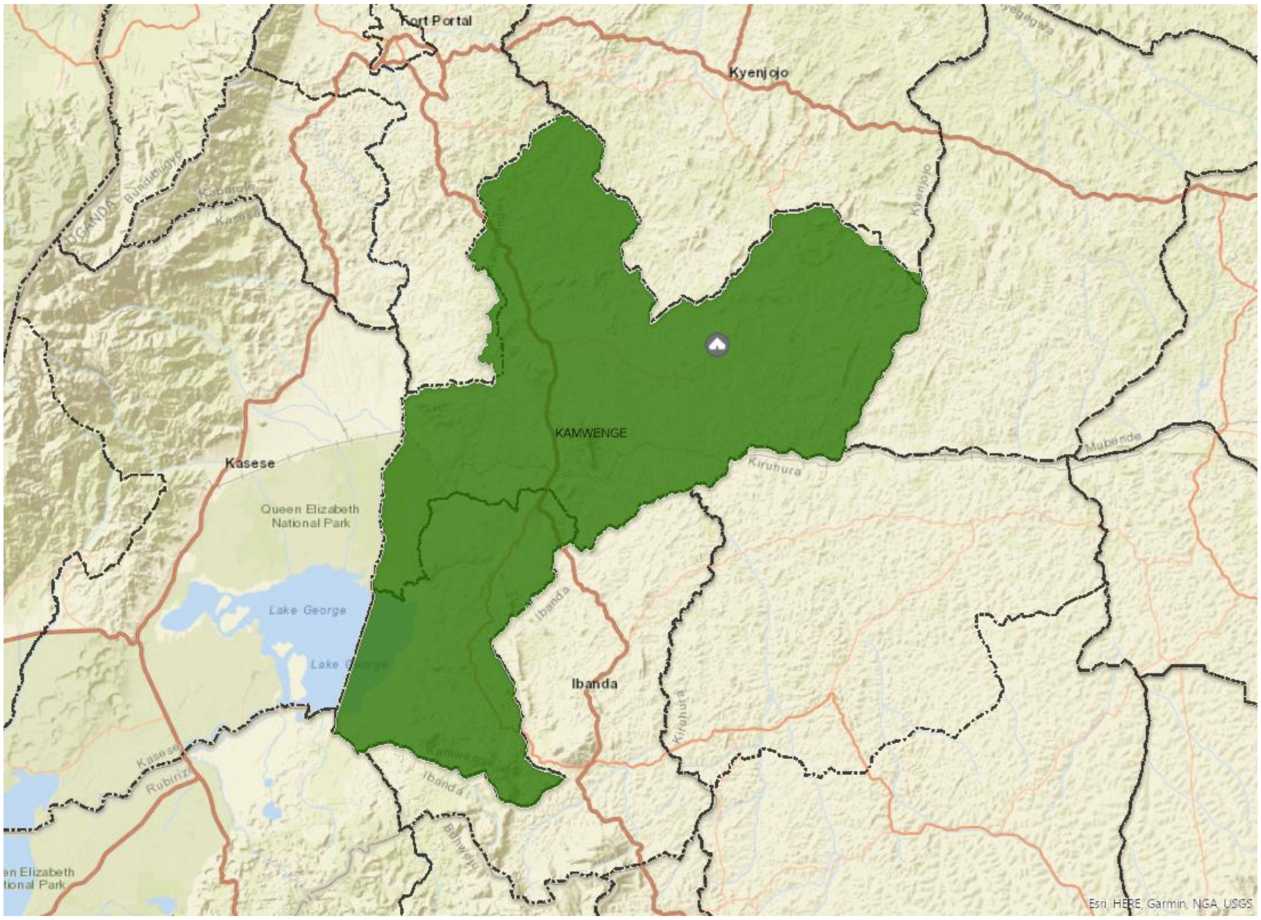


Figure 1: *Map of Kamwenge District (Source: ArcGIS Online)*

2.1.2 Demographics of Kole District

Kole district is a district in Northern Uganda, and it is bordered by Lira district to the east, Apac district to the south and Oyam district to the west and north. Kole, the district capital, is located approximately 28 kilometres (17 miles), by road, northwest of Lira, the largest city in the sub-region. This location is approximately 290 kilometres (180 miles), by road, north of Kampala, Uganda's capital and largest city. The coordinates of the district are 2.3031° N, 32.7633° E. Kole District was created by Act of Parliament and became operational on 1st July 2010. Prior to then, it was part of Apac District. The district is part of Lango sub-region. Kole district is subdivided into the following sub-counties: Aboke, Akalo, Alito, Ayer, Bala, Okwerodot and Ayer Town Council. According to the World Water Atlas, Kole district had a total population of 268,200 in 2018 and according to the national census 2014, 12% of the households in Kole town council have no toilet facility.

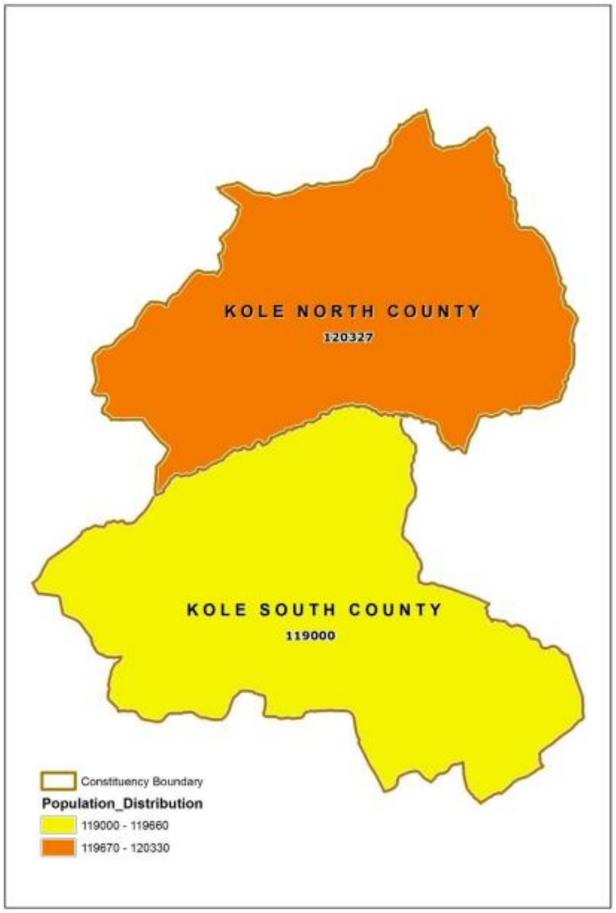


Figure 2: *Map of Kole District (Source: Uganda Bureau of Statistics, 2017)*

2.2 Faecal Sludge Characterization and Reuse as a Soil Amendment

2.2.1 Faecal Sludge Characterization

Sludge characteristics are important considerations when choosing a technology, and when making operational decisions; for instance, in the face of variable sludge quality. However, sludge characteristics are often poorly documented, or no analysis is done. This results in a lack of local data to make informed decisions (Simone Soeters et al., 2021).

FS characteristics are highly variable and are influenced by a wide range of existing technologies (for example, lined VIP latrines, unlined pit latrines, septic tanks) in use at the household level as well as by the number of users per system, average desludging intervals and physical factors (for example, soil, permeability, water table) (Lars Schoebitz et al., 2014).

Lined pit latrines consist of cement-mortar-sealed containment pits that prevent liquid loss, while unlined pit latrines act as leach pits by permitting infiltration of liquid content (leachate) into the surrounding soils. Unlined latrines in areas with weak soils could cause soils to cave in, during use or emptying operations and the soil could mix with the FS. These factors influence the FS characteristics in the different pit types and their locations as well as conditions in those areas and therefore in turn affect dewaterability characteristics such as particle size (S. Semiyaga et al., 2016).

Parameters that should be considered for the characterization of FS include solids concentration, chemical oxygen demand (COD), biochemical oxygen demand (BOD), nutrients, pathogens, and metals (Linda et al. 2014) and these are explored further below: -

1. Moisture Content

Moisture loss is speculated to be tied to the biodegradation rate, as suggested by Bakare (2014). In Bakare's (2014) laboratory batch experiments, it was found that an increase in the moisture content of sludge samples resulted in a decrease in the rate of degradation. The proposed explanation for this revolved around the settling of sludge with a liquid layer above it, particularly in test units with higher moisture content, therefore limiting the transfer of oxygen to the sludge.

Contributors to the moisture content in pit latrines are diverse. The decomposition of faeces, urine, anal cleansing material, and cleaning substances, including sullage occasionally tipped into the latrine, significantly adds to the moisture levels (Cotton et al., 1995). Furthermore, Buckley et al. (2008) pointed out that the addition of water by users or rain, especially due to damaged or poorly constructed superstructures, can be substantial contributors.

In the case of unsealed pits, the dynamics of moisture flow are influenced by the permeability of the soil and the water table's location beneath the pit. The inflow and outflow of liquids within the pit are intricately connected to the construction of the pit and the hydrogeology of its location (Cotton et al., 1995; Franceys et al., 1992). In essence, the movement of liquids in and out of the pit is contingent on these structural and environmental factors.

