Optimisation of Sludge Management
in eThekwini Municipality

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Prof. C. J. Brouckaert

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Abstract

Sewage sludge processing for use or disposal has been a continuing challenge for many municipalities within South Africa. The main challenges encountered are the operation complexity and environmental impact posed by sewage sludge handling and disposal methods, along with high capital and operation cost. The problem is getting more complex by the rising volumes of sewage and more stringent disposal regulations. On the other hand, the rising awareness of the beneficial use of this valuable resource is forcing a closer look at how to process sludge effectively to harvest its benefits yet protect public health. This thesis aims to identify optimum alternatives for the sludge management practices within eThekwini municipality as a case study through a semi-quantitative assessment methodology. The principal sludge treatment and disposal methods described in the literature are reviewed and evaluated to determine their comparative performance in; (1) reducing sludge volume/weight, (2) reducing or removal of pollutants, (3) reducing or removal of pathogens, (4) environmental impact, (5) operation simplicity, (6) produced sludge reuse potential, (7) suitability and practicality as an ultimate disposal method, (8) reliability and robustness, (9) sensitivity to sludge quantity and quality change, (10) CAPEX, (11) and OPEX. The findings are compared to the nine years (2010 – 2018) data collected and processed, covering technology used and characteristics (physical, chemical and microbiological) of sewage sludge produced from 25 wastewater treatment works owned and operated by eThekwini municipality. Accordingly, a semi-quantitative score has been given to each treatment and disposal method. The semi-quantitative scores are then converted into a single overall score that aided in identifying the optimum sludge management alternatives. Finally, a recommendation for improving the sustainability of the sludge management practices is presented. Moreover, there is not, and will never be, a one-size-fits-all solution. Further investigation needs to be performed from the local economy and geographical context perspective.

Acronyms

ADS	Aerobic Digested Sludge
ANDS	An-aerobic Digested Sludge
BOD	Biochemical Oxygen Demand
C	Carbon
CAPEX	Capital Expenditure
CFU	Colony Forming Unit
COD	Chemical Oxygen Demand
CHS	Chemical Sludge
DAF	Dissolved Air Flotation
DO	Dissolved Oxygen
DS	Dry Solids
DWAF	Department of Water Affairs and Forestry
ECA	Environment Conservation Act
FC	Ferric Chloride
F/M	Food to Micro-organisms
FRP	Fibre Glass reinforced Plastic
G	Mixing Velocity Gradient
GBT	Gravity Belt Thickening
HHV	High Heat Value
LHV	Low Heat Value
HRS	Heat Recovery System
HRT	Hydraulic Retention Time
K	Potassium
LC	leachable concentrations
LPO	Low Pressure Oxidation
MAF	Moisture and Ash Free
MBR	Membrane Bio Reactor
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MSW	Municipal Solid Waste
N	Nitrogen
N/A	Not applicable
NEMWA	National Environmental Management: Waste Act
OPEX	Operation Expenditure

Org-N	Organic Nitrogen
P	Phosphorus
PCCR	Per Capita Capacity Requirement
PFU	Plaque Forming unit
PPE	Personal Protecting Equipment
PS	Primary Sludge
PVC	Polyvinyl Chloride
RDT	Rotary Drum Thickening
SANS	South African National Standard
SBR	Sequencing Batch Reactor
SRT	Sludge Retention Time (Sludge age)
SVI	Sludge Volume Index
SWD	Side Water Depth
TC	Total Concentration
TFS	Trickling Filters Sludge
TKN	Total Kjekdahl Nitrogen
TP	Total Phosphorus
TS	Total Solids
VSR	Volatile Solids Reduction
VSS	Volatile Suspended Solids
VSL	Volumetric Solids Loading
WAS	Waste Activated Sludge
WC	Western Cape
WRC	Water Research Commission
wt.	Weight
WWTW	Waste Water Treatment Work

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1. Introduction

The rapid population growth leads to increased water usage (Qasim et al., 2018). Other than population growth, water usage is also influenced by economic development and water use efficiency as urban areas grow (Qasim et al., 2018). The rise in water usage increases the generated municipal wastewater flow that requires treatment before safe disposal or reuse (Gurjar et al., 2017). Typically, the municipal wastewater is collected and treated in wastewater treatment plants. The municipal wastewater treatment plants produce a by-product called municipal or sewage sludge. The quantity of sewage sludge produced is directly related to the characteristics and the average dry-weather flow of the municipal wastewater being treated (Sperling, 2007, Qasim et al., 2018).

Unlike the treated effluent produced by the municipal wastewater treatment plants, sewage sludge must undergo treatment before safe disposal to the environment or beneficial utilisation (Girovich, 1996). The construction and operation of a sewage sludge handling and disposal facility can represent a significant portion of a wastewater treatment plant's total capital and operation cost (Qasim et al., 2018).

Sewage sludge handling and disposal have been considered the most troublesome phase of municipal wastewater treatment. The high capital and operation cost are not the only reasons but also the operation complexity and environmental challenges posed by sewage sludge handling and disposal methods. The problem is getting more complex by the rising volumes of sewage and more stringent disposal and reuse government regulations. With all the foreseen problems with sewage sludge handling and disposal, its composition of organic and inorganic matters represents a valuable resource. The treated sewage sludge can be beneficially used as a fertilizer, soil conditioner and other beneficial use products. In addition, sewage sludge can be used as a source of energy. Even ashes resulting from the sewage sludge incineration can also be used beneficially in construction. To ensure the recognition of the sewage sludge value through beneficial use, the United States Environmental Protection Agency (EPA) and the Water Environmental Federation (WEF) promote the term Biosolids (Turovskiy and Mathai, 2006). However, in this thesis, the terms sludge or sewage sludge are used interchangeably.

Recognising the sewage sludge beneficial use and the importance of safe disposal, the South African Department of Water Affairs and Forestry (DWAF), along with the Water Research Commission (WRC), developed a guideline for beneficial use and safe disposal of sewage sludge. The guideline name is “Guidelines for the Utilisation and Disposal of Wastewater Sludge”, it consists of 5 volumes that provide the framework necessary for sludge quality classifications, utilisation and disposal options. The guidelines are discussed in further detail in the literature review chapter. However, it is not the only legislation that guides the use and disposal of sewage sludge in South Africa. Overview of legislation that governs the beneficial use and disposal of sewage sludge in South Africa are summarised in Table 1-1. However, it must be noted that the South African environmental legislative environment is complex and regulated by more than one Government Department (Herselman et al., 2009). The Department of Water Affairs and Forestry (DWAF) and Department of Environmental Affairs and Tourism (DEAT) are the lead regulatory authorities for sludge disposal (Herselman et al., 2009).

Table 1-1 Overview of Legislation that Governs the Beneficial Use and Disposal of Sewage Sludge in South Africa (WC- Sewage Sludge Status Quo Report, 2020/21)

Legislation	Overview
Environment Conservation Act (ECA) (Act No. 73 of 1989)	Sewage disposal is one of the listed activities in section 21 (2) (i) that may have a negative impact on the environment
Guidelines for the Utilisation and Disposal of Wastewater Sludge: Volumes 1 to 5	They are developed to assist different stakeholders in promoting the safe use and disposal of sewage sludge. The guidelines also define sewage sludge and detail a sludge classification system along with the appropriate beneficial use of disposal.
National Environmental Management: Waste Act (NEMWA) (Act No. 59 of 2008)	Schedule 1 (Section 19), Category A: identifies waste management activities that require a waste management licence. Annexure 1 - Waste Classification and Management Regulations GN 634 - (August 2013): specifies wastes that do not need to be classified (Regulation 4(1)) or assessed (Regulation 8(1)(a)) under SANS 10234. Sewage sludge is not specified under item 2 of Annexure 1; hence it must be classified and assessed according to SANS 10234.
National Norms and Standards for the assessment of waste for landfill disposal (August 2013)	This standard is part of the National Environmental Management: Waste Act (NEMWA) (Act No. 59 of 2008). Under Regulation 8(1) (a) of the Waste Classification and Management Regulations (2013), the standards provide requirements for waste evaluation before landfill disposal. The evaluation entails identifying chemical constituents in waste, sampling and testing to estimate the total (TC) and leachable (LC) concentrations of the elements and chemical substances listed in section 6 of the standard.
National Norms and Standards for disposal of waste to landfill (August 2013)	This standard is part of the National Environmental Management: Waste Act (NEMWA) (Act No. 59 of 2008). Regulation 8(1) (b) of the Waste Classification and Management Regulations (2013) establishes the requirements for waste disposal to landfills. As per section 4(1) of these standards, waste assessed following the Norms and Standards for Assessment of Waste to Landfill Disposal must be disposed of in a licenced landfill. The regulation also specifies deadlines for the prohibition of various waste types from landfill disposal, with the prohibition on liquid landfill disposal taking effect in August 2019. This could impact sewage sludge disposal to landfills, depending on the dryness of sewage sludge leaving wastewater treatment works.

1.1 Aims and objectives

This research aims to identify the optimum sewage sludge treatment, reuse and ultimate disposal method for eThekwini Municipality through semi-quantitative analysis. The objectives of this research are;

- To collect sewage sludge data from all wastewater treatment plants owned and operated by the municipality.
- Validate the collected data.
- Select technologies and equipment for evaluation.
- Develop feasibility factors for the technologies and equipment evaluation.
- Set the weighing scale for the semi-quantitative analysis selected for this research.
- Perform through a semi-quantitative analysis

The above will be performed taking the following into consideration;

- The sewage sludge type and quantities.
- The characteristics of the sewage sludge.
- Technologies and equipment currently in use by the municipality.
- Environmental regulations for disposal and reuse of sewage sludge.

The following research questions will be answered throughout the research;

1. What is the current sewage sludge treatment, reuse and disposal status within eThekwini Municipality?
2. What are the optimum treatment, reuse, and ultimate disposal alternatives - based on currently collected data?
3. How Likert Type Scale can be utilised by eThekwini Municipality to optimise the sludge management system selction , planning and decision making?

1.2 The research structure

Chapter 2- Literature review – depicts what constitutes sewage sludge and highlight the typical sewage sludge quantities and characteristics. It also includes (1) an in-depth review of several key equipment and technologies used in sewage sludge treatment, reuse and disposal, and (2) an introduction to the semi-quantitative Five-point scale scoring system used in the research.

Chapter 3- Materials and Methods – will illustrate and explain the validation of the collected data. Present a case study of sewage sludge reuse and disposal within eThekwini municipality. It highlights the technologies and equipment selected to be assessed for sewage sludge treatment, reuse and ultimate disposal. It also describes the selected feasibility factors (criteria) and their assessment methods to evaluate the selected technologies and equipment.

Chapter 4- Results and discussion – It will explain and discuss the results of assessing the selected technologies and equipment feasibility factors.

Chapter 5- Conclusion- will address the main conclusion established from this research.

Chapter 6- Recommendations- will address recommendations to improve the current situation within eThekwini municipality. It will also include recommendations for future studies.

2. Literature review

The following literature review examines the typical sewage sludge characteristics, quantities, treatment technologies, disposal methods and beneficial use. The title of some subheadings includes the reference(s) since it applies to the entire section.

2.1 Sewage Sludge Constituents, Typical Characteristics and Quantities

The constituents removed and/or produced in municipal wastewater treatment plants include Screenings, Grit, scum, primary sludge, secondary sludge and tertiary/chemical sludge. The source of these constituents varies according to the type of plant, treatment process used, and operation method. The primary and secondary sludge are by far the largest among all constituents (Turovskiy and Mathai, 2006). It is essential to determine the quality and quantity of each of these constituents and the disposal method in use since its presence in the sludge will significantly impact the selection of the sludge treatment equipment, technologies, and disposal method (Qasim et al., 2018).

2.1.1 Screenings (Qasim et al., 2018)

Screenings are residuals retained over coarse or fine screens. The quantity of the screenings may vary significantly between treatment plants. The variation of screenings quantity depends on the type of wastewater, geographical location, weather, type and size of the screen. Screens with smaller openings will retain larger screening quantities compared to screens with larger openings. For example, screens with openings size of 12.5 mm can retain an average quantity of 44–110 $m^3/10^6$ m^3 of screenings. However, screens with openings size between 3 to 6 mm can retain a screening quantity of 30–60 $m^3/10^6$ m^3 following a coarse screen.

The screenings collected by coarse screen may contain large debris of rags, paper, plastics, cans, leaves, and tree branches; however, the screenings collected by fine screen may contain small rags, paper, plastics, Grit, food waste and faeces. Typically, the screenings contain 60% to 80% moisture with density varying between 700 and 100 kg/m^3. The screenings are odorous and attract vectors. The most common method of screenings disposal is:

a) Landfill
b) Co-disposal with solid waste
c) Incineration
d) Discharge to head of works after grinding or comminution (not recommended)

The last disposal method is not recommended because many of the downstream equipment, such as mixers, air diffusers, and instrumentations probes, are subject to fouling from reconstituted rags and strings.

2.1.2 Grit (Qasim et al., 2018)

Grit can be described as small inert, dense and abrasive solids that are removed from wastewater after screenings. Grit includes sand, pebble, cinders, silt, bone chips, broken glass, coffee seeds, and eggshells. It does not decompose easily and is heavier than water. As a result, it settles and accumulates in pipes, channels and tanks, reducing flow and treatment capacities. Its abrasive nature is associated with wear to equipment such as pumps and mixers. For the above reasons, grit removal from wastewater is essential. Grit removal units always produce objectionable odorous compounds and VOCs due to stripping action either due to turbulence in non-aerated units or due to introducing air in aerated units. Grit is typically removed by settling at the following locations;

a) Before the raw wastewater pump station, this location provides maximum protection for the downstream equipment. Typically, the grit removal units at this location are deep and associated with high construction cost.
b) Downstream of the raw wastewater pump station. At this location, the grit removal unit is at the ground level; thus, they are easy to construct and operate. However, raw sewage pumps will be subject to severe wear if not abrasion resistance.
c) During Degrittering of Primary Sludge. However, the capital and operation cost of this option is low, the abrasive nature of the grit increase the maintenance cost.