2. Total Suspended Solids (TSS)

Total suspended solids (TSS) is a measure of organic and mineral matter that is suspended in sludge. This is the part of solid fraction that settles faster, for example in settling-thickening tank or be retained in drying beds (Bassan et al., 2016). It has been observed that high TSS slows the dewatering rate of FS through increase of dewatering extent (high %TS in dry cakes) as reported by Ward et al. (2019) and Benjamin Doglas et al. (2021).

3. Pathogens

For entrenchment to be employed as a viable method, it is important to understand for what period the entrenched sludge remains pathogenic, even if there is no movement of pathogens out of the trench (Bakare, 2014).

In 2002, research conducted by IWMI and SANDEC delved into the calculation of rates for pathogen die-off in faecal sludge. It was reported that the speed at which various pathogens undergo die-off is influenced by factors such as ambient temperature, with faster die-off in warmer climates, and the process of drying, which also contributes to the reduction in pathogen viability. Understanding these dynamics is pivotal in assessing the effectiveness of entrenchment as a method for managing faecal sludge.

4. Nutrient Content

The main nutrients in faecal sludge are nitrogen, potassium and phosphorus. Most of these nutrients are excreted through urine, and only some are found in faeces as shown in Table 2.

Nutrient	Urine (%)	Faeces (%)
Nitrogen	88	12
Phosphorous	67	33
Potassium	73	27

Table 2: *Percentage of Nutrients in Urine and Feces (CAWST, 2016)*

Bakare's (2014) research emphasizes that as the entrenched pit sludge undergoes additional stabilization, vital nutrients such as nitrogen, phosphorus, and potassium previously locked within the buried sludge are gradually released, effectively transforming it into a valuable fertilizer. This process leads to a reduction in the nitrogen and phosphorus content observed in the latrine sludge before burial, in comparison to the levels found in the sludge excavated from the trenches. The release of these essential nutrients during the stabilization of buried sludge highlights an additional benefit of entrenchment, demonstrating its potential role in nutrient recycling and soil enrichment.

When nitrogen leaches into the soil in the form of nitrate, it poses a potential risk of harmful concentrations in both surface and ground waters. According to Kays et al. (1999), entrenched sludge initially exhibited an average nitrogen content of 3.3% at the time of application, which then decreased to 1.2% by the end of the growth cycle. The study by Kays et. al. (1996) suggested that a significant portion of the nitrogen had undergone mineralization during this period. Importantly, up to 40% of the nitrogen might have been converted to nitrogen gas (N_2) through denitrification, a process facilitated by the wet anaerobic conditions prevalent in the trench.

5. Chemical Oxygen Demand (COD) & Biological Oxygen Demand (BOD)

COD is a measure of the oxidizable matter present in samples and is used as an indication of the amount of chemically oxidizable material in a sample (Bakare, 2014). BOD_5 is the measure of the dissolved oxygen required to stabilize organic matter in five days. COD and BOD_5 are some of the common indicators of stabilization of FS. Stabilization is achieved through the biodegradation of the more readily degradable molecules, resulting in a FS with a lower oxygen demand. In addition, stabilization ensures that organic forms of nutrients present in treatment end products are stable, and can be more predictably and reliably used.

In measuring the COD of sludge, fresh excreta would typically fall into class 3 with COD levels of 20,000 - 50,000 mg/litre; after treatment COD levels may drop to 500 mg/litre falling into class 1. Sludge from a pit latrine would typically include older layers of well-stabilized sludge but also fresher, unstable sludge, resulting in a classification of 3. Unstable sludge can be reclassified more favorably if one of the options for reducing the attraction of vectors can be applied (Partners in Development, 2022). High concentrations of COD would require longer treatment time and higher oxygen consumption for breakdown of the high organic matter (Gudda et al., 2017). Gudda et al. (2017) also stated that household disposal of solid waste into the pit latrine vaults lowers biodegradability of faecal sludge by increasing organic load.

Biodegradability potential of the pit latrine sludge can be measured by the BOD:COD ratio. The biodegradability potential of pit latrine sludge is relatively low when the ratio is closer to 3 and relatively high when the ratio is greater than 3.

2.2.2 Faecal Sludge Reuse as a Soil Amendment

Faecal sludge consists of high levels of organic carbon and nutrients, hence the reuse of sludge in agriculture as a fertilizer and for soil amendment is beneficial (Singh et al., 2017). As the population in the world grows and the demand for food increases, agriculture is an important factor for food production to supply people with nourishment. Excreta is a low-cost fertilizer which consists of all nutrients that are required for a crop to grow and is available where people live (World Health Organization, 2006).

However, the utilization of sludge in agriculture requires careful management to mitigate potential risks. Stringent safety measures are essential to prevent the uptake of harmful chemicals by humans or animals, environmental contamination, and the exposure of humans to sludge-borne pathogens. Surface application of sludge necessitates prior treatment to eliminate pathogens and achieve stability. Current options include composting sludge with organic materials, or mixing and covering it with soil in natural environments like veld or tree plantations. Notably, the entrenchment method, employed since the 1980s in the Washington, D.C./Baltimore, Maryland region of the USA, eliminates the need for treatment. This approach effectively manages odor and minimizes the risk of disease transmission, making it suitable for forestry, wildlife habitats, and land reclamation (David Still et al., 2012).

Stabilized and sterilized pit latrine sludge, even if treated, is typically unsuitable for surface or shallow incorporation methods in agriculture due to its rubbish content. In contrast, entrenchment, despite containing pathogens and odors, remains a feasible option, especially when sludge includes rubbish (David Still et al., 2012). This underscores the importance of considering specific sludge characteristics when determining appropriate methods for safe and beneficial utilization in different contexts.

2.3 Deep Row Entrenchment

2.3.1 Overview on Deep Row Entrenchment

The historical use of sludge in agriculture dates back to as early as 5000 BC-1450 AD, with inhabitants of the Amazon Basin employing the burial of faeces and household waste as a soil management system. This ancient technique resulted in nutrient-rich soil capable of supporting intensive agriculture and sustaining a high population density (David Still et al., 2012).

Deep Row Entrenchment (DRE) emerges as a simple technology for the safe disposal and, in some cases, reuse of faecal sludge. This method involves placing sludge into trenches, immediately covering them with soil, effectively addressing odour problems and containing human pathogens safely within the sludge. The planted trees, particularly those with high nutrient consumption rates such as eucalyptus, contribute to the utilization of nutrients present in the sludge (Simone Soeters et al., 2021). Variables to consider for entrenchment, as reported by Kays et al. (2007), encompass trench dimensions, spacing, filling methods (layered with soil or co-composted with vegetable matter), plant species, vegetation composition and density, and the intended purpose. The entrenchment process not only acts as a protective barrier over pathogens but also offers additional benefits, including erosion control and the creation of wildlife habitats (Buswell, 2006).

Partners in Development (2022) outlines various options for applying the DRE method, spanning commercial entrenchment involving partnerships between municipal wastewater treatment works and forestry companies, decentralized entrenchment for smaller tracts of land, and burial of sludge on household premises, especially in cases where space permits on-site entrenchment during pit latrine sludge disposal.

Studies generally report no adverse effects on surrounding groundwater. The entrenchment process, particularly for wastewater treatment plant sludge, provides recycling benefits of nutrients when trees are planted for commercial harvest. However, a major environmental concern revolves around the potential contamination of groundwater by leached nitrate (NO_3) and phosphorus (P) from the sludge (Simone Soeters et al., 2021). This highlights the importance of careful management and monitoring to ensure the environmental sustainability of the entrenchment method.

2.3.2 Benefits of Deep Row Entrenchment

DRE opens a range of possibilities for the disposal of both wastewater and pit latrine sludge, overcoming the problems associated with the stabilization of sludges, while providing benefits to non-edible crops and to soil (David Still et al., 2012). Burial of sludge adds carbon to the soil, leading to increased organic matter in the soil. This has a positive impact on soil health and can improve structural aspects, such as water holding capacity. In the long run, burial of sludge allows it to decompose underground and be used by organisms in the soil (Partners in Development, 2022).

DRE of sludge can be used to safely dispose of untreated or partially treated faecal material while achieving several benefits such as; improved soil fertility and increased agricultural productivity, enhanced growth of timber or other non-edible commercial crops, food security - improved nutrient value of fruit grown by households, and environmental rehabilitation - restoration or enhancement of ecosystems through remediation of poor or disrupted soils and stabilization of carbon in the soil, thus reducing greenhouse gas emissions (Partners in Development, 2022). Abreu-Junior et al. (2020) found that buried sludge led to an increase of 7% in wood volume in a Eucalyptus urograndis plantation when comparing plots where nitrogen requirement was met by wastewater sludge and those using NPK fertilizer. Similarly, Neethling and Still (2022) found that buried sludge led to an approximately 15% minimum increase in eucalyptus yields over a single growing season, based on estimated conical volume. When examining the impact on a second growing season on the same plot, with no additional sludge applied, volume of timber in plots with sludge application showed increases of approximately 30% within the first three years of growth when compared to plots without sludge.