Grit is typically characterised by;

- Moisture: 13 to 65% depends upon provided drainage.
- Volatile solids: 1 to 56% depending on the use of grit separators and washers.
- Bulk density: 1300 to 1900 kg/m^3, depends significantly on the moisture and organic matter content.
- Specific Gravity: 1.3 to 2.7, depends on organic matter. The higher the organic matter, the lower the Specific Gravity.

The volume of grit removed varies from 0.005 to 0.05 m^3/10^3 m^3 of wastewater. The combined sewer systems and sewers that contribute excessive infiltration and inflow typically contain significantly higher grit. Grit is typically sent for land fill. Some landfill sites will require lime stabilisation before landfilling. In large plants, grit may be incinerated with other solids, and the residue is landfilled or land spread.

2.1.3 Scum (Turovskiy and Mathai, 2006 , Qasim et al., 2018)

Scum consists of the floatable materials skimmed from the surface of primary and secondary settling Tanks. Primary scum consists of fats, oils, grease, wax, soaps, vegetable and fruit skins, hair and floating debris such as plastic, cotton, cigarette tips and rubber products. It can build up in piping, thereby restricting flow and increasing pumping costs, and can foul instruments (probes and elements). Secondary scum tends to be mostly floating activated sludge or biofilm, depending on the type of secondary treatment used. The moisture content of scum typically is not measured. The quantity of the scum is typically 8 g/m^3. It may be disposed of by pumping to sludge digesters, concentrating, and then incinerating with other residuals, or drying and then landfilling.

2.1.1 Primary Sludge (Turovskiy and Mathai, 2006 , Qasim et al., 2018)

The majority of wastewater treatment plants use primary settling to remove readily settleable solids from raw wastewater. Typically, in a plant with primary settling and a conventional activated sludge as a secondary treatment process, the dry weight of the settled primary sludge solids is about 50% of that for the total sludge solids. Fresh primary sludge is a grey or light brown suspension, due to its high organic content, it decays quickly. It becomes septic, which can be identified by its change to a dark grey or black colour and an objectionable odour. The total solids concentration in raw primary sludge can vary between 1 and 6%. The primary sludge final concentration in the primary settling tanks is affected by (a) the type of solids in the raw wastewater (b) and the frequency of sludge withdrawn from the primary settling tank. Some operators withdraw the primary sludge less frequently; this allows the sludge to thicken further in the primary settling tanks, thereby increasing the Primary sludge concentration. Primary Sludge is easier to dewater if compared to biological and chemical sludges. First, it’s readily thickened by gravity, either within the primary settling tank or in a gravity thickener. Second, it comprises discrete particles and debris and will produce a drier cake and give better solids capture with low conditioning requirements. Physical Characteristics and quantity of Primary sludge is presented in Table 2-1; and typical composition is presented in Table 2.2

2.1.2 Secondary Sludge (Turovskiy and Mathai, 2006)

Secondary sludge, also known as biological sludge, excess activated sludge, biosolids and biological biosolids, is produced by treatment processes such as activated sludge, membrane bioreactors, trickling filters, moving beds bioreactor and rotating biological contactors. The secondary sludge is made of bacterial colonies and suspended, inert and volatile material. A sludge floc is a name given to this combination. The sludge floc's integrity and composition play a critical role in the gravity separation process in the secondary settling tanks. The secondary sludge produced by a healthy treatment system is typically light grey or dark brown. Wastewater treatment Plants with primary treatment (Screening, Grit Removal and primary settling tanks) typically produce a relatively pure secondary sludge due to the bacteria consuming the soluble and insoluble biodegradable organics in the secondary treatment system. Secondary sludge containing debris such as grit, plastics, paper, and fibres, will be produced at plants lacking primary treatment. The level of putrescibility of the secondary sludge depends on the type of biological treatment applied. In some processes where extensive aeration and low loaded system are used; the produced secondary sludge may be stable enough to not require any further stabilisation step. Secondary sludge is more difficult to dewater than primary sludge because of the way the water is distributed and trapped within the sludge floc.

In the secondary treatment process, the essential variables to quantify the secondary sludge production thus the amount to be wasted daily (WAS) are (a) the amount of organic substrate (BOD or COD) removed, (b) the mass of microorganisms in the system, (c) the inert suspended solids in the influent to the system, (d) and the amount of suspended solids lost in the effluent.

These variables can be presented in the following equations

$$P_X = Y\,S_r - K_d\,X \quad \text{.. (1)}$$

$$WAS_T = P_X + I_{NV} - E_T \quad \text{.. (2)}$$

where

P_x = net growth of biological solids as volatile suspended solids (VSS), kg/d

Y = gross yield coefficient, kg/kg

S_r = The substrate removed, BOD or COD (S_0 – S), Kg/day

S_0 = influent substrate (BOD or COD), kg/d

S = effluent substrate (BOD or COD), kg/d

k_d = endogenous decay coefficient, d^{-1}

X = biomass in aeration tank (MLVSS), kg

WAS_T = total waste activated sludge solids, kg/d

I_{NV} = influent non-volatile suspended solids, kg/d

E_T = effluent suspended solids, kg/d

By rearranging equation (1) the effect of the Sludge age (Sludge Retention time - SRT) can be shown

$$P_X = \frac{Y\ S_r}{1 + K_d\ (SRT)} \quad \text{.. (3)}$$

Similarly, equation (1) can be rearranged to show the effect of Food-to-Microorganisms ratio (F/M).

$$P_X = Y\ S_r - \frac{K_d\ S_r}{F/M} \quad \text{.. (4)}$$

The above equations show that the secondary sludge production P_X increases with the increase of F/M and S_r . It also shows that the secondary solids production P_X decreases as SRT increase and F/M decrease. As sludge handling is typically expensive, minimising the sludge production is a goal to most of the wastewater treatment plants. This can be achieved by using high values of SRT or low values of F/M. However, there are other cost factors to be considered, such as increases in the aeration tank volume, long aeration hours, and so on. Operating across a range of conditions is therefore desirable. Trial-and-error is required to determine the least costly and most efficient system operation philosophy.

Equation (1) can be rearranged to predict the relation between the net growth of the secondary sludge P_x/X and net substrate removed per day S_r/X ;

$$\frac{P_x}{X} = Y\ \frac{S_r}{X} - K_d \quad \text{... (5)}$$

Equation (5) shows that the relation between P_x/X and S_r/X is linear , and the slope is the gross yield coefficient (Y), and the decay coefficient (k_d) is represented by the interception.

If Sr/X or SRT (X/Px) are known, and the secondary sludge production can be measured. In that case, a simple observed net yield Y_{obs} might be calculated, assuming a negligible amount of cell debris and the I_{NV} to be added to the net WAS; Equations (1) and (3) are rearranged to show:

$$Y_{obs} = \frac{P_X}{S_r} = Y - \frac{K_d}{S_r/X} = \frac{Y}{1 + K_d\ SRT} \quad \text{... (5)}$$

Where Y_{obs} is the Observed net yield coefficient = Kg VSS produced / Kg Substrate (BOD or COD) removed.

Equations (1) , (2) and (5) can be combined and simplified using the flow to quantify the daily sludge wasted WAS_T as follows;

$$WAS_T = \frac{Q[Y_{obs}\,(S_0 - S) + I_{NV}]}{10^3\ g/Kg} \quad \text{.......} \quad (6)$$

Y_{obs} = observed yield, g VSS /g substrate removed

Q = influent flow, m3/d

S_0 = influent substrate concentration, g/m^3 (mg/L)

S = effluent substrate concentration, g/m^3 (mg/L)

I_{NV} = influent non-volatile suspended solids concentration, g/m^3 (mg/L)

The other factors that affect secondary sludge production are; (a) Nitrification/denitrification process, (b) substrate composition, (c) Dissolved oxygen type (air or pure oxygen) and level maintained in aeration tank, (d) wastewater temperature, (e) feed pattern and (f) type of process used.

The water (moisture) distribution within the secondary sludge (biosolids) ; The water content in biosolids can be as high as 99%, with the following distribution forms; (1) free water; is not attached to the biosolids particles and can be separated by gravity settling; (2) interstitial water (Floc water) that is trapped within the flocs and can be removed by strong mechanical forces; (3) surface water;
is held on to the surface of the solid particles by adsorption and adhesion and can be also removed by mechanical forces.; and (4) intracellular and chemically bound water; is biologically and chemically bound to the biosolids' organic and inorganic matter as part of cell material (Gurjar et al., 2017). Physical Characteristics and quantity of secondary sludge are presented in Table 2-1, and typical composition is presented in Table 2-2.

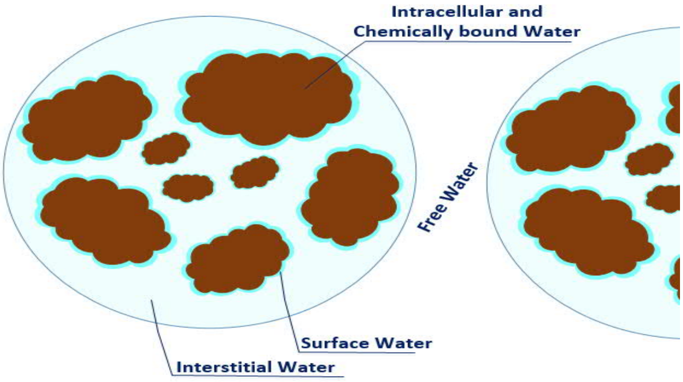


Figure 2-1 Water distribution within the secondary sludge

2.1.3 Tertiary and chemical sludge (Turovskiy and Mathai, 2006 , Qasim et al., 2018)

Tertiary sludge is the sludge produced downstream of the secondary treatment through filtration, flocculation or precipitation without chemicals addition. This sludge has the same characteristics as the secondary sludge.

Chemical sludge is the sludge produced upstream or downstream of the secondary treatment by the addition of chemicals. The chemicals are used to precipitate and remove hard-to-remove substances. In other instances, the chemicals are used to improve the removal of the suspended solids. An example of precipitation and removal of hard-to-remove substances using chemicals is the precipitation and removal of phosphorus. Typical chemicals used for phosphorus removal include lime, alum, ferrous chloride, ferric chloride, ferrous sulphate, and ferric sulphate. Some treatment plants utilise the secondary treatment to add the chemicals; thus, the sediments are mixed with the biological sludge. Some other treatment plants add chemicals to the secondary treated effluent before filtration or settling to improve the final effluent's solids removal or remove excess phosphorus. The addition of chemicals to the primary settling tank to remove phosphorus is also exercised in some treatment plants. It has to be noted that the addition of chemicals will influence the sludge characteristics and influence it’s dewaterability. The addition of some chemicals may have a side effect such as changing water pH and alkalinity and may require the addition of an alkaline chemical to readjust these parameters.

The chemical sludge production is typically calculated from the anticipated chemical reactions. However, competing reactions that are not considered may lead to a wrong estimate. Therefore it’s recommended to perform a jar test to establish the optimum operating parameters (pH, mixing, reaction time, etc.) and the sludge quantity to be produced.

Table 2-1 Typical Physical Characteristics of Primary, Secondary and Tertiary / Chemical Sludge (Qasim, 2018)

Source of Sludge	**Quantity mg/l (g/m^3)**	**Typical Range**			
		Solids Content %	**Ratio Kg VSS/Kg TSS**	**Specific Gravity (Water =1)**	
				Dry Solids	**Bulk Sludge**
PS	105 - 170	1 - 6	0.6 – 0.85	1.1 – 1.5	1.001 - 1.02
WAS	70 - 100	0.8 – 1.2* 0.2 – 0.6**	0.7 – 0.85	1.1 – 1.4	1.000 – 1.003
PS and WAS	150 - 250	1 – 4	0.65 – 0.85	1.1 – 1.5	1.001 – 1.015
ANDS	120 -220	3 - 6	0.4 – 0.6	1.3 – 1.8	1.01 – 1.03
CHS					
- **Metal Salts**	200 – 300	0.5 – 4	0.5 – 0.6	1.3 – 1.6	1.001 – 1.015
- **Low lime**	240 – 400	2 – 8	0.4 – 0.5	1.5 – 1.9	1.01 – 1.04
- **High lime**	600 - 1300	4 - 10	0.3 -0.45	1.6 – 2.1	1.02 – 1.06

Note: * from secondary settling tank / ** from aeration tank

Table 2-2 Typical Composition of Raw Primary and Secondary and Combined Digested Sludge (Qasim,2018)

Parameters	**Raw Primary Sludge**	**Raw Wate Activated Sludge**	**Combined Digested Sludge**
pH, standard unit	5 - 8	6.5 - 8	6.5 - 7.5
Alkalinity, mg/L as $CaCO_3$	500 - 1500	200 - 1100	2500 - 3500
Organic acids, mg/L as HAca	200 - 2000	1100 - 1700	100 – 600
Ratio of BOD_5/VSS	0.5 – 1.1	-	-
Ratio of COD/VSS	1.2 – 1.6	2 - 3	-
Ratio of Org-N/VSS	0.05 – 0.06	0.08 -0.1	-
Cellulose, % of dry wt.	8 - 15	5 - 10	8 - 15
Hemicellulose, % of dry wt.	2 - 4	-	-

Parameters	Raw Primary Sludge	Raw Wate Activated Sludge	Combined Digested Sludge
Lignin, % of dry wt	3 - 7	-	-
Grease and fats (ether soluble), % of dry wt.	5 -8	5 - 12	5 - 20
Protein, % of dry wt.	20 - 30	30 - 40	15 - 20
Nitrogen as N, % of dry wt.	1.5 - 4	2.5 – 8.5	1.5 – 6
Phosphorus as P, % of dry wt.	0.3 – 1.2	1.2 - 9	1 – 5
Potassium as K, % of dry wt.	0 – 0.8	0.4 – 0.6	0.1 - 2
Heat content, kJ/kg VSS	20 000 – 29 000	16 000 – 23 000	6 000 – 14 000
Lindane as $C_6H_6C_{16}$, mg/kg	0.6	1	-
Chlordane, mg/kg	2.6	4.4	-
Metal, mg/kg dry solids			
• Arsenic	-	1.1 – 230	-
• Cadmium	-	1 – 3 410	3 - 3 400
• Calcium	-	-	1 000 – 250 000
• Chromium	-	10 – 99 000	25 – 28 000
• Cobalt	-	11.3 -2 490	-
• Copper	-	84 – 17 000	80 – 10 000
• Iron	-	1 000 – 154 000	1000 -150 000
• Lead	-	13 – 26 000	15 – 20 000
• Magnesium	-	-	1 000 – 20 000
• Manganese	-	32 - 9870	20 – 7 000
• Mercury	-	0.6 – 56	0.5 - 10
• Molybdenum	-	0.1 - 214	-
• Nickel	-	2 - 5300	2 – 3 500
• Selenium	-	1.7 – 17.25	-
• Tin	-	2.6 - 329	2.5 - 300
• Zinc	-	101 – 49 000	100 – 28 000

Typical heavy metals found in sludge, vary widely, as shown in Table 2-2 . High concentrations of such toxic heavy metals may limit the sludge utilisation for composting and land application.