Deep row applications of sludge for forestry production has been reported to have the potential to solve many of the problems associated with agricultural land application and other land disposal methods. Surface sludge application has been shown to provide plant nutrients, enhance soil productivity, and improve soil properties (WRC, 1997); however, offensive odour and perceptions of health and environmental problems may result in application restrictions. In addition, landfill application and even surface application results in the decomposition of carbon to carbon dioxide, which is a greenhouse gas. Thus, burying sludge can provide some mitigation of climate change in the long run (Partners in Development, 2022).

Partnerships between municipalities and forestry could provide mutual benefit to both, with sludge handled, applied, and monitored by forestry companies on their own land or with sludge entrenched and monitored by municipalities on municipal land with a forestry company contracted to manage a timber crop on the entrenchment site (David Still et al., 2012).

Other benefits entrenchment of sludge has the potential to provide if done properly, include; a solution to an urgent waste management and public health problem, improved crop yields over multiple crop cycles and improved soil health (for example, increase in organic content), solid waste disposed of in VIPs is automatically co-disposed of with sludge with the potential for disposal of other solid waste with the sludge if needed, planting of trees creates a nutrient sink, reducing movement of potentially harmful nutrients from the trench and utilization of sludge by trees allows for repeated disposal of sludge at the same site over cycles of entrenchment and harvest, unlike landfills where re-use of site can only be done by adding additional layers (Partners in Development, 2022).

2.3.3 Deep Row Entrenchment Process

2.3.3.1 Trench site selection

A suitable site for DRE is dependent on several factors which include;

(i) Good soil permeability, for easy leaching of percolate from FS.
(ii) Flat surface, for easy operations.
(iii) Distance from human habitation.
(iv) Distance from surface or ground water resources.
(v) Least possibility of trespassing by human or animals.
(vi) Should not have any vegetation on it.
(vii) Should not be a shallow or flood prone area.

During site selection, it is important to be aware of the risk of contaminating the surrounding land and groundwater resources. Strict controls are needed to ensure that treated effluent is responsibly managed to avoid local and downstream impacts (Simone Soeters et. al., 2021).

Partners in Development (2022) advises that a site with any of the following characteristics should not be considered for deep row entrenchment unless mitigation measures can be taken to alleviate any potentially negative impacts:

- Within the 100-year flood line (wetlands, vleis, pans and flood plains) due to risk of water pollution.
- Unstable areas (fault zones, seismic zones and dolomitic or karst areas)
- Steep gradients (greater than 15°) due to potential for instability and erosion, and greater movement of pollutants
- Distance to fissured rock below surface less than three metres
- Areas of groundwater recharges
- Highly permeable soils (>5 cm/s percolation rate)
- Areas immediately upwind of a settled area
- Natural habitat of endangered species which could be disturbed by entrenchment activity.

2.3.3.2 Trench Design

The length and the depth of the trench depends on the highest groundwater level and the quantity of faecal sludge. The trench can be lined, for example with a layer of clay, to reduce the risk of groundwater contamination (CAWST, 2016).

Trench design depends on;

(i) Soil type
(ii) Quantum of sludge

Partners in Development (2022) highlights the following factors to assess the long-term viability of the operation:

(i) Is the site large enough to accommodate the volume of sludge it will receive over the growth cycle (trench size/volume/size of community serviced/planting cycle – that is, trenches that are planted are tied up for 6-9 years, can stockpiling be avoided?)
(ii) Distance to source of sludge and means of transport (are VIPs that will need emptying in future years located further from the burial site?)
(iii) Access to site for vehicles transporting sludge.

In terms of the impact on the degradation of the entrenched sludge over time, optimal dimensions for trenches are 800 mm deep and 600 mm wide, spaced 2.4 m apart edge to edge (or further apart). This will allow for an application rate of 990 m^3 per hectare with 300 mm backfill covering the sludge (David Still et. al., 2012).

Trenches should be dug parallel to the ground contours. Trench spacing and dimensions will depend on the spacing of trees. It is advisable to prepare test trenches to ensure that the desired dimensions and spacing of trenches are feasible for the specific site conditions (Partners in Development, 2022).

2.3.3.3 Application of Sludge

The sludge should be emptied in an even layer into the trench, and then allowed to dry for 2 to 3 days. Thereafter, it should be covered with a layer of 50 mm thickness soil (backfill soil) to prevent exposure to air and vectors. After the entire trench is filled, it caves in due to leaching and decomposition of the sludge after some time. The time taken for this caving to occur depends on several factors such as weather, soil type, biological activity etc. Therefore, after the caving occurs, it should be filled with soil again to maintain a flat surface. Three months after the trench gets filled again as outlined in the previous point, the trenches can be planted with trees or used as a green space. For further sludge disposal, a new site might be identified and used keeping in mind the site selection parameters (Sanitation Capacity Building Platform (SCBP), 2021).

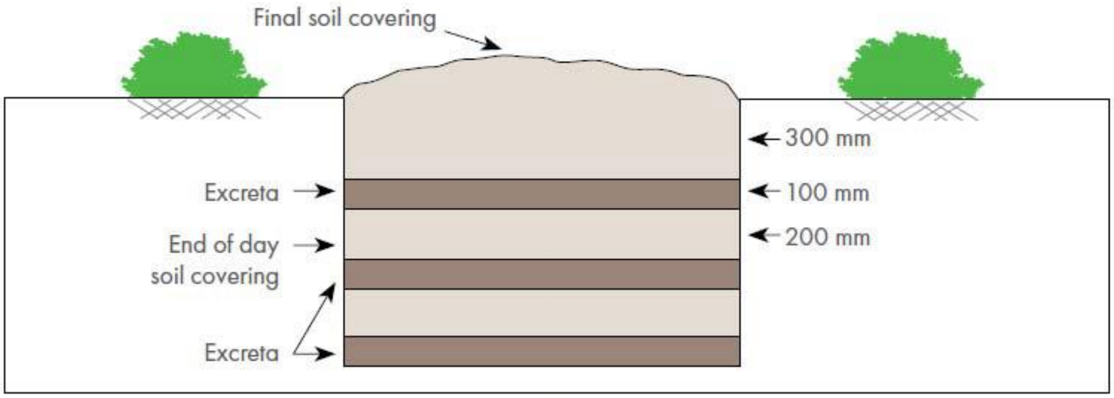


Figure 3: *Cross section of trench ((Partners in Development, 2022)*

The backfill over the trenches should be left heaped or ridged until planting to allow the backfill to settle and prevent erosion. Monitoring boreholes should be located to intersect groundwater moving away from a disposal site (Partners in Development, 2022).

Provision should be made at the site for cleaning, disinfection and storage of equipment and protective gear, which may have come into contact with pathogens in the sludge. Facilities should be provided at the site for workers to shower and disinfect their hands as needed during and at the end of their workday. Workers must wear protective gear while handling sludge to prevent infection by bacteria, viruses, or intestinal parasites in the sludge and it is recommended that sludge producers (municipalities, in most cases) provide regular (three monthly) deworming treatment to workers working with sludge and provide a full orientation to educate workers about pathogens, routes of transmission and procedures to protect their health before they begin work (Partners in Development, 2022).

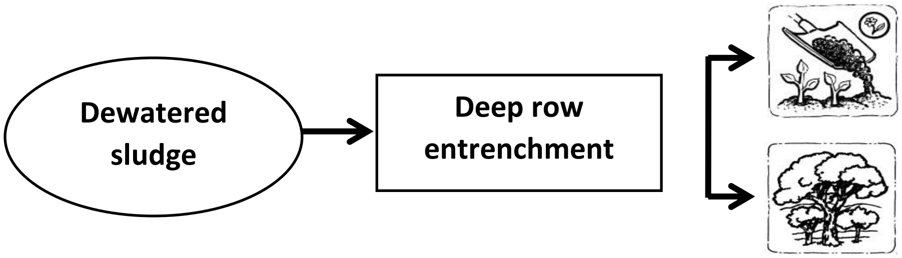


Figure 4: *Deep Row Entrenchment Process (Eawag-Sandec, 2016)*

2.3.3.4 Precautions of O&M

Sanitation Capacity Building Platform (SCBP) (2021) states a few of the essential aspects of operation and maintenance for DRE as follows;

1) Avoid sludge disposal before and during rainfall and snowfall seasons. This can be done by not emptying the on-site containments during this time.
2) The DRE site must be used to dispose of only FS from residential, and commercial buildings (like schools, colleges, hotels/resorts and offices). No other waste such as food waste from restaurants nor industrial waste of any nature whatsoever or toxic sludges shall be disposed of on DRE sites.
3) All on-site personnel, including the emptier should use appropriate personal protective gear.

4) The DRE site must be demarcated, fenced with GI wire mesh of 3 inch by 3 inch and provided with appropriate signages so that there is no trespassing by humans or animals including for grazing.

In addition, during rainfall seasons, the frequency of emptying in the same trench can be lowered. During the rainy season, the leaching effect may be low (WASH Institute, 2021). Therefore, trenches should be used interchangeably in this season.

2.3.3.5 Planting of Trees

Trees may be grown to produce timber for building, fencing, fuel or for the paper and pulp industry. Species, which have a high demand for water, will assist in absorbing the leachate produced by sludge, reducing the risks of groundwater contamination. Trees with some nitrogen-fixing capacity, such as wattle (*acacia mearnsii*) will benefit less from increased nitrogen loading through sludge (Partners in Development, 2022).

While fruit can be grown safely on trees planted on sludge buried on site at households, fruit should not be grown commercially for sale unless adequate measures are taken to disinfect the fruit from possible surface contamination. A variety of other crops can be considered for planting over buried sludge, such as maize, sugarcane, or wheat, but current research in South Africa does not provide information about the responses of these crops to sludge (Partners in Development, 2022).

2.3.3.6 Monitoring

It is the duty of the sludge user to ensure that both during and after the period that sludge is being actively utilized the safety of groundwater is not compromised, and pathogenic material is safely contained. Baseline values of groundwater and soil should be established before sludge is entrenched at the site to provide a basis for assessing the impact of the entrenched sludge on the site over time (Partners in Development, 2022).

It should be kept in mind that unanticipated factors may arise which could alter the environmental impact of entrenchment during or after the period of use. For example:

- Heavy rains or flooding may cause pollutants and contaminants to rise to the surface or move further, more quickly or in higher concentrations through groundwater
- Encroachment of human settlement may reduce buffers, resulting in use of water near the entrenchment site for drinking, which was not the case at the time of the site characterization (Partners in Development, 2022).

Surface and Ground Water

Monitoring of water on the site should include both microbiology (faecal coliforms and *E. coli*) and chemistry: alkalinity, organic nitrogen, nitrate-nitrogen, ammonium-nitrogen, chlorides, pH, COD, zinc, cadmium, copper, and specific conductivity. Nitrate-nitrogen ($N0_3$) for drinking. If the depth of the water table is less than 5 m, monitoring should be done three monthly for dry sludge and monthly for liquid sludge and during the rainy season. Composite samples should be collected and analyzed 20-50 m upstream and downstream from the site and from neighbouring residential wells (Partners in Development, 2022).

Less frequent monitoring may be adequate where the soil clay content is greater than 35%, where dewatered sludge is entrenched above a water table deeper than 10 m, or where liquid sludge is entrenched above a water table deeper than 20 m. In some cases, monitoring of groundwater may not be necessary due to the depth of the water table or other factors. This must be demonstrated through a study by a qualified person. Detailed procedures and methodology for sampling and testing surface and groundwater are provided by DWS (Herselman & Snyman, 2009).

Soil

Monitoring of soil allows the movement of pollutants to be detected before they reach the groundwater, providing an early warning system. The required frequency of monitoring will be determined by the clay content and pH of the soil and the water content of the sludge. If the site contains different soil types, different monitoring schedules may be necessary. Soils should be sampled at intervals to a depth of at least 500 mm below the bottom of the trench (Partners in Development, 2022).

2.3.3.7 Protecting Public Health and The Environment

Animals and the public must be restricted from sites, which are in use for burial of VIP sludge to prevent sludge being disturbed, and pathogens spread. The site should be fenced securely with a gate that is locked when workers are not on the property. Stringent protocols must be followed by workers to prevent the spread of pathogens via vehicle wheels, tools, or protective wear as they enter and exit the site (Partners in Development, 2022).

2.3.3.8 Closure of Site

If entrenchment is to be discontinued at the site, soil samples should be assessed for pathogens and metals, and viability and levels of metals and nutrients, which could migrate to the groundwater over time. If there is a risk of ongoing contamination, an aftercare plan should be developed to manage potential threats to public health or the environment; dependent on the planned future use of the site by the municipality or the company that owns the site until year soil sampling indicates that the levels of pathogens and metals have reduced to within acceptable limits. A final planting of trees or other plants on the site can assist with preventing contact with pathogens by humans or animals through digging or farming (Partners in Development, 2022).

2.4 Literature Review Summary

Literature suggests that for a site to qualify for DRE, it should have the following characteristics; good soil permeability - for easy leaching of percolate from FS, flat surface - for easy operations, a water table deeper than 15ft from bottom level of the trench, surface water body minimum distance - 45ft, distance between nearest habitation and site - 200m with least possibility of trespassing by human or animals and should not be a in a shallow or flood prone area.

For a site that meets these standards, literature reported that the variables to be considered for deep row entrenchment of sludge include trench dimensions, spacing, and method of filling (layered with soil or co-composted with vegetable matter), plant species, composition and density of vegetation and end purpose.

The literature reviewed also showed that sludge characteristics are an important consideration when choosing a technology because FS characteristics are highly variable and are influenced by a wide range of existing technologies. The suggested tests for the characterization of FS included solids concentration, chemical oxygen demand (COD), biochemical oxygen demand (BOD), nutrients, pathogens, and metals.

Literature reported the benefits of DRE to include adequate management of odour and the risk of disease transmission and is feasible even when sludge contains rubbish. It was also reported to have a benefit to forestry, wildlife habitats and assist in the reclamation of land. Literature also pointed out that DRE is a more appropriate method for application of pit latrine sludge, even if sludge was stabilized and sterilized, due to the rubbish content.

3.0 MATERIALS AND METHODS

3.1 Material

3.1.1 Faecal Sludge

Faecal sludge was collected from both residential and institutional structures, that is, schools, as indicated in Table 2. This was done to ensure that the sludge did not contain a concentration of toxic elements that could potentially lead to soil and groundwater contamination.

In total, 151 barrels were dumped in the trenches at the Kole site. The sludge was of a relatively thin consistency, requiring a larger quantity to adequately cover the trenches due to the lower volume occupied by the thin sludge.

Date	Quantity of Sludge (barrels)	Source
14/04/22	10	Household
20/05/22	14	Household
15/06/22	16	Household
17/06/22	16	School
20/06/22	16	Household
23/06/22	15	Household
21/07/22	16	Household
23/07/22	8	School
29/07/22	8	Household
10/09/22	16	Household & School
23/09/22	8	Household & School
29/07/22	8	School
TOTAL	**151**	

First Trench covered

Table 3: *Data on Faecal Sludge received at the Kole Site*

3.1.2 Faecal Sludge Characterization

The initial tests were on the sludge in its original state as received at the site, aiming to analyze its baseline characteristics. Four subsequent tests were carried out intermittently over a fourteen-month period to evaluate faecal sludge stabilization within the trenches. These tests focused on the physical characteristics, nutrient composition, and pathogen content of the faecal sludge samples and test parameters included the following; -

Moisture Content

Moisture content of faecal sludge has been speculated to influence the biological degradation rate of faecal sludge. Moisture loss may be found to accompany biological degradation and the rate of reduction in moisture content could be a function of the biodegradation rate (contrary to the situation within pit latrines) (Bakare et al., 2014).

Total Suspended Solids (TSS)

It has been observed that high TSS slows the dewatering rate of FS through increase of dewatering extent (high %TS in dry cakes) as reported by Ward et al. (2019) and Benjamin Douglas et al. (2021).

Pathogens

Pathogen reduction over time will give an understanding of the time that the sludge remains pathogenic. Pathogen survival depends on the prevailing environmental conditions of temperature, pH, nutrient availability, growth inhibitors, predators, etc. The pathogens monitored were e-coli, helminth eggs and faecal coliforms.

Nutrient Content

Nutrients such as nitrogen, phosphorus and potassium are valuable for crop growth and are found to exist different forms. It was highlighted by Bakare (2014) that as further stabilization of entrenched pit sludge occurs, nutrients (nitrogen, phosphorus, and potassium) locked up in the buried sludge are released as fertilizers therefore reducing the amount of nitrogen and phosphorus found in the latrine sludge before burial compared to that obtained from the exhumed sludge in the trenches. and amines).

COD & BOD$_5$

COD and BOD$_5$ are the main indicators of stabilization of faecal sludge. Stabilization is achieved through the biodegradation of the more readily degradable molecules resulting in an FS with a lower oxygen demand.

3.1.3 Pit Latrine Description

Both lined and unlined pit latrines were considered for this pilot provided that there was no risk of collapsing for the unlined pit. Common pit latrine designs included; pit latrine without slab, pit latrine with slab and the Ventilated Improved Pit (VIP) latrine.

Pit latrines emptied for this pilot were located within the communities or in the outskirts where the sites were selected. During the initial pit emptying activity, vulnerable community members who couldn't afford these services were identified with the assistance of a village health inspector. A total of five latrines were emptied, including those belonging to three widows and two single mothers, as specified in Table 4. Water For People covered the expenses for the initial pit emptying activity to ensure timely sampling of the faecal sludge.