2.1.4 Pathogenic organisms in sludge (Andreoli et al., 2007)

Several organisms may be found in the sludge such as saprophytes, commensals, symbionts or parasites. Only parasites are pathogenic and able to cause illness to humans and animals. There are five groups of pathogenic organisms may be found in sludge (a) helminths, (b) protozoa, (c) fungi, (d) viruses and (e) bacteria. The pathogenic organisms' origin is either human sources, reflecting the population's health status and the region's sanitation level or from animal sources, or through vectors in sewers, mainly rodents. The pathogens in sludge, pose risks to human health due to:

- High incidence of parasitism especially in the developing countries
- Helminth eggs can survive for a long time in the environment; for example, Ascaris sp. eggs can survive up to seven years.
- The dose required to infect the host is low; for example, one egg or cyst may be enough to infect the host.

The level of pathogens in the wastewater from a specific municipality varies greatly, and it mainly depends on (a) Socio-economic level of the population, (b) Sanitation conditions, (c) Geographic location, (d) and the presence of agro-industries. The typical concentration of pathogens in the sludge is presented in Table 2-3.

Table 2-3 Typical concentration of pathogenic organisms in sewage sludge

Pathogen	Type of sludge	Density of pathogens (dry weight)
Helminth Ova	Primary Sludge WAS Anaerobic Digested Sludge Dewatered Raw sludge Anaerobic Sludge	10^3 - 10^4 CFU/Kg 10 - 1.4 × 10^3 CFU/Kg 10^2 - 10^3 CFU/Kg 10^1 - 10^3 CFU/Kg 6.3 X 10^3 - 1.5 x 10^4 CFU/Kg
Protozoan cysts	Primary Sludge Digested Sludge Dewatered Raw sludge	7.7 X 10^4 - 3.1 x 10^6 CFU/Kg 3.1 X 10^4 - 4.1 x 10^6 CFU/Kg 70 - 10^2 CFU/Kg
Total coliform	Primary Sludge Waste activated sludge	10 - 8.8 x 10^6 CFU/g 7 x 10^8 CFU/g
Faecal coliform	Primary Sludge Waste activated sludge	10 - 8.8 x 10^6 CFU/g 8 x 10^6 CFU/g
Viruses	Primary Sludge Anaerobic Digested Sludge Waste activated sludge	3.8 X 10^3 - 1.2 x 10^5 PFU/ L 10 - 10^3 PFU/ L 10 - 8.8 x 10^6 PFU/ L

2.2 Processing/treatment and disposal of sludge

This section discusses the broad subject of sewage sludge processing/treatment and disposal. Sludge processing/treatment and disposal procedures are reviewed and evaluated by discussing methods, materials and equipment used today. The sludge treatment units' design aspects are not part of this thesis and will not be discussed in detail. This section begins with the Sludge thickening and ends with ultimate sludge disposal. Figure 2-2 summarises the sludge handling and disposal alternatives that will be discussed. This section is critical to understand the selected sludge treatment technologies and equipments performance, and limitations to aid the scoring.

2.2.1 Thickening (Wang et al., 2007)

Thickening is the process of removing free water from sludge after it’s separation from wastewater. The main objective of thickening is to reduce the volume of the water and concentrate the biosolids. Thickening is utilised at most wastewater treatment plants to concentrate the biosolids and reduce capital and operation cost of subsequent sludge processing steps by reducing its volumetric loading. For example, thickening sludge from 1 to 2% solids concentration, halves the sludge volume. Further concentration to 5% solids, reduces the volume to one-fifth of its original volume. Some of the thickening processes may provide additional operational benefits, such as Sludge blending, Flow equalisation, Storage, Scum removal and clarification. The most commonly used sludge thickening processes are (a) gravity thickening, (b) dissolved air floatation thickening, (c) Centrifugal thickening, (d) gravity belt thickening, (e) and rotary drum thickening. More datils on the type of thickening processes can be found in Appendix 5.

2.2.1 Sludge Stabilisation

After thickening, the sludge may undergo conditioning and dewatering, or it may be sent directly for stabilisation (McFarland, 2001) . The purpose of this process is to stabilise the organic biodegradable (volatile) fraction of the sludge and/or alter the physical/chemical properties of the sludge to achieve the following process objectives; (1) reduction or elimination of vector attraction, (2) reduction of pathogen concentrations, (3) elimination of offensive odours, and (4) Inhibition or reduction or elimination of the potential for putrefaction (McFarland, 2001).

The sludge stabilisation can be accomplished by one of the following methods (Andreoli, 2007);

- Biological methods: specific bacteria promote the stabilisation of the biodegradable fraction of the organic matter. The principal methods are aerobic-digestion, Autothermal thermophilic aerobic digestion, anaerobic-digestion and composting.
- Non-Biological methods: this includes physical and chemical means of stabilisation. The principal methods are lime stabilisation, heat treatment and chlorine oxidation

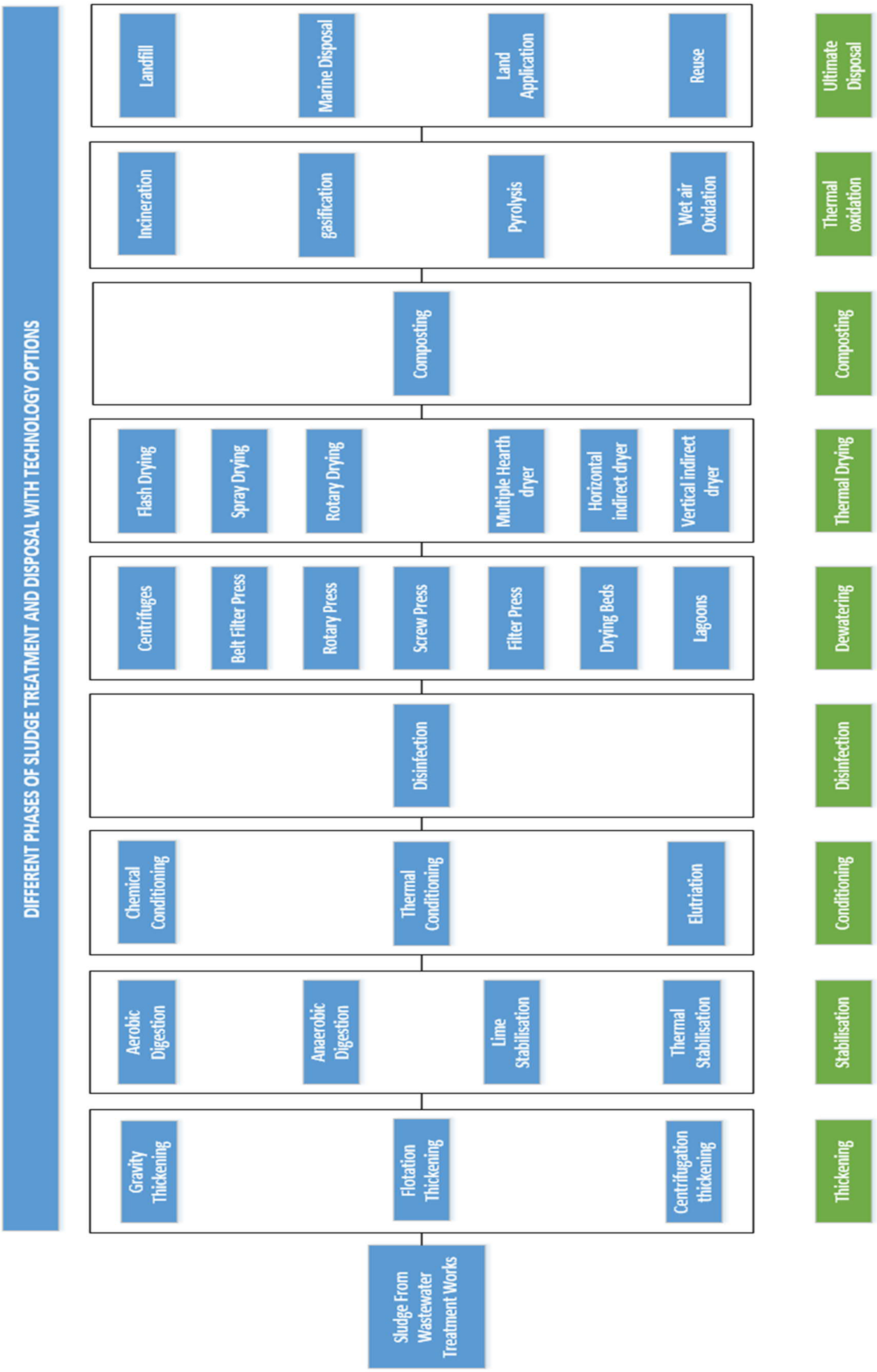
In addition to the above objectives, stabilisation, except for lime stabilisation, reduces sludge volume to be used or disposed of (McFarland, 2001). The selection of the most suitable stabilisation method depends mostly on the ultimate sludge disposal method (Qasim et al., 2018).

The most common sludge stabilisation processes are; (1) Aerobic digestion , (2) anaerobic digestion, (3) lime stabilisation, and (4) Thermal stabilisation. More details on the stabilisation processes can be found in Appendix 6.

2.2.2 Sludge Conditioning

Sludge conditioning is a process to enhance sludge thickening and dewatering characteristics primarily by increasing particle size by combining the small particles into larger aggregates and minimising hydration (Gurjar et al., 2017). Sludge conditioning is more common as a pre-dewatering step (Andreoli et al., 2007). Sludge conditioning is typically performed using chemical and physical methods(Qasim et al., 2018). The chemical methods utilise inorganic and organic chemicals (Qasim et al., 2018). However, the physical methods include heat treatment, elutriation, freeze and thaw, irradiation, and ultrasonic vibration (Qasim et al., 2018). Chemical conditioning is the most common method among all (Qasim et al., 2018). Some conditioning processes exhibit additional benefits, such as disinfection and odours elimination (Andreoli et al., 2007). The most common sludge conditioning processes are; (1) chemical conditioning, (2) thermal conditioning, and (3) elutriation. More details on the sludge conditioning processes can be found in Appendix 7.

Figure 2-2 Summary of sludge handling and disposal alternatives



2.2.3 Disinfection (Wang et al., 2007 , Wang et al. 2008)

Humans may be exposed to pathogens in sludge in various ways and at wildly varying concentrations; all depends on the processing and disposal methods utilised. Therefore sludge disinfection becomes an essential procedure to ensure public health safety. Typical methods for sludge disinfection include Heat, chemicals and radiation processes. Heat disinfection involves processes such as thermal conditioning, thermal stabilisation, heat drying, composting and pasteurisation. However; Chemical disinfection involves the use of chemicals such as lime, chlorine and Ozone. Finally, the radiation disinfection process involves the use of beta (high-energy electrons) and gamma rays. Sludge digestion, aerobic and anaerobic, reduce pathogenic organisms; however, it does not achieve complete inactivation. The most common sludge disinfection processes are; (1) pasteurisation, (2) chemical disinfection, (3) long-term storage, and (4) irradiation. More details on the sludge disinfection processes can be found in Appendix 8.

2.2.4 Dewatering

The dewatering process removes water from sludge to reduce its volume and convert it from a fluid state into a solid-state called cake (Metcalf and Eddy/AECOM, 2014) . The water removed during the dewatering process is only the free water and partial interstitial water; however, it’s sufficient to reach the cake state (Qasim et al., 2018). Due to the substantial volume reduction achieved by dewatering, the capital and operation cost of subsequent conversion processes and/or direct disposal processes is significantly reduced (Turovskiy and Mathai, 2006) . The feed sludge to the dewatering process is typically thickened with a dry solid concentration between 4 to 20% (Turovskiy and Mathai, 2006). The dewatering process typically performed either by mechanical systems or natural systems (Turovskiy and Mathai, 2006). The mechanical dewatering systems are commonly centrifuge, belt filter press, rotary press, screw press and filter press (McFarland, 2001). On the other hand, the common natural dewatering systems are drying beds and sludge lagoons (McFarland, 2001). The natural dewatering systems are prefered for small remote plants with available land (Gurjar et al. 2017, Qasim et al., 2018). However, the mechanical dewatering processes are typically used for large plants with limited space and located near the built up area(Gurjar et al. 2017, Qasim et al., 2018). The selection of the most suitable dewatering process may depend on (Qasim et al., 2018) (1) characteristics of the sludge to be dewatered, (2) compatibility of dewatering process with plant size, (3) compatibility of dewatering system with subsequent treatment/disposal processes (4) availability of space, (5) location of the plant, near or far from residential areas, and 6) required moisture concentration of the sludge cake. More details on the sludge dewatering processes can be found in Appendix 9.

2.2.5 Thermal drying

Thermal drying is also known as Heat drying (Turovskiy and Mathai, 2006). The thermal drying process utilises heat to evaporate all types of water from sludge (Qasim et al., 2018). A sludge dewatering step is typically required before thermal drying to remove the free water and significantly reduce the thermal dryer size, operation cost and capital cost (Turovskiy and Mathai, 2006, Wang et al., 2007) . The thermal drying process may also require an air pollution control system to remove odour and particulates from the exhaust gases formed during the drying process before releasing them into the atmosphere (Wang et al., 2007). Thermal dryers evaporate the water from the sludge without destroying the organic matter content of the sludge; for this reason, the sludge temperature is kept between 60 and 93°C (Wang et al., 2007). Depending on the dried sludge subsequent processing or disposal alternatives, the sludge can be dried to between 40% to 95% (Gurjar et al., 2017). The feed sludge water content and its characteristics are the major factors that influence the achievable degree of dryness (Turovskiy and Mathai, 2006). The principal advantages of the thermal drying process are (Metcalf & Eddy/AECOM, 2014, Qasim et al. 2018); (1) easy packaging of final dried sludge for marketing (i.e. agriculture reuse), (2) Pathogen reduction, (3) increase the fuel value of sludge to be used as a fuel source or for incineration (discussed in further details under thermal oxidation), and (4) reduce sludge transportation costs. However, the principal disadvantages are; (1) high capital cost, (2) high operating costs, (3) abrasion and corrosion of moving parts increase maintenance cost, (4) complex process to operate, (5) requires highly skilled operators, (6) produce liquid effluent requires treatment, (7) release gases to the atmosphere, (8) risk of foul odour, (9) the combination of combustible particles, heat, oxygen, and high gas velocities make these systems susceptible to fire and explosion risk, and (10) The chemically bonded water due to the addition of chemical conditioning in the dewatering step may increase the amount of water retained in the dried sludge beyond the required moisture level.

The thermal drying process is classified according to the methods of transferring the heat to the sludge (Turovskiy and Mathai, 2006). These methods are (Turovskiy and Mathai, 2006, Qasim et al., 2018); (1) convection (direct drying), (2) conduction (indirect drying), (3) radiation (Infrared or radiant heat drying), and (4) a combination of these methods. However, direct drying and indirect drying are the most commonly used methods.

2.2.4.1 Direct drying (Turovskiy and Mathai, 2006);

In this process, the heat required for water evaporation is transferred to the sludge through direct contact with hot gases. The water vapour is carried out with the hot gases. The most common direct dryers are Flash dryers, rotary dryers and fluidised bed dryer.

2.2.4.2 Indirect drying (Turovskiy and Mathai, 2006);

In this process, the heat required for water evaporation is transferred to the sludge through contact with a hot surface. Typically metal sheets separate the sludge from the heating media. The heating media is commonly steam or oil. The most common indirect dryers are either vertical (Pelletech dryer) or horizontal (paddle dryer, hollow-flight dryer, and disk dryer) dryers.

2.2.4.3 Radiation dryer (Infrared or Radiant heat drying) (Turovskiy and Mathai, 2006);

In this process, the heat required for water evaporation radiate either electrical resistance element, gas-fired incandescent refractories, or infrared lamps. The most common radiant heat dryer is the multiple-hearth furnace, typically used for sludge incineration.
More details on the different type of sludge dryers can be found in Appendix 10.

2.2.6 Composting

Composting is a method of treating and converting sewage sludge into a stable end product that is easy to handle, store and use (Metcalf & Eddy/AECOM 2014). The treatment and conversion process occurs due to the microbial decomposition of organic matters (WEF, 2010). Composting can be practised for dewatered sludge or dewatered digested sludge (Metcalf & Eddy/AECOM 2014) . However, composting of digested sludge is preferred due to the less odour produced during composting and the quality of the end compost product (Metcalf & Eddy/AECOM 2014). Approximately 20–30% of volatile solids are converted to carbon dioxide and water (Metcalf & Eddy/AECOM 2014). In addition, the decomposition process generates heat of approximately 21 MJ/kg of organic matter decomposed (Qasim et al., 2018). The generated heat raises the compost temperature to the pasteurization range (thermophilic range) 50˚C to 70˚C, which is maintained for several days leading to the destruction of pathogenic organisms (Qasim et al., 2018). Organic matter decomposition can occur under anaerobic or aerobic conditions (Metcalf & Eddy/AECOM 2014). However, aerobic composting is predominant as it accelerates the decomposition rate resulting in higher temperature rise and less nuisance odour (Metcalf & Eddy/AECOM 2014). It has to be noted that even the aerobic decomposition is never completely aerobic, and anaerobic decomposition may occur but at a minimal and negligible rate(Metcalf & Eddy/AECOM 2014). Composting systems are categorised into two main categories, Static and agitated (Metcalf & Eddy/AECOM 2014). In the agitated system, the sludge being composted is agitated and mixed periodically to introduce oxygen and control temperature to obtain a uniform end product (Metcalf & Eddy/AECOM 2014). In the static system, the sludge being composted remain static, and the air is blown through it (Metcalf & Eddy/AECOM 2014). The most common agitated composting system is known as windrow; however, the most common static composting system is known as aerated static pile (Metcalf & Eddy/AECOM 2014). In addition, a proprietary system known as an in-vessel composting system has also been in use (Metcalf & Eddy/AECOM 2014). The three systems are explained below in further details. The selection of the composting process and the system to use for composting depends on (Metcalf & Eddy/AECOM 2014); (1) daily sludge production, (2) availability of land and (3) characteristics of sludge to be composted (stabilised, dewatered, conditioned etc.). For example, an aerobic or anaerobic stabilised sludge may reduce the composting facility size by up to 40% (Metcalf & Eddy/AECOM 2014). More details on sludge composting processes can be found in Appendix 11.

2.2.7 Thermal oxidation

The primary objective of the thermal oxidation process is to substantially reduce the quantity of the sludge requiring disposal (up to 95% reduction in volume and weight) or converting it into an energy-rich product for reuse (WEF, 2010). The thermal oxidation process objective is achieved by converting the sludge into oxidised products or partially oxidised products that can be reused, released or disposed of safely into the environment (WEF, 2010). The oxidised products are produced under a high-temperature oxidation process in the presence of excess air, and the primary oxidised products are carbon dioxide, water vapour, sulphur dioxide and inert ash (WEF,2010). However, the partially oxidised products are produced under high-temperature oxidation processes but in the absence of air to produce energy-rich products such as gas, oil or tar, and char (WEF,2010). The thermal oxidation processes in use include (Qasim, 2018); (1) incineration, (2) gasification, (3) wet air oxidation, and (4) pyrolysis. More details on the thermal oxidation processes can be found in Appendix 12.

2.2.8 Ultimate disposal

The ultimate disposal of sludge can be categorised into ultimate beneficial disposal and ultimate un-beneficial disposal (Turovskiy and Mathai, 2006, Gurjar et al., 2017). The ultimate beneficial disposal, also called beneficial use, covers land application, energy recovery, biofuel production, and reuse in manufacturing (ex. Bricks and tiles) (Gurjar et al., 2017). A study looking at the possibility of using sewage sludge in fired clay bricks found a saving up to 25% of the energy can be achieved during the firing in an electric furnace and that the concentration of heavy metals leached is insignificant (Ukwatta et al., 2016). Another study found that ash can be used as a substitute for clay in making bricks and adding of raw sludge (with any treatment) is also applicable as a degreaser, as it will minimise the risk of cracks forming in the bricks during the drying process (Moreno et al., 2016).

However, ultimate unbeneficial disposal covers landfill and marine disposal. It has to be noted that some of the ultimate beneficial disposal methods produce by-products that require disposal. However, its quantity and volume are considered insignificant compared to the original sludge quantity and volume. For example, the ash produced during the energy recovery processes as well as biofuel production processes. The quality of these by-products will determine their optimum final disposal method. In recent years the ultimate beneficial disposal became the objective of most if not all countries as it solves the sludge disposal problem and provides additional advantages (Turovskiy and Mathai, 2006, Gurjar et al., 2017). The other reasons for the ultimate beneficial disposal being the preferred alternative is the unavailability of landfill sites and the negative impact of the sludge on the environment (Turovskiy and Mathai, 2006, Gurjar et al., 2017). The main three regularity requirements that govern the beneficial use are pathogens concentration, sludge stability (vector attraction) and pollutants (mainly heavy metals) concentration (Turovskiy and Mathai, 2006, Gurjar et al., 2017, Snyman et al., 2006). To encourage the beneficial use of sludge, the South African based Water Research Commission has developed a guideline for the use and disposal of sewage sludge under the name of “Guidelines for the utilisation and disposal of wastewater sludge”. This guideline has replaced all previous guidelines for managing sewage sludge and became legally binding as per the Department of Water Affairs. The guideline consists of 5 volumes, each dealing with a specific utilisation and disposal alternative.

Volume 1: Selection of Management Options (Snyman et al., 2006)

This volume covers sludge characteristics and divides it into three classification classes; microbiological class, stability class (volatile solids content) and pollutants class (Heavy Metals content). The classification system is presented in Table 2-4. The guideline has described a minimum of three composite samples to be collected from each sludge stream considered for utilisation or disposal. The limits of the classification classes is presented in Table 2-4 is detailed in Table 2-5, Table 2-6 and Table 2-7. The beneficial use or disposal option will be determined based on the results of this classification.

Table 2-4 Classification System for Sludge

Classification class	**Best quality**	**Intermediate quality**	**Worse quality**
Microbiological class	A	B	C
Stability class	1	2	3
Pollutant class	a	b	c

Table 2-5 Microbiological Class

Microbiological class	**A**	**B**		**C**
Microbiological class	All three samples comply with the following standard	Two of the three samples comply with the following standard	The sample that failed does not exceed the following standard	One or more of the samples exceed the following concentration
Faecal coliforms (CFU/g_{dry})	< 1000	$< 1 \times 10^6$	1×10^7	$>1 \times 10^7$
Helminth Ova (Total viable ova/g_{dry})	< 0.25 (or one viable ova/$4g_{dry}$)	< 1	4	>4

Table 2-6 Stability Class

Stability class	**1**	**2**	**3**
	Plan/design to comply with one of the options listed below on a 90 percentile basis.	Plan/design to comply with one of the options listed below on a 75 percentile basis.	No stabilisation or vector attraction reduction options required.
Vector attraction reduction options (Applicable to Stability class 1 and 2 only)			
Option 1	Reduce the mass of volatile solids by a minimum of 38%		
Option 2	Demonstrate vector attraction reduction with additional anaerobic digestion in a bench-scale unit		
Option 3	Demonstrate vector attraction reduction with additional aerobic digestion in a bench-scale unit		
Option 4	Meet a specific oxygen uptake rate for aerobically treated sludge		
Option 5	Use aerobic processes at a temperature greater than 40 C (average temperature 45 °C) for 14 days or longer (e.g. during sludge composting)		
Option 6	Add alkaline material to raise the pH under specific conditions		

Stability class	1	2	3
Option 7	Reduce moisture content of sludge that do not contain unstabilised solids (from treatment processes other than primary treatment) to at least 75% solids		
Option 8	Reduce moisture content of sludge with unstabilised solids to at least 90% solids		
Option 9	Inject sludge beneath the soil surface within a specified time, depending on the level of pathogen treatment		
Option 10	Incorporate sludge applied to or placed on the surface of the land within specified time periods after application to or placement on the surface of the land		

Table 2-7 Pollutant Class

Metal limits for South African Wastewater Sludges (mg/kg)			
Pollutant class	**a**	**b**	**c**
Arsenic (As)	<40	40 - 75	>75
Cadmium (Cd)	<40	40 - 85	>85
Chromium (Cr)	<1200	1200 - 3000	>3000
Copper (Cu)	<1500	1500 - 4300	>4300
Lead (Pb)	<300	300 - 840	>840
Mercury (Hg)	<15	15 - 55	>55
Nickel (Ni)	<420	420	>420
Zinc (Zn)	<2800	2800 - 7500	>7500
Benchmark Metal Values (mg/kg)			
Antimony (Sb)	<1.1	1.1 - 7	>7
Boron (B)	<23	23 - 72	>72
Barium (Ba)	<108	108 - 250	>250
Beryllium (Be)	<0.8	0.8 - 7	>7
Cobalt (Co)	<5	5 - 38	>38
Manganese (Mn)	<260	260 - 1225	>1225
Molybdenum (Mo)	<4	4 - 12	>12
Selenium (Se)	<5	5 - 15	>15
Strontium (Sr)	<84	84 - 205	>205
Thallium (TI)	<0.03	0.03 - 0.14	>0.14
Vanadium (V)	<85	85 - 430	>430

It should be noted that the three classification classes of each sample must be determined. The guideline has also indicated that the routine analysis of organic pollutants in sewage sludge is not required, with a recommendation of testing for a set of poly-aromatic hydrocarbons (PAHs). The most beneficial classification is “A1a”; this sludge can be used in agriculture; however, “A1c” indicates a high level of pollutants and ca not be used in agriculture.

Volume 2: Requirements for the agricultural use of sludge (Snyman et al., 2006)

This volume covers the characteristics, monitoring requirements, regularities, technical aspects and restrictions for the safe use of sludge as a soil conditioner or a fertilizer at agronomic rates.