Name	Vulnerability	Location	Contact No.
1. Akullu Vicky	Widow	N2^{0}16^{1}17.11591 E32^{0}40^{1}37.1794”	0772-804956
2. Apio Deborah	Widow	N2^{0}16^{1}17.7098” E32^{0}40^{1}41.04529”	0775-009155
3. Anuna Joyce Mary	Single mother	N2^{0}16^{1}2.83025” E32^{0}40^{1}5.23812”	-
4. Karen Owiny	Single mother	N2^{0}15^{1}59.31074” E32^{0}40^{1}17.36705”	0781-953999
5. Akulu Judith	Single mother	-	0760-739664

Table 4: *Vulnerables that were supported with Pit Emptying Services*

Figure 5 & 6: *Pit Latrines belonging to the Vulnerables*

3.2 Experimental Procedure

3.2.1 Site Selection Criteria

Sites for this activity were selected based on availability of land in the town councils and several factors highlighted in literature which included; -

i) Good soil permeability, for easy leaching of percolate from FS.
ii) Flat surface, for easy operations.
iii) Distance from human habitation.
iv) Far away from surface or ground water resources.
v) Least possibility of trespassing by human or animals.
vi) Should not have any vegetation on it.
vii) Should not be a shallow or flood prone area.

3.2.2 Pit Emptying Mechanisms

Pit emptying was a collaborative effort involving established pit emptiers in both Kole and Kamwenge. Specifically, we partnered with Sani Waste Solutions in Kole and RWASHO in Kamwenge. Although other pit emptying companies, including Ayer Sanitation Link, Tii Ilwak Sanitation, Kole Cleaning Sanitation Link Services for Kole, and Elite Sanitation & Cleaning Agency for Kamwenge, were engaged, their contributions to the pilot project were limited.

The Gulper IV was the primary method employed for the pit emptying process. The collected sludge was then transferred into barrels and transported via a pickup truck to the designated site.

Figure 9: *Pit Emptiers Emptying Latrine using the Gulper IV*

3.3 Experimental Protocol

3.3.1 Step 1 - Site Selection

Site selection was a collaborative process involving key stakeholders, including Town Clerks, Mayors, District Health Officers, and Natural Resources Officers from the respective towns and districts. An introductory meeting was held to introduce the concept of the pilot project and outline the site requirements. Through fruitful discussions, district and town leaders identified potential sites aligned with the project's criteria, which were then collectively inspected. The chosen site was decided upon using specific criteria found in previous research. Main considerations included;

- i) Distance from human habitation.
- ii) Distance from surface or ground water resources.
- iii) Groundwater depth
- iv) Soil type

Figure 10 & 11: *Inspection of Prospective Sites with the Town Clerk of Kole Town Council (left) and District Health Inspector of Kamwenge District (right)*

3.3.2 Step 2 - Design of the trenches

The trench type selected for the sites was the shallow trench. This was based on the estimated load of faecal sludge to be disposed of and the depth of ground water. Each site had two shallow trenches each with a length of 7-8m, depth of 1m and width of 1m. In between the trenches, was a section of 3m to facilitate movement of the pit emptier trucks, as shown in Figure 12.

Since the trenches were shallow, there was no need for lining with a sand barrier or agri-film cover. This was because the vertical distance between the bottom of the trenches and the groundwater remained within permissible limits, which were set at 15 feet or three times the depth of the pit.

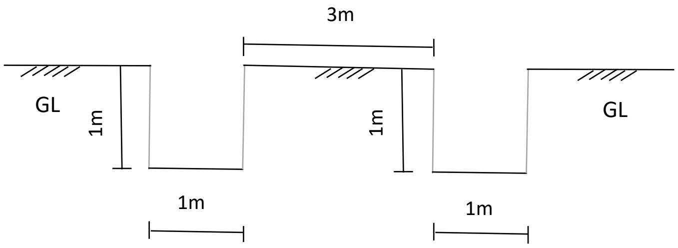


Figure 12: *Cross-section of the DRE trenches*

The usable volume for each trench was calculated to be 5.6 m³ and 4.9 m³ for Kole and Kamwenge, respectively, as shown in Table. This converted to 28 and 25 barrels for Kole and Kamwenge, respectively, with each barrel having a size of 200 litres. However, for the Kole site, the actual number of barrels needed to fill one trench turned out to be over 80 barrels as shown in Table under section 3.1.1. This discrepancy was due to the thin consistency of the sludge, requiring a larger quantity to adequately cover the trench due to the lower volume occupied by the thin sludge.

	Kole	Kamwenge
The length of the trench	8m	7m
The volume of the trench	8m^3	7m^3
Volume of backfill	2.4m^3	2.1m^3
Usable volume	5.6m^3	4.9 m^3

Table 5: *Trench Volumes*

3.3.3 Step 3 - Excavation of the trenches

The initial step involved clearing the sites of existing vegetation and shrubs. Subsequently, trench demarcations were laid using measuring tape, nylon wire, poles, and ash. Next, a manual excavation of the trenches was done, using hoes and pickaxes which took approximately two to three days.

Figure 13, 14 & 15: *Trench Layout and Excavation*

3.3.4 Step 4 - Fencing Off Site

The area was fenced off using pre-cut painted angle bars of approximately 1.5m in height, with barbed wires and binding wires. Additionally, a warning sign was installed on the gate. The final layout of the site was as illustrated in Figure 16.

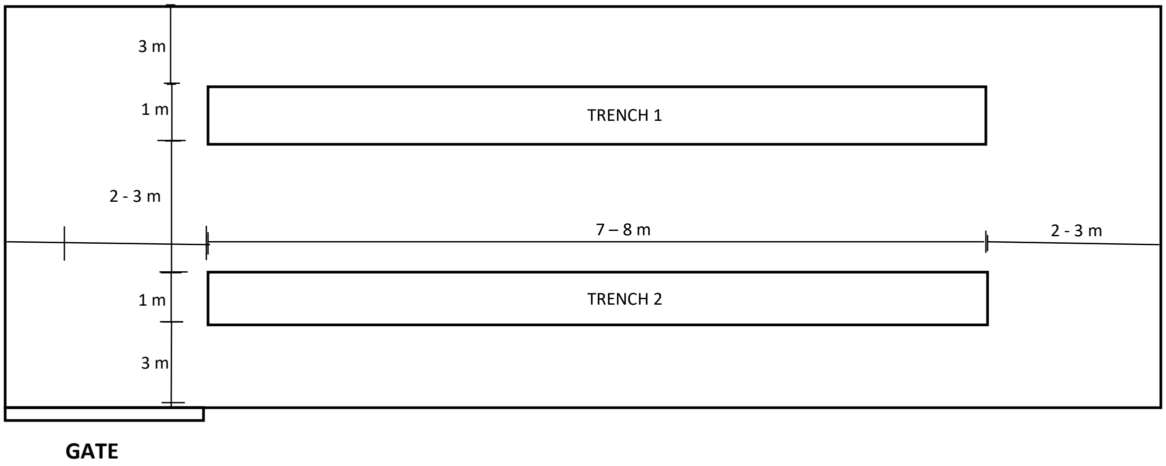


Figure 16: *Site Layout*

3.3.5 Step 5 - Dumping of Sludge

Sludge was poured into the trenches and left to dry for 2 to 3 days. Afterward, it was covered with a layer of soil to prevent exposure to air and vectors. This process was then repeated for a new layer of sludge. An allowance of 0.2 – 0.3 m was given in the trenches for backfill.

Figure 18: *Faecal Sludge Disposed in the Trench*

Figure 17: *Backfilled Trench*

3.3.6 Step 6 - Set up of tree plots

After backfilling the trenches, a 3-month period was given for the natural decomposition of faecal sludge before proceeding to plant trees on the trenches. Eucalyptus trees were chosen for their high nutrient consumption rate. To facilitate a comparative analysis, a control plot was set up beside the trench-planted trees. Monitoring focused on key tree growth indicators, including leaf count and height, aiming to comprehensively evaluate the trench reuse through tree planting.

Figure 19: *Eucalyptus Trees Planted at the DRE Site in Kole*

3.4 Operating Conditions of the Site

One of the main advantages of deep row entrenchment is low operation and maintenance costs, but still, there are guidelines required in the maintenance of these sites. Key guidelines that were used include;

1. A logbook was kept noting down the date and time of collection and disposal, source of the sludge and the details of the emptier.
2. The DRE site was used to dispose of only FS from residential, and commercial buildings (like schools, colleges, hotels/resorts and offices). No other waste such as food waste from restaurants nor industrial waste of any nature whatsoever or toxic sludges were disposed of on DRE sites.
3. During rainfall seasons, the frequency of emptying in the same trench was lowered as during the rainy season, the leaching effect may be low (WASH Institute, 2021). More than one trench was used in this season.
4. The site was kept locked for safety reasons and to avoid trespassing by passersby. This was done by the pit emptiers using the site.

3.5 Site Monitoring

The following were the stages under monitoring and evaluation;

3.5.1 Stage 1 - Surface or Ground Water Tests

The risk of pollution of water sources was found to be minimal as sites were located at distances further than 30m from any point water sources and the water table was found to be deeper than 5m from the bottom level of the trench, hence minimal risk of pollution through leaching. In addition, results revealed no risk of nitrate and nitrite contamination of ground water as no concentrations of these were found in the fresh FS.