Volume 3: Requirements for the on-site and off-site disposal of sludge (Snyman et al., 2006)

This volume guides the selection of on-site and off-site disposal options. Off-site disposal options cover general or hazardous landfill sites and ocean disposal; however, on-site disposal covers mono-fill or lagoon. It provides details on the operational, monitoring and legal requirements of onsite and off-site disposal, in addition to rehabilitation and phaseout requirements of the unlined sludge stockpile facilities. This volume also addresses the potential leachability of the metals in the sludge and introduce a new pollutant class for on-site and off-site disposal of sludge based on the leachable metal fraction in the sludge instead of the total metal content.

Volume 4: Requirements for the beneficial use of sludge at high loading rates (Herselman et al., 2009)

This volume addresses the beneficial sludge application to land at a rate higher than agronomic rates. It covers operational, technical, restrictions and legislative aspects for the application of the sludge at a once-off high rate, continuous high rate and as land-fill cover. Once-off high rate application includes rehabilitation of mining sites, the establishment of golf courses, racecourses, road embankments and public parks. Continuous high-rate application includes the use of sludge in natural forests, cultivation of grains, cultivation of non-food crops and cultivation of lawns.

Volume 5: Requirements for the thermal sludge management practices and for commercial products containing sludge (Herselman et al., 2009)

This volume is divided into two sections. Section A, covers operational, technical, monitoring requirements, restrictions and legislative aspects of thermal treatment of sludge. In addition to exhaust gas emission and its quality monitoring. It also includes the general risk-based equation to determine the pollutant limits for sludge destined for incineration. The second section covers the legal requirements for commercial products containing sludge such as ash, fertilizer, compost, and pelts. It also provides limited guidance on the use of commercial products containing sludge as raw material in construction, for example, in the manufacturing of bricks, cement, artificial aggregates and artificial rocks.

2.2.7.1 Land application

The land application includes applying sludge to the soil surface or just below the soil surface for beneficial use (Turovskiy and Mathai, 2006) . This practice includes sludge utilisation for (Turovskiy and Mathai, 2006, Wang et al., 2008); (1) agriculture purposes to enhance the production of food and non-food crops, (2) to enhance forest, pasture and rangeland, (3) land reclamation, (4) parks, golf courses, racecourses, home lawns and gardens, and (5) dedicated land disposal. Land application is well-suited for managing sludge from any size wastewater treatment facility (Wang et al., 2007 , Hung et al., 2014). Land application is most favourable when agricultural land is available near the wastewater treatment plant to reduce transportation costs (Wang et al., 2007). Sludge may be transported by pipeline, truck, barge, rail, or a combination of these (Qasim et al., 2018). The mode of transportation is selected based on the sludge quantity, moisture content, distance and quality (Turovskiy and Mathai, 2006). Typically for distances less than 100Km, trucks are used (Turovskiy and Mathai, 2006). Road tankers are used to transport liquid sludge to eliminate spills, odour and any possible pathogens contamination (Turovskiy and Mathai, 2006). On the other hand, dewatered and dry sludge may be transported in open trucks (Turovskiy and Mathai, 2006). However, plastic sheets should be used to cover the sludge (Turovskiy and Mathai, 2006). In addition, linear to cover the bottom of the truck is to be used while transporting dewatered sludge (Turovskiy and Mathai, 2006).

Sludge utilisation for agriculture purposes, application of sludge over agricultural land improve soil texture and water-retaining capacity, resulting in better conditions for root growth and increasing vegetation drought tolerance (Hung et al., 2014). In addition, sludge reduces or eliminates commercial fertilizer use as it provides essential nutrients for plant growth, such as nitrogen and phosphorus (Hung et al., 2014). Sludge also provide essential micronutrients such as nickel, zinc and copper (Hung et al., 2014). The organic nature of the nutrients in the sludge offers several advantages over inorganic fertilizers as it is released slowly into the soil and less likely to leach into groundwater or runoff into surface water due to its low water solubility (Wang et al., 2007, Hung et al., 2014). However, sludge characteristics, site selection and application rate are critical factors to consider to avoid phytotoxicity, ground and surface water contamination, and public health or nuisance (Wang et al., 2007, Hung et al., 2014). The use of sludge for agriculture purposes is typically designed around the crops nitrogen and/or phosphorus needs, assuming that the sludge meet class A1a as per the Guidelines for the utilisation and disposal of wastewater sludge. The sludge is typically applied to the agricultural lands at agronomic rates on an annual basis; however, monitoring of sludge and soil characteristics is essential(Wang et al., 2007, Hung et al., 2014, Qasim et al., 2018). The criteria to consider during the evaluation for the use of sludge for agriculture purposes are;

- The microbiological class, pathogen class and pollutant class must comply with the Guidelines for the utilisation and disposal of wastewater sludge (Snyman et al., 2006).
- The sludge fertilizer value (N-P-K value) ; which is primarily based on the sludge content of nitrogen (N), phosphorus (P) and potassium (K). The sludge typically contains a sufficient amount of phosphorus and nitrogen that may meet the requirements of agriculture. However, Potassium is found in insufficient amounts. The N-P-K value of common chemical fertilizers is 8% nitrogen : 8% phosphorus (as P_2O_2) : 8% potassium (as K_2O) (Snyman et al., 2006, Girovich, 1996).
- The pollutants (heavy metals) content in the soil. In addition to the short and long term cumulative concentration considering the applied sludge pollutants content (Snyman et al., 2006, Hung et al., 2014)
- Comply with the monitoring requirements as detailed in the Guidelines for the utilisation and disposal of wastewater sludge (Snyman et al., 2006).
- Comply with operational requirements such as application rate, the application method (liquid or dewatered/dry) , storage, frequency, crop needs and climate conditions (Snyman et al., 2006).

Sludge utilisation to enhance forest, pasture and rangeland, can be a major utilisation and disposal option due to the availability of land throughout eThekwini and nearby areas. The application rate depends on the soil condition, tree and vegetation species and sludge quality (Qasim et al., 2018). The sludge can be reapplied every several years at a rate higher than the agronomic rates (Qasim et al., 2018). A proper management plan must be in place to eliminate any negative impact on vegetation, surface and groundwater, animals and humans (Qasim et al., 2018). The management plan should include acceptable biosolids quality, application rate, application method, site selection criteria, pollutants accumulation, operation practices, environmental constraints and monitoring requirements(Wang et al., 2007, Qasim et al., 2018). This may also apply to parks, golf courses, racecourses, home lawns and gardens; however, the application practice, rate and frequency may differ significantly (Gurjar et al., 2017).

Sludge utilisation in land reclamation (Turovskiy and Mathai, 2006, Qasim et al., 2018); the surface mining of coal and other minerals, exploration for minerals, spoils from underground mins and tailing from mining operation has drastically disturbed a significant land area. These lands do not support vegetation growth due to a lack of nutrients and organic matter, low pH, low water-retaining capacity, low water infiltration rates and permeability, and the presence of toxic levels of pollutants (heavy metals). The major benefits of using sludge to reclaim such lands are to (1) beneficially dispose of the sludge by using its fertilizing capacity, (2) revegetating of the reclaimed land to reduce water and wind erosion, (3) rehab these lands for possible agriculture production and animal grazing and (4) possible reforestation for lumber and pulp production. The use of sludge for land reclamation can also include the establishment of golf courses or racecourses. Land reclamation typically requires a one-time high rate application. However, if the land is used for agriculture or reforestation, an annual or semi-annual application rate may be required. Typically detailed management plan is developed, including site selection, environmental constraints, soil chemistry, climate, sludge nutrients, heavy metals, monitoring requirements and biosolids loading rates, generally conducted on a case-by-case basis.

Dedicated Land Disposal (Turovskiy and Mathai, 2006, Qasim et al., 2018); this option is developed mainly to provide environmentally friendly and sustainable sludge disposal by spreading sludge over land at a high application rate. The principal disadvantage of this option is the high potential for groundwater contamination. However, it can be avoided by proper site selection with respect to groundwater aquifers locations, use of dewatered sludge, intercepting and collecting leachate by installing impermeable liners. A high application rate can be used since the production of crops, improvement of soil characteristics or use of nutrients are secondary to sludge disposal. The same as other methods, a detailed management plan should be developed, including site selection, environmental constraints, soil chemistry, climate, sludge nutrients, heavy metals, vegetation, monitoring requirements and biosolids loading rates, generally conducted on a case-by-case basis.

The principal advantages of the over all land application disposal method are (Wang et al., 2007, Hung et al., 2014); (1) It is a final disposal method, (2) utilisation of the fertilizing value of the sludge, especially with the slow release of nutrients, (3) Organic matter in sludge improves soil properties, (4) relatively inexpensive disposal alternative, (5) cheap product if compared to chemical fertilizers, and (6) liquid sludge can be used if agriculture land is available in close proximity.

The principal disadvantages for overall land application disposal method are (Wang et al., 2007, Hung et al., 2014); (1) weather dependent and limited to a specific time of the year, (2) storage for sludge is required during the non-application periods, (2) requires a high level of management to avoid groundwater contamination, vector attraction and odour, (3) transportation; expensive alternative if the land is unavailable in close proximity, especially for agriculture use, (4) public acceptance and, (5) market availability.

2.2.7.2 Landfill disposal

Landfill disposal should only be exercised if the sludge is not fit or more than required for beneficial use. The different residuals produced by the wastewater treatment plants and can be landfilled are; screenings, grit, scum, ashes or dewatered sludge (Qasim et al.,2018). These residuals can either be disposed of in a mono-landfill or co-disposed with municipal solid waste (Qasim et al., 2018).

Mono-landfill sites are specially designed only to receive sludge from wastewater treatment plants (Andreoli et al., 2007). In Co-disposal, the sludge is sent to municipal solid waste (MSW) landfill sites (Andreoli et al., 2007). Mixing of sludge with municipal solid waste is found to aid the overall biodegradation process within the landfill site (Andreoli et al., 2007). However, it may reduce the landfill site lifetime due to the significant amount of sludge to be disposed (Andreoli et al., 2007). For co-landfill disposal, the level of pollutants (heavy metals) in the sludge is fundamental as it determines if the sludge can be landfilled in a non-hazardous landfill site or a hazardous landfill site (Herselman et al., 2009). However, characteristics such as pathogen level are not of primary concern while choosing landfill as a final disposal method (Andreoli et al., 2007). The typical criteria to be investigated to determine the suitability of sludge for landfilling are (Qasim et al., 2018) ; (1) sludge handling method within the wastewater treatment plant, (2) sludge final dry solids content, (3) type of chemical used during sludge handling (if any), (4) sludge organic and nutrient content, and (5) heavy metal content. The preferred sludge characteristics for landfill are (Qasim et al., 2018); (1) dry solids content of not less than 20% mainly for mono-fill sites, (2) pH more than 10 to eliminate heavy metals leaching, (3) low pollutants concentration, (4) low organic content and (5) low nutrient content. Sludge that meets these characteristics reduces the risk of groundwater contamination, odour, explosions and fire. The common methods of sludge landfill are (Herselman et al., 2009, Qasim et al., 2018); (1) trenching, (2) area fill, (3) toe method, and (4) South African method. Typically landfill sites are equipped with a leachate collection system as well as a gas collection system (Qasim et al., 2018). The cover material is usually excavated soil(Qasim et al., 2018). The daily cover is up to 15 cm, and the top cover 0.6 to 1 m (Qasim et al., 2018). The sludge dry solids content plays an important role in landfilling, as sludge with dry solid content between 15 to 20% ca not support the weight of the cover or machinery (Qasim et al., 2018). In this case, dry soil or MSW is mixed with sludge to increase workability and bearing capacity (Qasim et al., 2018).

Trenching method (Wang et al, 2007, Qasim et al., 2018); is classified into a narrow or wide trench. The narrow trench width is 0.6 to 3 m; however, the wide trench width is 3 to 15 m. In this method, the sludge is placed in the trench and covered by excavated soil and waste.

Area fill method (Wang et al, 2007, Qasim et al., 2018); the sludge is spread over the original ground or previous waste body, then covered by a thin layer of soil/waste and compacted.

Toe method; the sludge is spread at the sloped toe of a previous cell, then covered by soil/waste and compacted.

Finally, the South African method (Herselman et al., 2009); a method recershed in South Africa, it is typically a pre-mixing technique between the sludge and the bulking agent (soil or MSW), which is exercised in all other types of landfill methods.

The common factors that affect the design of a landfill site are (Qasim et al., 2018) ; (1) leachate control, including containment, removal, treatment and disposal, (2) Gas control; the gas generated in the landfill is 50 to 65% methane, and 30 to 45% carbon dioxide and the balance percentage contains nitrogen, oxygen, water vapours, ammonia, and hydrogen sulphide, (3) Stormwater management around the landfill, and (4) environmental factors including odours, dust, vector control, and aesthetics.

The co-disposal of sewage sludge with municipal solid waste on landfills in South Africa is governed by the waste management publications issued by the Department of Water Affairs & Forestry, namely “Minimum Requirements for the Handling, Classification and Disposal of Hazardous waste” and “Minimum Requirements for Waste Disposal by Landfill” (Herselman et al., 2009). Off-site land disposal – waste permit in terms of Section 20 of the Environment Conservation Act (Act No. 73 of 1989) is required for off-site disposal, either for dedicated land disposal or Co-disposal(Herselman et al., 2009). The applicable act governing the off-site disposal practice is the Environmental Conservation Act (Act No. 73 of 1989) Natural Environment Management - Waste Management Act (Herselman et al., 2009). Complying with Volume 3 of the Sludge Guidelines for the utilisation and disposal of wastewater sludge is also a requirement for both the sludge producer and landfill owner/operator.

eThekwini municipality landfill sites (Herselman et al., 2009, Bosch Munitech Report, 2016, eThekwini Municpality, 2021); eThekwini municipality owns and operates four landfill sites, namely Bisasar Road landfill, Buffelsdraai landfill, Mariannhill landfills and Lovu landfill. All four sites operate under G:L:B^+ licence classification. The G indicates that the landfill site is for general waste only (no hazardous waste), L indicates that the size of the landfill is large and is designed to receive more than 500 tonnes per day. B refers to the site water balance, which is either positive or negative. The positive sign means the precipitation exceeds potential evaporation, and a significant amount of leachate will be generated. However, the negative sign means evaporation exceeding potential precipitation, and the amount of leachate generated is insignificant. In the last years, Bisasar Road landfill site and Marianhill landfill site have discontinued receiving domestic and commercial waste due to the unavailability of airspace. Currently, both sites only receive builder’s rubble, cover material, and garden refuse. Other landfill sites are owned and operated by eThekwini municipalities, such as Shallcross and Wyebank, but they are only for Garden refuse. It has to be noted that Wyebank landfill site has reached full capacity and is currently closed. General waste landfill sites can only accept non-hazardous waste; therefore, the sludge hazard rating must be determined before disposal. The toxicity (Lethal dose - LD50), ecotoxicity (Lethal concentration - LC50), carcinogenicity, mutagenicity, teratogenicity, persistence, environmental fate and Estimated Environmental Concentration (EEC) of the waste are used to determine the sludge hazard rating. The Hazard Rating is categorised into two levels as follows;

- Hazard Rating 1 and 2: extreme and high risks hazard
- Hazard Rating 3 and 4: medium and low risks hazard

On the other hand, the landfill sites for hazard waste are classified into two categories as follows;

- H:H landfill site for extreme and high risks hazard waste
- H:h landfill site for medium and low risks hazard waste

Therefore, the sludge with hazard rating 1 and 2 can only be disposed into an H:H landfill site. However, sludge with hazard rating 3 and 4 can be disposed into and H:H and H:h landfill sites. Typically, sewage sludge is classified as medium and low risks hazard. As a result of this classification, sewage sludge can be disposed into H:H and H:h landfill sites. Within eThekwini municipality, there is only one hazard landfill site which is the Shongweni landfill site. Shongweni landfill site is privately owned and operated by Enviroserve. It has a classification of H:h, which indicate that waste with a hazard rating of 3 and 4, such as sewage sludge, can be disposed of within the landfill site.

The principal advantages of sludge landfill are (Herselman et al., 2009, Wang et al., 2007) ; (1) reduce landfill leachate production by increasing the moisture storage capacity of the site, (2) the high pH of sludge precipitate metal and decrease its mobility, (3) increase landfill site compaction density and (4) power generation through the production of methane gas.

The principal disadvantages of sludge landfill are (The author); (1) high operation cost considering the transportation, (2) not utilising the maximum benefits of the sludge, (3) environmental risk (groundwater contamination, odour, etc), and (4) unavailability of enough landfill sites for hazard waste within eThekwini municipality.

2.2.7.3 Marine disposal

Disposal of sludge to the marine environment (sea & ocean) is being practised in many coastal cities worldwide (Gurjar et al., 2017). This practice is currently coming under increasing pressure to be banned because of its perceived adverse effects on the environment (Gurjar et al., 2017). However, marine disposal of sludge appears to be very site-specific and heavily influenced by the sludge constituent and its concentration(Gurjar et al., 2017). The marine disposal takes place either via outfall (shallow or deep pumping) or barge (USEPA, 1979). Typically, the marine disposal is economically justified (Roperts et al., 2010). However, in decentralised wastewater treatment plants where the treatment plants located in land and sludge transportation is involved, or deep ocean outfall is required the construction and operation cost may increase substantially, making marine disposal an unfavourable alternative (Roperts et al., 2010, Gurjar et al., 2017). Besides the cost, marine disposal has a potential negative impact on the marine environment if not planned, designed, operated and monitored correctly (Gurjar et al., 2017). Typically an environmental study is performed before the adoption of this disposal option (Gurjar et al., 2017). Safe marine disposal of the sludge requires meeting the following conditions (Wang et al., 2008, Gurjar et al., 2017):

1. Bacteria levels at the beaches remain within the safe level.
2. Washout of scum / oil& grease and floating solids to the shoreline must be avoided.

3. No objectionable odour.
4. Deposit and accumulation of solids at the sea/ocean floor must be avoided.
5. Aquatic life must be protected from any toxic materials.

The aim of sludge disposal in the ocean is to achieve a certain degree of dilution and dispersion (Brewster et al., 1992). The degree of dilution and dispersion of sludge in the ocean, depends on topographic and oceanographic conditions of the point of discharge and only a well-designed outfall will lead to a satisfactory results (Brewster et al., 1992). Typically, sludge is treated prior to marine disposal, the extent of the treatment is a function of the sludge characteristics, cost of the treatment required and the distance of the point of release from the shore (Kullenberg, 1985). The higher the concentration of the pollutants in the waste the further offshore it must be discharged to prevent unacceptable environmental impact (Kullenberg, 1985). The principal contaminants in the sludge that may have the potential to create environmental problems in the marine environment are; organic matter, oil and grease, pathogens (bacteria and virus), heavy metals, organochlorines, floatable solids and scum, and nutrients (Gurjar et al., 2017).

Organic matters (Gurjar et al., 2017); the decomposition of sludge organic matter by the marine bacteria creates a drop in the oxygen concentration if sludge dispersion is not achieved. The severe drop in oxygen level in the disposal area results in the death of aquatic life. To minimise or eliminate this effect, the outfall location and the disposal area should be carefully selected to maximise sludge dispersion over the disposal area and avoid the build-up of sludge sediments over the sea/ocean floor.

Oil and grease (Gurjar et al., 2017); effective dispersion plays an essential role in the effective degradation of oil and grease by marine bacteria. Although oil and grease are difficult to degrade, it's degradation is possible. However, if not dispersed effectively, it may accumulate and form grease balls that are more difficult to degrade and considered hazardous if washed to the shore as it may also contain pathogens.

Pathogens (bacteria & viruses) (Gurjar et al., 2017); The primary concern about pathogens in the sludge being disposed of into a marine environment is human health. Pathogen transmission to humans is either through swimming in polluted water or consumption of seafood (i.e. shellfish). The selection of the site location and disposal area where good dispersion is achieved may significantly reduce the risk of transferring pathogens to humans.

Heavy metals (Gurjar et al., 2017); As most of the heavy metals in the sewage wastewater are accumulated in the sludge, their disposal to the marine environment becomes a concern. The primary concern is the accumulation of heavy metals in the marine food web leading to a high concentration of these toxic metals in aquatic animals tissues. Recent studies have shown that the accumulation of heavy metals in aquatic animals tissues is not necessarily the cause of their metabolic disorder. These studies have also elaborated on the fact that heavy metals already exist in sea/ocean water, although in minimal concentrations, aquatic animals have developed a detoxification system. It comes down to regulating the maximum acceptable concentration of heavy metals in the sludge to be disposed into the marine environment and selecting the outfall and disposal area location where good dispersion is achieved to minimise the effect of heavy metal accumulation.

Organochlorines (Gurjar et al., 2017); Organochlorine compounds such as viz. dieldrin, heptachlor, hexachlorobenzene (HCB) and polychlorinated biphenyls (PCBs) are discharged into the marine environment as a result of industrial discharge to the sewerage system. The same as heavy metals, these compounds concentrate in the sludge, and thus, marine disposal of the sludge increases organochlorine compounds concentration in the marine environment. The increase in the concentration of such compounds harms aquatic life as they accumulate in the food chain. Kepone, DDT and PCBs have the most harmful impact on the marine environment among chlorinated hydrocarbons. These compounds are the leading cause of various lethal and sublethal diseases to aquatic life, such as fin rot disease. Strict control for industrial effluent discharge to sewerage systems should be implemented if marine disposal is the ultimate/final disposal method.

Floatable solids and scum; must be removed before sludge disposal to the marine environment. It tends to float and travel on the surface and reach the shore. It poses a risk to humans as it contains a large number of pathogens. It may also cause odour problems. This issue is typically solved by screening and skimming of sludge before disposal.

Nutrients (Gurjar et al., 2017); sludge contains a considerable amount of nutrients, specifically nitrogen and phosphorus. Releasing these elements to the marine environment can lead to eutrophication. Eutrophication is a process of increasing the growth of certain species that favour the high concentration of nutrients, such as algae and phytoplankton, over other types of species. This occurs due to the considerable growth of plant material (i.e. algae and phytoplankton) that predators ca not consume, but bacteria instead decompose it. The decomposition process of dead plant materials by the bacteria reduces the oxygen leading to that most of the species, including predators, disappear. However, in deep-sea/ocean disposal, where good dispersion is achieved, eutrophication unlikely to occur.

Operation and environmental monitoring are the two main parameters that lead to thriving marine disposal of sludge (Wang et al., 2008). The marine disposal of the sludge in South Africa is governed by the National Water Act (Act No. 36 of 1998) (Herselman et al., 2009).

Marine disposal of sludge has several principal advantages when compared to other disposal methods; (1) it is an ultimate disposal method where all the sludge produced is disposed of with no remains, (2) low capital cost if compared to other disposal alternatives, (3) simple operation, (4) does not require highly skilled operators, and (5) marine disposal offer more flexibility to plant operation.

On the other hand, marine disposal has several principal disadvantages; (1) high environmental pollution risk if not operated and appropriately monitored, (2) high environmental monitoring cost, and (3) high transportation cost.

eThekwini Municipality owns and operates two deep-sea outfalls at Southern wastewater treatment work (known as Southern Works) and Central wastewater treatment work (known as Central Works) (Bailey, 2000). The Southern works outfall was completed in November 1968, and the Central works outfall in January 1969 (Bailey, 2000). Southern works outfall pipeline length is 4.2 km offshore with

34 diffusers, discharging at a depth of 54 to 64 meters, with a 230 Ml/day design capacity (Bailey, 2000). It is discharging domestic and industrial effluent (Newman et al., 2012). However, the Central works outfall pipeline length is 3.2 km offshore with 18 diffusers, discharging at a depth of 48 to 53 meters, with a 135 Ml/day design capacity (Bailey, 2000). It is predominantly discharging domestic effluent (Newman et al., 2012). The raw sewage at both wastewater treatment works undergoes screening, de-gritting and primary sedimentation (Bailey, 2000). However, the removed sludge used to be further treated before safe disposal (Bailey, 2000). At Southern works, the removed sludge was thickened, anaerobically digested and mechanically dewatered before being disposed of on-site (Bailey, 2000). At Central works, the removed sludge was thickened, dewatered and incinerated (Bailey, 2000). The incineration ash was disposed of on-site (Bailey, 2000). Currently, at both wastewater treatment works, the removed sludge does not undergo any treatment before disposal. The removed sludge is combined with the settled effluent before being pumped to the ocean.

2.3 Five-point scale scoring system (Likert Type Scale)

Likert semiquantitative scale is the creation of Rensis Likert and was first introduced in 1932 (Lik-ert, 1932). Likert semiquantitative scale received a wide range of acceptance (Pimentel, 2010). The scale is most widely used in social science research; however, its use has expanded to cover areas such as education, medicine, nutrition, nursing, finance, engineering, and human study (Pimentel, 2010). In its most popular form, the respondent is presented with a question in a scale typically be-tween three to seven response points to measure the degree of satisfaction or acceptance (Anderson et al., 1998). There is typically a small practical difference in results using even or odd numbers of response choices (Liao et al., 2004). However, the 5-point scale is the most practical since it is easy to respond to, straightforward to analyse, and sufficient for most needs (Anderson et al., 1998).

The use of Likert type scales has been found to have some advantages, such as it is easier to use and to understand both for the researcher and the respondent and that analysis as well as interpretation is easier (Musangu et al., 2012). It also takes less time to explain to respondents (Musangu et al., 2012). The limitations of the Likert type scale are that the category wording description most prob-ably affects the selection, and category description may not be enough to describe a complex phe-nomenon (Musangu et al., 2012). In addition, too many answer categories can make selection diffi-cult, and too few answer categories can lead to inadequate selection and sensitivity, and respondents do not reflect their true intentions. (Hasson and Arnetz, 2005).

In the paper published by the Environmental Science & Technology in 2006, Cartmell et al. have utilised the semiquantitative Likert-type five-point scale to evaluate the risk associated with five scenarios of sewage sludge co-combustion. The risks associated with each scenario were presented on a scale of 1 to 5, distinguishing between the possibilities and consequences common to each scenario. They also included sustainability assessment for the same five scenarios of sewage sludge co-combustion using the following feasibility factors; (1) economic performance, (2) social impact, (3) environmental performance and (4) technology flexibility, However, the Likert type scale was simpler where each feasibility factor scored on a scale -2 (very negative), through 0 (neutral, or bal-ance of negative and positive), to +2 (very positive).

In another paper published by The Journal of Cleaner Production in 2020, Teoh et al. had indicated that developing a scoring system based on the semiquantitative Likert-type five-point scale to assess multiple feasibility factors for sewage sludge treatment and disposal enable decision-makers to eval-uate each method in a relatively simple manner. The same semiquantitative Likert-type five-point scale proposed by Cartmell et al. was adopted in this research paper, where treatment and disposal methods were assigned a positive score of +2 for good performance, Through 0 (neutral) and a nega-tive score of -2 for poor. The assessment included the performance and environmental impact of several treatments and disposal methods such as; (1) Anaerobic digesters, (2) Composting, (3) Lime stabilisation, (4) Incineration, (5) Pyrolysis, (6) Gasification, and (7) Thermal drying

Another sludge optimisation study by Bertanza et. al. has also utilised a semiquantitative approach for the evaluation. However, the final results were expressed by a traffic light type colour utilised in this study to present the final scenarios.

2.4 Summary

Sewage sludge management is a crucial step in the operation of any wastewater treatment plant (WWTP), as sludge treatment and disposal can account for a significant portion of the plant's operating costs. However, if not managed properly, it can turn a water pollution control problem into a solid waste disposal problem.