3.5.2 Stage 2 - Faecal Sludge Tests

To monitor sludge stabilization, tests were conducted every six months, analyzing samples for solids concentration, nutrient content, and pathogens. Tests included moisture content, total solids, chemical oxygen demand (COD), biological oxygen demand (BOD_5), faecal coliform, E. coli, helminth eggs, total nitrogen, potassium, and total phosphorous.

3.5.3 Stage 3 - Monitoring Progress of DRE Sites

Following set up of the DRE sites, sites were monitored to ensure that faecal matter is being disposed of correctly and site is being managed properly. This was done through periodic site inspections and engagements with the pit emptier on dumping procedures at the site.

3.5.4 Stage 4 - Tree Planting and Monitoring

Three months after backfill of the trenches, trees were planted on the trenches and their growth monitored. A control plot was also set up to compare tree growth on and off the trenches. Tree growth was to be monitored basing on height, number of leaves and stem diameter.

3.6 Faecal Sludge Test Parameters

Characterization of faecal sludge was done by testing for moisture content, total solids (TS), total suspended solids (TSS), pathogens, nutrient content, COD and BOD_5.

Moisture content was determined according to the gravimetric method at 105^oC over a 24-hour period (APHA/AWWA/WEF, 1998). Moisture content was then obtained by taking the difference between the initial weight of sample before oven drying at 105^oC and that after, as a percentage of the original weight of the sample.

Total solids were measured according to the gravimetric method at 105^oC over a 24-hour period (APHA/AWWA/WEF, 1998). Results were reported as g/Kg.

Total suspended solids (TSS) was quantified as the sludge that does not pass through a 0.45 µm filter after heating the sample at 105°C for 24h (APHA, 1998). Results were reported as mg/L.

COD was quantified as the oxygen needed to oxidize all organic matter in a sample. Results were reported as mg/L and mg/Kg.

BOD value was determined by incubating the sample with microbial seeds for five days at 20 ºC temperature and measuring dissolved oxygen (DO) level before and after incubation (APHA, 1998) and was reported as mg/L and mg/Kg.

Total nitrogen was quantified as the sum of total kjeldahl nitrogen (ammonia, organic and reduced nitrogen), NO_3 and NO_2. Results were reported as mg/L or mg/Kg of total N.

Total phosphorus (TP) is a measure of the sum of all P (dissolved form – orthophosphate, inorganic and organic). Similarly to nitrogen, phosphorus is an important source of nutrients. It was quantified by colorimetry after acid hydrolysis (APHA, 1998). Results are reported as mg/L or mg/Kg as P.

Coliforms and E. coli were measured by the pour plate method results. The number of colonies counted on a plate gives the colony-forming units, which is divided by the volume of sample used to get the CFU/volume (CFU/mL) (Velkushanova et al., 2021).

Helminth eggs are the infective agents for the types of diseases caused due to worms, known as helminthiases. These eggs are microscopic (around 20 to 80 µm for those that are important in the sanitary field) and are contained in variable amounts in wastewater, sludge and excreta. The modified Bailenger method was utilized to determine the helminths or presence of their eggs.

4.0 RESULTS, ANALYSIS AND DISCUSSION

4.1 Site Description

4.1.1 Kole Town Council

The site was located in Bung village, Eastern Ward B parish in Kole South County. Site coordinates were N 2˚17’8.0785”, E 32˚41’52.54732”. It was situated at approximately 134 m from the main road, 99 m from households, 53 m from wells and 49 m from a swamp. The site was located in a low-lying area, with a groundwater level of 9 meters.

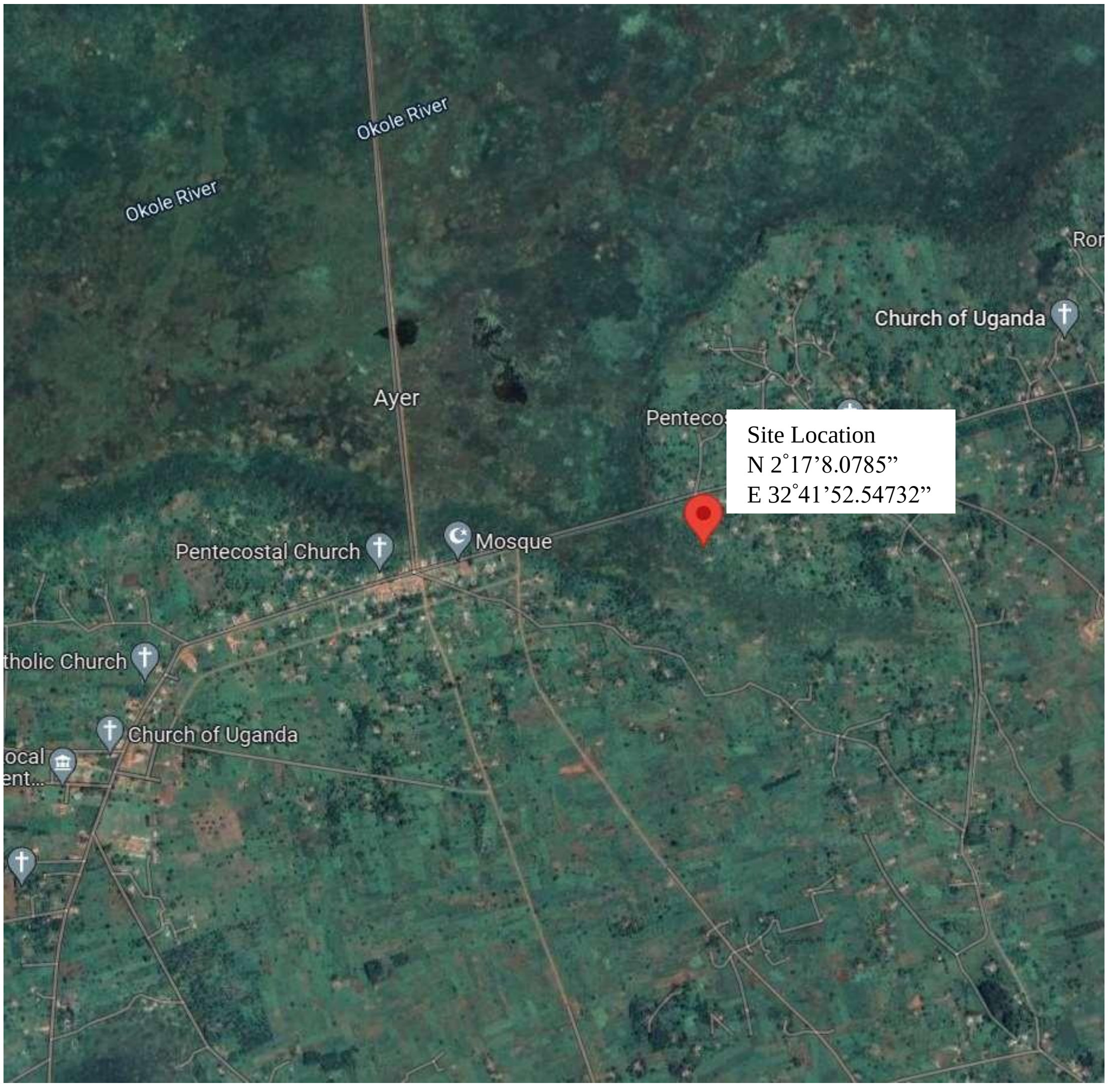


Figure 20: *Site Location in Kole Town Council*

In selecting the site, we received support from Kole Town Council leaders, including the Town Clerk and Mayor. Due to land constraint issues in the district, where the majority of the land is privately owned rather than government-owned, our options for site selection were limited.

Upon observation, the soil at this site appeared to be a combination of sand and clay. The soil felt coarse in texture, indicating a predominant presence of sand particles. There was no observable living organic matter in the soil.

Figure 21: *Soil Sample from the Kole Site*

4.1.2 Kamwenge Town Council

The site was located in Nsorora village, Kaburaisoke parish, Kibale County. The site coordinates were N 0º10’19.69876”, E 30º26’59.63276”. It was positioned around 420 meters from the main road, 100 meters from households, and no nearby wells. The site was situated on a hilly terrain with the groundwater level exceeding 15 meters.

Figure 22: *Site Location in Kamwenge Town Council*

Site selection was a collaborative effort involving Kamwenge district and town council leaders, including the Town Clerk, District Health Officer, and District Water Officer. Upon observation, the soil at this site was characterized as rocky or gravelly.

Figure 23: *Soil sample from the Kamwenge DRE site*

4.2 Faecal Sludge Sampling and Characterization

Initial faecal sludge samples were collected in April 2022 during the first dumping activity to analyze the characteristics of the sludge as received at the site. The second set of samples was collected in November 2022, six months after the initial dump. For the second sampling stage, the estimated age of the oldest sample was seven months, while the newest sample was five months, based on faecal sludge dumping records. Additional impromptu samples were collected in February 2023, with characterization focused on BOD$_5$, COD, E-Coli, and Faecal Coliform, due to concerns about possible sample contamination following results showing high BOD$_5$ and COD, which were later rectified as a miscalculation by the laboratory. The final set of samples was collected in July 2023 with the oldest samples being fourteen months.