The steadily increase in sewage sludge production is due to population growth and the application of stringent disposal regulations for the treated sewage. Additionally, the variety of solids produced by the WWTW with different handling and disposal methods and the difficulties of finding a solution to reduce sludge production of the treatment plants is making sludge management more and more problematic.

This chapter's primary focus is to identify the different types of solids produced by the wastewater treatment plants, their quantities and their characteristics. Furthermore, to highlight the different sludge treatment processes and disposal methods available with advantages and disadvantages.

Since eThkwinin municipality is facing challenges with the current sludge management practices, this thesis is intended to; (1) understand the current sludge management situation within the municipality, (2) evaluate different technologies and disposal methods in light of the data and information collected, (3) develop different management scenarios including processes and technologies that are in use or not in use by the municipality, and evaluate their technical, environmental and economic feasibility and sustainability and (4) develop a tool that aid the municipality engineers in decision making during the selection of sludge management system.

3. Material and methods

3.1 Data collection and validation

Historical municipal sludge data from 24 wastewater treatment works within the eThekwini municipality were collected to satisfy this thesis's objectives. The collected data covers the period from 2007 to 2019. The data included quantities, types, physical, chemical and microbial characteristics of the municipal sludge. The data covers the sludge quantities are for the period between 2010 and 2018. However, the data covers sludge characteristics is only for 2007 and 2019. The 24 WWTW's covered under this thesis are listed in Table 3-1; the table also includes the type of sludge, dewatering unit used and final disposal method for each WWTW.

Table 3-1 Sludge Type, Dewatering Method, and Final Disposal Methods

Treatment Work	Type of Sludge	Dewatering Unit Used	Final Disposal
LOWER UMGENI AREA			
KwaMashu	RAW** & Mixed (50% Dig. Sludge** & 50% WAS*)	Belt Filter Press & Screw Press	Outfall/Agriculture/On-site
New Germany	WAS*	No Dewatering	Sea outfall (Pumping to Northern works)
Northern	Mixed (50% Digested** & 50% WAS*)	Belt Filter Press	Agriculture/On-site
NORTHERN COASTAL AREA			
Phoenix	WAS* & Digested Sludge** (Dewatered separately)	Belt Filter Press	Landfill/On-site
Umhlanga	WAS*	Centrifuge	On-site
Tongaat Central	WAS*	Screw Press	Landfill
Verulam	WAS* & Digested Sludge** (Dewatered separately)	Screw Presses/Drying Beds	On-site
Gennazanno	WAS*	Drying Beds	On-site
Umdloti	WAS*	Drying Beds	On-site
SOUTHERN COASTAL AREA			
Kingsburgh	WAS*	Drying Beds/ No dewatering	Sea Outfall (Tankered to Southern Works) / On-site
Amanzimtoti	WAS* & Digested Sludge**	No Dewatering	Sea Outfall (Tankered to Southern Works)
Umkomaas	WAS*	Drying Beds	Landfill
Craigieburn	WAS*	Drying Beds	Landfill
Isipingo	Digested Sludge	Drying Beds	On-site
INLAND AREA			
Hillcrest	WAS*	Screw Press/Drying Beds	Landfill
Hammarsdale	WAS*	Centrifuge / Drying Beds	Landfill
Dassenhoek	WAS*	Drying Beds	On-site
KwaNdengezi	Digested Sludge**	Drying Beds	On-site
Mpumalanga	Digested Sludge**	Drying Beds	On-site
Fredville	WAS*	Lagoon	On-site

Treatment Work	Type of Sludge	Dewatering Unit Used	Final Disposal
CENTRAL COASTAL AREA			
Umbilo	Mixture (Dig.** & WAS*)	Belt filter Press/Drying Beds	Landfill
Southern	RAW & Effluent Sludge	N/A	Sea Outfall
Umhlatuzana	WAS*	N/A	Sea Outfall (Tankered to Southern Works)
Central	RAW** & Effluent Sludge	N/A	Sea Outfall

* WAS: Sludge extracted from waste activated sludge line or secondary settling tanks

** Primary sludge: is fed to digesters if available or directly to dewatering or disposed directly to an outfall

Two issues are identified during the analysis of the collected data. These issues are the lack of consistency and technical errors in the excel sheets collected. The lack of consistency is because the operators of the different wastewater treatment works are not providing the same information on a daily or monthly basis. It was a significant limitation since some data had to be collected directly from the plant managers, and in some cases, the data was not available. The technical errors are due to the use of multiple data capturers, including students. The first issue was resolved since the collected data covers an extended period where mathematical relations can be developed to close the gaps. However, it would have been more reliable if the centralised records were maintained up-to-date. The second issue was addressed by thoroughly checking and correcting the excel sheets and all linked cells.

The collected data quality plays a critical role in determining the correctness of this thesis. From this perspective, although the two identified issues with the collected data are addressed, a data uncertainty analysis (Lindfors, 1995) was performed for the following aspects

a. Reliability of the data source;
b. Independency of samples;
c. The credibility of data;
d. Representativeness of the year;
e. Representativeness of the geographical location;
f. Representativeness of the technology.

These six assessment indicators encompass the main factors that influence the quality of data collected. To assess the data quality level points were awarded based on a five-point scale, where one point represents high-quality data, and five points represent low-quality data, as summarised in Table 3-2.

Table 3-2 Matrix Used for Data Quality Assessment (Wang et al., 2012)

AREA ASSESSED	**SCORING CRITERIA**				
	1	**2**	**3**	**4**	**5**
Reliability of the data source (DQA1)	Raw data obtained from measurements	Data calculated based on measurement methods	Some data calculated based on assumptions	Data obtained based on assessment(s) by leading expert(s)	Data obtained through unreliable assessment(s)
Independency of samples (DQA2)	Validated data samples from public or independent databases	Validated sample data from the studied organisation	Independent data samples from unvalidated sources within organisations	Data from unvalidated sources within organisations	Data from unvalidated sources within the studied organisation
Credibility of data (DQA3)	Adequate sample size, appropriate data collection duration	Slightly smaller data range but with appropriate data collection duration	Adequate data range but with a slightly shorter data collection duration	Small data range and short data collection duration or inadequate data range and inadequate collection duration	Data from unknown range and duration or inadequate data from a small data range and short data collection duration
Representativeness of the year (DQA4)	Time-independent data or data from the last 3 years	Data from the last 6 years	Data from the last 10 years	Data from the last 15 years	Data from unknown year(s)
Representativeness of the geographical location (DQA5)	Data from the study area	Average data from a larger area, which includes the study area	Data from areas with highly similar production conditions and productivity levels	Data from areas with moderately similar production conditions and productivity levels	Data from unknown areas or from areas with completely different production conditions and productivity levels
Representativeness of the technology (DQA6)	Data obtained from the studied organisation	Identical technology, processes, and raw materials but different organisation	Identical technology but different processes and raw materials	Different technology but identical products	Data of similar products used due to the lack of data

3.2 Methodology

3.2.1 Methodology approach

In this thesis, attempts were applied to find the best combination methods for treatment/processing and disposal/reuse of sewage sludge produced from 24 WWTW within the eThekwini municipality area. To accomplish the objectives of this thesis, the work was divided into two parts: literature review and examining the sludge data collected from eThekwini municipality.

The selection of an appropriate treatment and disposal method is typically based on the sludge characteristics and final classification of the sludge according to the “Sludge Guidelines” (Snyman & Herselman, 2006).

For the purpose of this study, the engagement with EWS as a primary stakeholder was essential to discuss their sewage sludge treatment and disposal challenges and establish the feasibility factors needed to complete the assessment. It started with a lengthy meeting held on 20 September 2019 attended by EWS key stakeholders.

- Mr. Teddy Gounden - Strategic Executive: Research Innovation and Knowledge Management
- Mr. Mohammed Dildar - Process Engineering Service Lead
- Mr. Lusapho Tshangela - Senior Engineer
- The late Professor Chris Buckley - Pollution Research Group - University of KwaZulu-Natal

This meeting discussion covered sludge treatment and disposal challenges within EWS, ongoing planning, disposal and reuse alternatives, the environmental impact of current practices, social concerns and the market availability of the treated sludge. Several subsequent meetings were held with plant managers and operators, such as Umpilo WWTW, Northern WWTW, KwaMashu WWTW and Southern WWTW. COVID19 pandemic restrictions had affected several planned site visits. However, the exchange of phone calls and e-mails with EWS stakeholders discussing disposal methods alternatives and opportunities within the eThekwini area was the alternative. Being the lead inspector of the initial inspection and assessment of Northern WWTW and KwaMashu WWTW under the EWS water reuse project initiative significantly helped to understand the operation and maintenance challenges and to point out the key issues, particularly in the sludge treatment and disposal part of the works. The feedback and the knowledge gained from the above interactions and the existing guidelines for the utilisation and disposal of wastewater sludge were the core basis of selecting the feasibility factors to evaluate and the ranking is shown in Table 3-4. As a result, the following commonly used processes by eThekwini municipality were selected for assessment; Thickening, Dewatering (Mechanical and Natural) , Anaerobic digestion. In addition, composting, thermal drying and oxidation (incineration and pyrolysis) were also selected for assessment. The assessment also included the following ultimate disposal methods; Landfill, Land application (agriculture) and Marine disposal (sea-outfall).

Transportation was also assessed as it plays a critical role in the overall sludge management plan.

For the purpose of this research, a scoring system based on a semi-quantitative Likert-type five-point scale (Cartmell et al., 2006, Teoh et al., 2020) is developed to assign a relative numerical score to each of the twelve feasibility factors assessed. The scoring system enables the consideration of multiple feasibility concerns of the methods in a relatively simple manner. Methods that perform well are assigned positive scores, whereas those that perform poorly are assigned negative scores. The methods are scored against each feasibility factor on a scale of -2 (very negative) through 0 (neutral, or balance) to +2 (very positive). The Semi-quantitative numerical scores are given according to the matrix shown in Table 3-4. Appendices 5 to 12 have been used to develop the tables to assess the feasibility factors.

3.2.2 Case study: Current sludge management in eThekwini municipality

The sludge physical, chemical and microbiological characteristics were collected from 24 wastewater treatment works owned and operated by eThekwini municipality. The sludge quantities, treatment and disposal methods for the period of 2010 to 2018 were also collected. The collected data were tabulated and analysed in terms of their quality, quantities, treatment and disposal method.

3.2.3 Assessing processes performance

Performance is defined as the reported percentage reduction in sludge volume/weight or pollutant reduction/removal or stabilisation (Teoh et al., 2020). An extended list of typical parameters used for sludge treatment and disposal methods performance evaluation was developed and summarised in Table 3-3. The principal parameters required for the evaluation of each treatment technology are marked with “X”. Unfortunately, the municipality does not measure all the identified parameters. For this reason, colour coding was developed to distinguish between the measured data, unavailable data and calculated data. The colour coding is as follows: green represents measured data, orange represents calculated data, and light blue represent unavailable data (not measured or technology not in use by eThekwini municipality). For the technologies in use by eThekwini municipality, the process performance assessment was accomplished by comparing the feed and produced sludge/cake volume, concentration, level of stabilisation, level of pollutant reduction or removal and pathogens reduction or elimination. A table was developed for each WWTW listing the collected data required for performance assessment. The individual tables were then used to develop an overall table for the 24 WWTW, where minimum, maximum, average and standard deviation were calculated for each performance parameter to aid the assessment. However, the technologies not in use by eThekwini municipality were assessed using values listed in the literature. For example, the operational performance parameters for a process such as incineration (i.e. volatile solids concentration, dry solids content, etc.) were collected and compared with the available data. A five-point scale, as shown in Table 3-4 was developed with +2 representing the highest weight on the scale and -2 representing the lowest weight on the scale. The scoring results are inserted in Table 4-13 to calculate the final average scoring for each treatment process and disposal method. Since Table 3-3 represent the typical parameters for operation control and effectiveness of sludge treatment and disposal methods and Table 3-4 represent the assessment matrix used to score the feasibility factors, these two tables are considered critical, and the heart of the evaluation and have been referenced in the assessment of all the feasibility factors (sections 3.2.4 through section 3.2.11).