Sampling was done using a backhoe at three points in the trench, as depicted in Figure 3. The collected samples were stored in air-tight containers, placed in a cooler box (Figure 24), and promptly delivered to the laboratory on the same day for analysis.

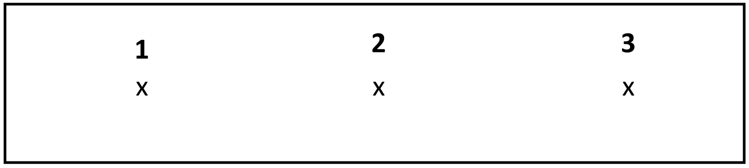
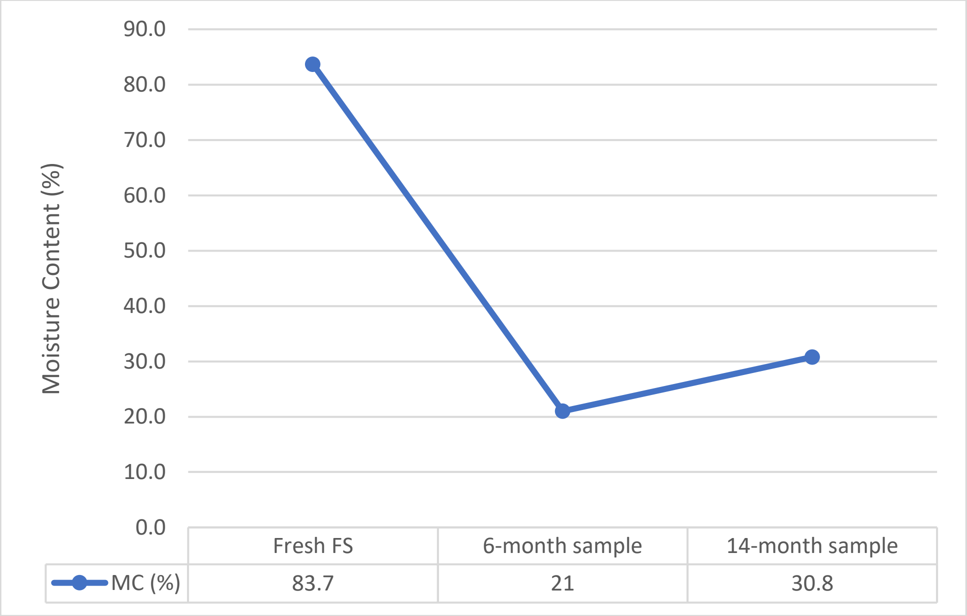


Figure 24: *FS Sampling Points*

Figure 25: *FS Samples in Ice Cooler Box*

4.3 Stabilization of Faecal Sludge

4.3.1 Moisture Content



	Fresh FS	6-month sample	14-month sample
MC (%)	83.7	21	30.8

Figure 26: *Moisture Content of FS*

The average moisture content of the received faecal sludge as received at the site was determined to be 83.7%. This aligns with findings from prior studies, such as Chaggu (2004), reporting an average moisture content in unlined pits during rainy and dry seasons to be between 80% and 92%, and Kimuli et al. (2016), noting an average of 80.9% ± 2.9%. After six months of burial, there was a significant reduction in the average moisture content to 21.2%, indicating a decrease of 75%. However, at fourteen months of burial, the moisture content slightly increased to 30.8%, attributed to rainwater ingress into the trenches during the rainy season.

4.3.2 Total Solids

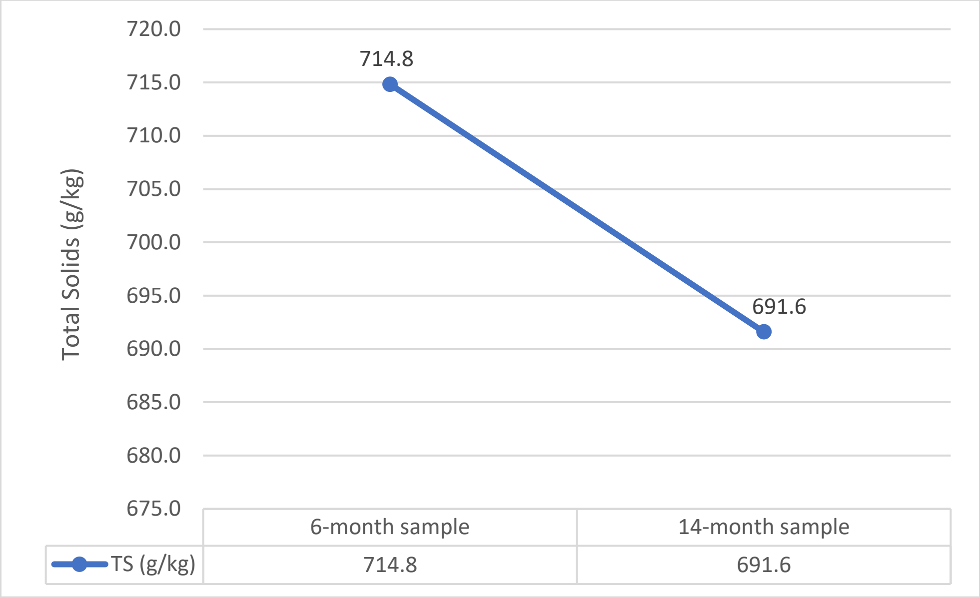


Figure 27: *Total Solids Content*

Total Solids (TS) represents the sum of suspended and dissolved solids. Total Suspended Solids (TSS) refers to the total filterable residue, measured in milligrams per liter, that either floats on the surface of or is in suspension in water, wastewater, or other liquids. It is removable by filtration as specified in Standard Methods.

The TSS of the faecal sludge samples as received at the site was reported to have an average of 64,640 mg/L. This surpassed the 52,500 mg/L recorded by Kone and Strauss (2014) and was nearly double the average of 33,356 mg/L from a study by Schoebitz et al. (2016).

After six months of burial, the TS averaged 705.8 g/Kg. This indicates a decrease in TSS content and total dissolved solids which shows a reduction in both organic and inorganic matter, suggesting an increase in the dewatering extent of the faecal sludge.

4.3.3 Helminth Eggs

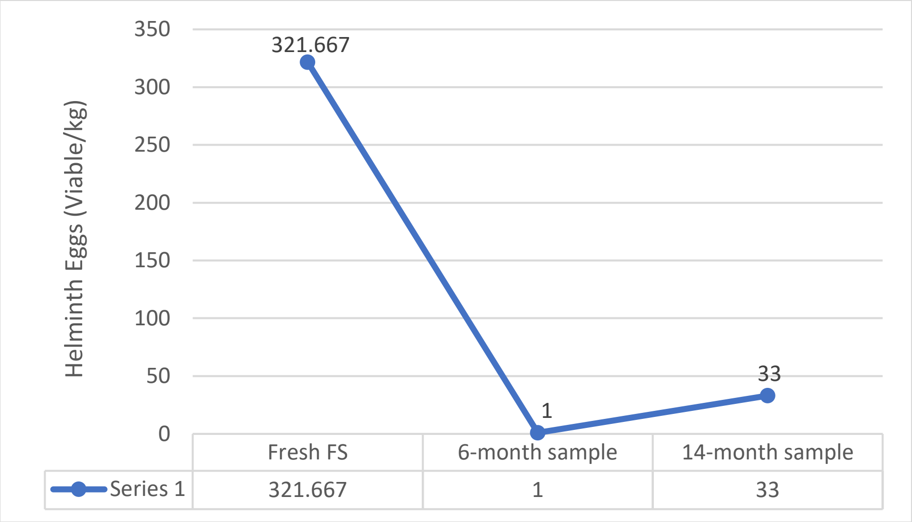


***Figure 28:** Helminth Eggs*

Helminth eggs are very resistant to environmental stress (for example, dehydration and heat) and are an important indicator of sludge quality. Helminths (parasitic worms) are eukaryotic parasites, which are prevalent in about one third of the world's population. Helminths include nematodes (round worms), cestodes (flat worms) and trematodes (flukes) (Strande et al., 2014). To be infectious they need to be viable and larval development needs to occur (Blanca, n.d.).

The initial count of Helminth Eggs in sludge, as received at the site, was reported to be 321.667 viable/kg. This count significantly reduced to 1 viable/kg after six months of burial. This indicated a substantial decrease in potentially viable helminth eggs due to the entrenchment of pit sludge. This observation aligns with a study conducted by IWMI and SANDEC (2002), which concluded that the rates at which various pathogens die off are influenced by ambient temperature, with more rapid die-off in warmer climates. According to IWMI and SANDEC (2002), the calculated survival time for Ascaris eggs in wet faecal sludge at ambient temperature is 10-12 months, and for tapeworms, it is 6 months.

These results suggest that buried pit latrine sludge poses minimal risk of helminth infection after six months of burial. However, at fourteen months of sludge burial, the helminth egg count was reported to have increased to 33 viable/kg. This increase is attributed to favorable conditions for the multiplication of helminth eggs within the trenches, likely due to the increase in moisture content as reported under section 4.3.1.

4.3.5 Chemical Oxygen Demand (COD)

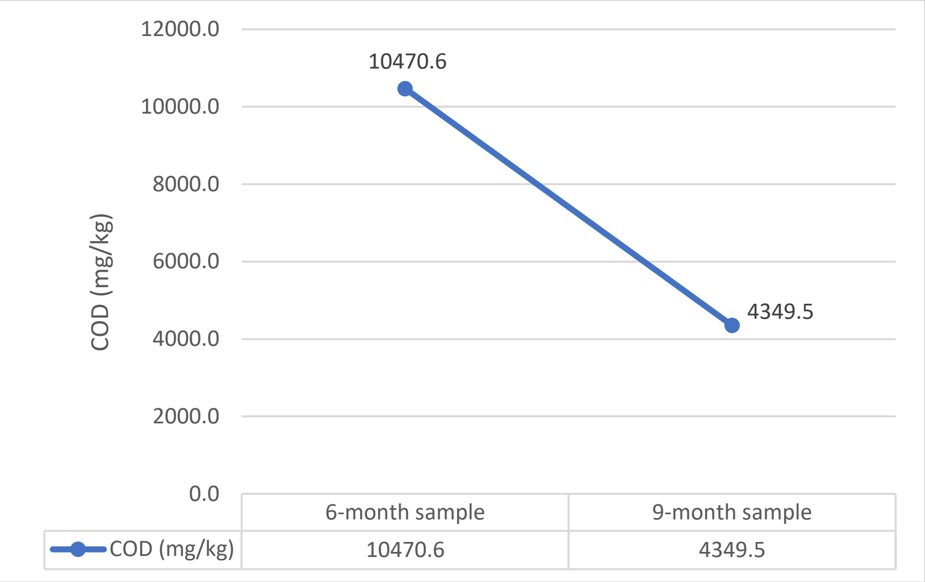


Figure 29: *Chemical Oxygen Demand*

COD (Chemical Oxygen Demand) measures the amount of oxygen required to oxidize organic matter in a sample. Initial results showed an average COD of 35,097.67 mg/L, much higher than the 21,520 mg/L reported by Kimuli et al. (2016). This elevated COD is attributed to a high concentration of organic matter in the pit latrine sludge samples, aligning with findings from Gudda et al. (2017). Higher COD concentrations necessitate longer treatment times and increased oxygen consumption for breaking down the substantial organic matter (Gudda et al., 2017).

After six months of sludge trenching, the average COD reduced to 10,470.6 mg/kg. Subsequently, at nine months, the COD further decreased to 4,349.5 mg/kg. This reduction signifies a significant level of stabilization in the sludge within the nine-month period.

4.3.6 Biological Oxygen Demand (BOD_5)

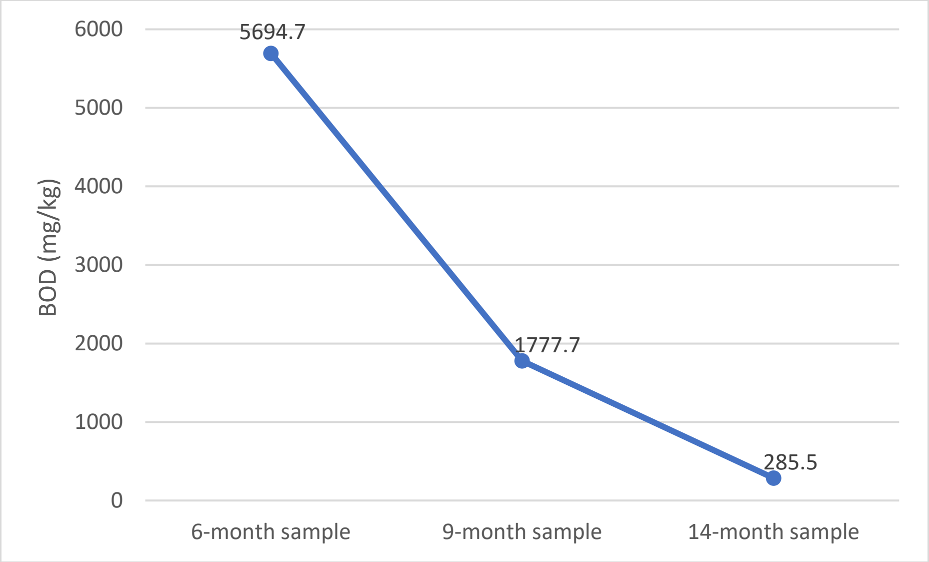


Figure 30: *Biological Oxygen Demand*

Fresh faecal sludge samples exhibited an average BOD_5 value of 5,724.67 mg/L, comparable to 7,600 mg/L reported by Koné & Strauss (2004) and twice the 2,126 mg/L reported by Bassan et al. (2013). This elevated BOD_5 aligns with the results observed in COD. Gudda et al. (2017) suggested that the disposal of solid waste into pit latrine vaults reduces the biodegradability of faecal sludge by increasing the organic load, which may contribute to these results, considering the presence of rubbish in the sludge.

After six months of sludge trenching, the average BOD_5 was reported at 5,694.7 mg/kg. Subsequently, at nine months, the BOD_5 further reduced to 1,777.67 mg/kg and 285.5 mg/kg at fourteen months. This reduction in BOD_5, similar to the COD results, indicates that the sludge has undergone significant stabilization within the fourteen-month period.

4.3.4 Nutrient Content

The average value of total nitrogen (TN) in fresh faecal sludge samples was 4,971 mg/L. After six months of sludge trenching, the TN average decreased to 22.75 mg/kg. This reduction was anticipated due to the conversion of TN into nitrogen gas under anaerobic conditions within the trenches. Moreover, as further stabilization of entrenched pit sludge occurs, nutrients like nitrogen, phosphorus, and potassium are released as fertilizers, leading to lower amounts in buried sludge compared to fresh sludge samples.

Fresh faecal sludge samples lacked traces of nitrates and nitrites, likely due to limited oxygen and the presence of microbes capable of producing them. However, in six-month-old entrenched samples, minute quantities of nitrates (3.26 mg/kg) and nitrites (1.77 mg/kg) were detected. This may have resulted from aerobic conditions in the trenches due to sludge exposure before backfilling, leading to nitrification. These minimal quantities were expected to be absorbed by tree roots, posing no risk of groundwater contamination. Nutrient content is expected to decrease further as stabilization continues, releasing nutrients as fertilizers that are absorbed by tree roots as stipulated by Bakare (2014).

4.4 Effect on Water Quality

The third objective of this project, which focused on the effect of faecal sludge on water quality, was not monitored. This decision was based on the fact that the existing water points were located at distances greater than thirty metres from the sites. For Kole Town Council, the site was approximately 53 meters away from the nearest seasonal wells, 134 meters from the main road, and 99 meters from the nearest households. Similarly, in Kamwenge, there were no nearby wells, and the site was approximately 100 meters from the nearest households and more than 500 meters away from the main road.

4.5 Effect on Tree Growth

Trees were planted on one of the sites but monitoring of tree growth had not yet begun.

5.0 CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

Selected sites were found to be suitable because of key characteristics such as, distance from surface and point water sources which was more than fifty metres, water table was deeper than five metres from the bottom level of the trench and flat surface which enabled easy operations. In addition, site set up was not complicated and sites were found to require minimal operation and maintenance.

Entrenched sludge samples of 6-months, 9-months and 14-months were found to have undergone stabilization with significant reductions in COD and biological oxygen demand (BOD_5). Reduction in moisture content, total solids and nutrient content was also realized. The results also revealed minimal risk of health infection from helminth eggs as the viable count was reported to have reduced from 322 viable/kg to 1 viable/kg.

The risk of pollution of water sources was found to be minimal as sites were located at a distance further than thirty metres from any point water sources and the water table was deeper than five metres from the bottom level of the trench, hence minimal risk of groundwater pollution through leaching. In addition, results revealed no risk of nitrate and nitrite contamination of ground water as no concentrations of these were found in the fresh FS.

Through this pilot project, we have developed a deeper comprehension of certain elements of DRE. These include aspects of site selection and the stabilization of faecal sludge in the trenches. As indicated by our findings, it is evident that DRE can serve as a viable interim solution for areas without adequate faecal sludge treatment facilities. This is achievable when due diligence is given to the selection of appropriate sites and the proper handling of faecal sludge.

5.2 Recommendations

- Further research on other reuse options of entrenchment, such as crop growth.
- Further study on the effects of entrenchment on septage. This study only investigated the effect of entrenchment on pit latrine sludges. The findings of this study are not transferable to septage.
- For future design of FSTPs in these towns, DRE can be considered as a method to reliably estimate the FS quantity and quality to develop cost efficient FSTPs.

5.3 Challenges

The major challenges encountered during project execution included:

- Limitations in the sampling of the entrenched samples as possibilities of contamination could not be ruled out.
- Solid waste in the FS which is non-biodegradable
- A section of pit emptiers did not have adequate FS transport mechanisms even when they were encouraged to dump.

5.4 Way Forward

The plan is to carry out a Technology Applicability Framework assessment and develop a business and management model for the technology’s scalability.

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