Table 3-3 Typical Parameters for Operation Control And Effectiveness of Sludge Treatment and Disposal Methods

Parameter	**Treatment and disposal Methods**											
	Anaerobic	**Thicken-ing**	**Mecanical Dewater-ing**	**Air Drying**	**Thermal Drying**	**Transporta-tion**	**Landfill**	**Compost-ing**	**Agricul-ture**	**Sea outfall**	**Incinera-tion**	**Pyrolysis**
Temperature	x	x	x	x	x			x		x	x	x
Density		x		x		x						
Rheological prop.			x	x	x	x	x	x	x	x	x	x
Settleability		x	x							x		
Dry solids	🟩 x	x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x
Volatile solids	🟩 x		🟩 x		🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x
Digestability	x											
pH	🟩 x		🟩 x				🟩 x	🟩 x	🟩 x	🟩 x		
Volatile acids	🟩 x									x		
Oils and grease	x		x					x	x	x		
Heavy metals	🟩 x				🟩 x		🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x
Nutrients	🟩 x							🟩 x	🟩 x	🟩 x		
Particle size		x	x							x		
Specific resistance		x	x									
Compressibil-ity			x									
Dewaterability			x									
Calorific value					🟧 x						🟧 x	🟧 x
Leachability							x					
Pathogen's concentration		🟩 x	🟩 x					x	x	🟩 x		

🟩 Measured Data

🟧 Calculated Data

⬜ Unavailable Data

Table 3-4 Assessment matrix

Score	Performance				Environmental Impact	Operation simplicity	Reuse potential	Amount of sludge or by-products after each process	Reliability and robustness	Sensitivity to change in feed sludge quality and quantity	CAPEX	OPEX
	Sludge volume/weight reduction	Pollutant reduction or removal	Pathogens reduction or elimination	Stabilisation								
+2	Very High volume/weight reduction	Very High reduction or removal of heavy metals concentration	Very High reduction or elimination of pathogens	Very High reduction, removal, or stabilisation for a wide range of organic matters	No risk of adverse impact	Simple to operate, current operators can operate the system effectively	High Reuse potential	Complete disposal of sludge or minimal amount of sludge or by-products still to be processed, utilised or disposed	High	It can handle the change in any quantity and any quality of municipal sludge	Very low CAPEX	Very low OPEX
+1	High volume/weight reduction	High reduction or removal of heavy metals concentration	High reduction or elimination of pathogens	High reduction, removal, or stabilisation for Organic matters	low risk of adverse impact	Relatively simple to operate, current operators can operate the system with and/or without training	Relatively high reuse potential	A small amount of sludge or by-products still to be processed, utilised or disposed	Relatively High	It can handle a significant change in quantity and quality of municipal sludge	Low CAPEX	Low OPEX
0	Moderate change in volume/weight	Moderate reduction or removal of heavy metals concentrations	Moderate reduction or elimination of pathogens	Moderate reduction, removal, or stabilisation for Organic matters	Moderate risk of adverse impact	Moderately complex to operate, current operators may require training to operate the system	Moderate reuse potential	A moderate amount of sludge or by-products still to be processed, utilised or disposed	Moderate	It can handle a moderate change in quantity and quality of municipal sludge	Moderate CAPEX	Moderate OPEX
-1	low change in volume/weight reduction	Low change in heavy metals concentrations	Low reduction or elimination of pathogens	Low reduction, removal, or stabilisation for Organic matters	high risk of adverse impact	Complex to operate, current operators require training to operate the system	low reuse potential	a relatively large amount of sludge or by-products still to be processed, utilised or disposed	Relatively Low	It can only handle a small change in quantity and quality of municipal sludge	High CAPEX	High OPEX
-2	Little or no change or improvement in volume/weight or effects uncertain or variable	Little or no change or improvement in heavy metals concentrations, or effects uncertain or variable	Little or no reduction or elimination of pathogens, or effects uncertain or variable	Little or no change or improvement in organic matters concentrations , or effects uncertain or variable	extremely high risk of adverse impact	Very complex to operate, current operators require intensive training to operate the system	no reuse potential	A large amount of sludge or by-products still to be processed, utilised or disposed	Low	It can only handle a very minimal change in quantity and quality of municipal sludge	Very high CAPEX	Very high OPEX

3.2.4 Assessing the risk of adverse effects on the environment

The following criteria were used to assess the risk of adverse effects on the environment by the sludge treatment and disposal methods covered under this thesis (Wang et al., 2008, Qasim et al., 2018) , ; (1) odours, vector attraction, (2) noise, (3) air contamination, (4) soil and subsoil contamination, (5) Surface water /underground water contamination, (6) eutrophication potential, (7) depreciation of nearby areas, and (8) annoyance to affected populations. A five-point scale was developed with +2 represent the highest weight on the scale and -2 representing the lowest weight on the scale, as presented in Table 3-4. The scoring for each of the criteria mentioned above was assigned based on the literature. For illustration, The average score was converted into a percentage using the following empirical formula: [100% - (50% + (25% X Average score))]. The average scoring results were then inserted in Table 4-13 to represent the final scoring of the adverse effect on the environment and conclude the overall score for each treatment technology and disposal method.

3.2.5 Assessing operation simplicity

Operation simplicity is a criterion measuring how easy to operate the applied technology (Andreoli et al., 2007). The simpler the technology and its accompanying equipment, the easier to operate which require lower qualifications of WWTP operators. The need for highly qualified operators grows as technology becomes more complex. In practice, simple conventional technologies are more favourable solutions than newer and/or sophisticated ones. Even though some may consider modern technologies simple due to the high level of automation and full monitoring, this advantage fades away when no trained personnel are available to operate the system. The five-point scale developed to assess operation simplicity is presented in Table 3-4. The simplicity of the treatment and disposal methods is assessed based on the municipality operators' familiarity with the technology and literature. The average scoring results were then inserted in Table 4-13 to represent the final scoring of the operational simplicity and conclude the overall score for each treatment technology and disposal method.

3.2.6 Assessing reuse potential

Prior to utilising the sludge for any beneficial use, it should be treated to satisfy the following general requirements in the South African guideline for the utilisation and disposal of wastewater sludge (Herselman et al., 2009, Snyman et al., 2006) (WRC Reports No. TT 261/262/349/350/351):

a) Pathogen reduction: elimination or reduction to an acceptable level of potential disease-causing organisms in biosolids (bacteria, viruses, protozoa, helminths).
b) Stability Class (odour and vector attraction): elimination or reduction to an acceptable level of odour and attraction to vectors (e.g., rats, insects, flies).

c) Pollution Class: pollutants (heavy metals) should not exceed limits established by the guidelines. These regulations apply to the trace metals content of biosolids, as well as emissions from processing facilities.

The reuse potential of the sludge was assessed using the above criteria, in addition to the potential for energy recovery and revenue potential. A five-point scale presented in Table 3-5 was developed to assess these criteria (summarised in Table 3-4). For illustration, The average score was converted into a percentage using the following empirical formula: [50% + (25% X Average score)]. The scoring was assigned based on the literature. The average results of the above scoring are then inserted in Table 4-13 to represent the scoring of the reuse potential of each treatment process and disposal method.

Table 3-5 Reuse Potential Five-Point Scale

	Pollutant reduction or removal	Pathogens reduction or elimination	Stabilisation	Potential for Energy Recovery	Revenue Potential
+2	Very High reduction or removal of heavy metals concentration	Very High reduction or elimination of pathogens	Very High reduction, removal, or stabilisation for a wide range of organic matters	High energy recovery	High revenue
+1	High reduction or removal of heavy metals concentration	High reduction or elimination of pathogens	High reduction, removal, or stabilisation for Organic matters	Relatively high recovery	Relatively high revenue
0	Moderate reduction or removal of heavy metals concentrations	Moderate reduction or elimination of pathogens	Moderate reduction, removal, or stabilisation for Organic matters	Moderate recovery	Average revenue
-1	Low change in heavy metals concentrations	Low reduction or elimination of pathogens	Low reduction, removal, or stabilisation for Organic matters	Low recovery	Low revenue
-2	Little or no change or improvement in heavy metals concentrations, or effects uncertain or variable	Little or no reduction or elimination of pathogens, or effects uncertain or variable	Little or no change or improvement in organic matters concentrations , or effects uncertain or variable	No recovery	No revenue

3.2.7 Assessing the amount of sludge or by-products after each treatment process

The primary objective of this assessment is to establish the amount of sludge or by-products after each treatment process that still need to be processed, utilised, or disposed. A five-point scale is developed primarily based on the amount of sludge or by-products remaining for disposal or utilisation after each treatment process or disposal method. The scoring was assigned primarily based on the literature and presented in Table 3-4. The results of the above scoring are then inserted in Table 4-13 to determine the overall scoring of each treatment process and disposal method.

3.2.8 Assessing reliability and robustness

This assessment's primary objective is to establish a weighing score of sludge treatment and disposal methods with their reliability and robustness (RR) characteristics. Systems are typically designed to provide a high level of reliability, with low service failure frequency over their design life when subject to operation conditions (Butler et al., 2014). Four main factors are identified to establish such correlation (Davis, 2020, Von Sperling, 2007) (1) operating hours, (2) Operating temperature, (3) equipment control intensity, and (4) the required operator experience level. A five-point scale was developed as presented in Table 3-6(and summarised in Table 3-4) to rate the identified factors. For illustration, The average score was converted into a percentage using the following empirical formula: [50% + (25% X Average score)]. The scoring was assigned based on the literature. The average scoring results of the above criteria are then inserted in Table 4-13 to represent the scoring of the reliability and robustness of each treatment process and disposal method.

Table 3-6 Reliability and Robustness Five-Point Scale

	Operating hours	**Equipment control intensity**	**Operating temperature**	**required operators experience**
+2	Less than 8h/day	Low	Low	Low
+1	between 8 to 12h/day	relatively low	relatively low	relatively low
0	16h/day	Moderate	Moderate	Moderate
-1	16 to 20h/day	Relatively high	Relatively high	Relatively high
-2	20 to 24h/day	High	High	High

3.2.9 Assessing the performance sensitivity to feed sludge characteristics deterioration and quantity overload.

This assessment's primary objective is to establish a weighing score for the performance sensitivity of the sludge treatment and disposal methods with respect to feed sludge characteristics deterioration and quantity overload. The deterioration can either be a decrease or an increase. The feed sludge characteristics that influence the performance of treatment processes and disposal methods vary as shown in Table 3-3. However, only the principal sludge quality characteristics that were measured by eThekwini were assessed. These characteristics are; (1) dry solid concentration, (2) volatile solids concentration, (3) moisture content, (3) biological inhibiting substances, (4) heavy metals, (5) pH, (6) temperature, (7) Ash content, (8) calorific value, (9) nutrients concentration, and (10) pathogens concentration. The hydraulic and solids loading were also assessed to evaluate the performance sensitivity to feed sludge quantity overload. A five-point scale was developed as follows;

- +2 insignificant to no impact on performance.
- +1 Low impact on performance.
- 0 Moderate impact on performance.
- -1 High impact on performance.
- -2 Significantly high impact on performance.

As found in the literature, the deterioration effect of the characteristics mentioned above was considered to determine the final score for each treatment and disposal method. For illustration, The average score was converted into a percentage using the following empirical formula: [100% - (50% + (25% X Average score))]. The average scoring results of the above criteria are then inserted in Table 4-13 to represent the scoring of the performance sensitivity of each treatment process and disposal method.

3.2.10 Assessing the capital cost (CAPEX)

The following criteria were used to assess the capital cost of the sludge treatment and disposal methods covered under this thesis (Wang et al., 2008 , USEPA, 1985) ; (1) footprint (including the cost of land), (2) construction complexity (include; level of monitoring and instrumentations, safety requirements, piping and layout), (3) equipment cost, and (4) Structures and/or buildings cost. A five-point scale was developed with +2 represent the highest weight on the scale and -2 represent the lowest weight on the scale, as presented in Table 3-4. The scoring for each of the criteria mentioned above was assigned based on the literature. The average score was then calculated for each sludge treatment and disposal method. For illustration, The average score was converted into a percentage using the following empirical formula: [50% + (25% X Average score)]. The average scoring results were then inserted in Table 4-13 to represent the scoring of the capital cost and conclude the overall score for each treatment process and disposal method.

3.2.11 Assessing operational cost (OPEX)

The cost of the following criteria was used to assess the operational cost of the sludge treatment and disposal methods covered under this thesis (Wang et al., 2008 , USEPA, 1985); (1) personal, (2) chemicals, (3) auxiliary fuel, (4) electricity, (5) maintenance, and (6) miscellaneous (include: transportation cost, sludge removal, excavation, special cleaning requirements, testing cost, fuel for heavy equipment and fees). A five-point scale was developed with +2 represent the highest weight on the scale and -2 represent the lowest weight on the scale, as presented in Table 3-4. The scoring for each of the criteria mentioned above was assigned based on the literature. The average score was then calculated for each sludge treatment and disposal method. For illustration, The average score was converted into a percentage using the following empirical formula: [50% + (25% X Average score)]. The average scoring results were then inserted in Table 4-13 to represent the scoring of the operational cost and conclude the overall score for each treatment process and disposal method.

4. Results and discussion

4.1 Introduction

Ensuring a safe disposal of sewage sludge is considered an integral part of good planning, design and management of any wastewater treatment facility. eThekwini Municipality was selected as a case study since they are facing major challenges with treatment and disposal of sewage sludge. The results in this chapter outline the challenges with the process performances and the optimisation process to ensure a proper selection of well-suited sludge management system for the municipality.

The results have addressed several treatment scenarios and selected the most suited based on the findings of the case study, such as, (1) technical feasibility, (2) Economic feasibility, (3) Environmental sustainability, (4) Implementation route and familiarity, (5) operation and maintenance and (6) potential risk.

In order to provide a proper interpretation of the results, the following points must be noted:

- Validation of the data was performed using only the data provided by the municipality, and no assumptions or exceptions were taken.
- The results are only valid for the assessed wastewater treatment plants.

4.2 Case Study: current sludge management in eThekwini municipality

eThekwini Municipality owns and operates 27 wastewater treatment works, of which 24 produces sewage sludge (Moodley, 2012). The sludge production records for the 24 works for ten years of operation (from 2010 to 2018) were collected in person from eThekwini municipality.

The average daily production for this period is approximately 115 dry tonnes per day. The significant amount of sludge produced daily makes the handling and disposal operation complicated and financially exhausting. Figure 4-2 illustrates the percentage of sludge disposal through the disposal methods employed by eThekwini Municipality between 2010 and 2018. However, Table 4-1 presents the equivalent quantities (m^3) disposed of during the same period. It is evident that most of the sewage sludge is sent to sea outfall (71%), followed by landfill (18%), on-site (10%), and finally, 0.17% is used for agriculture. In light of current legislation, it is becoming clear that sludge is no longer acceptable at general waste landfill sites. With only one private hazardous landfill site (Shongweni landfill site) within the eThekwini municipality region, this disposal alternative is becoming very limited and costly considering the high transportation cost. The same applies to sea outfalls, with the potential impact on the receiving water and the high transportation cost, except that this disposal option has a low operation cost. It is also evident that agriculture is currently the only beneficial use with a negligible percentage compared to other disposal methods. Figure 4-1 is a map illustrating the location and distances between the

24 WWTW's owned and operated by eThekwini municipality, as well as the landfill sites and available sea-outfalls.

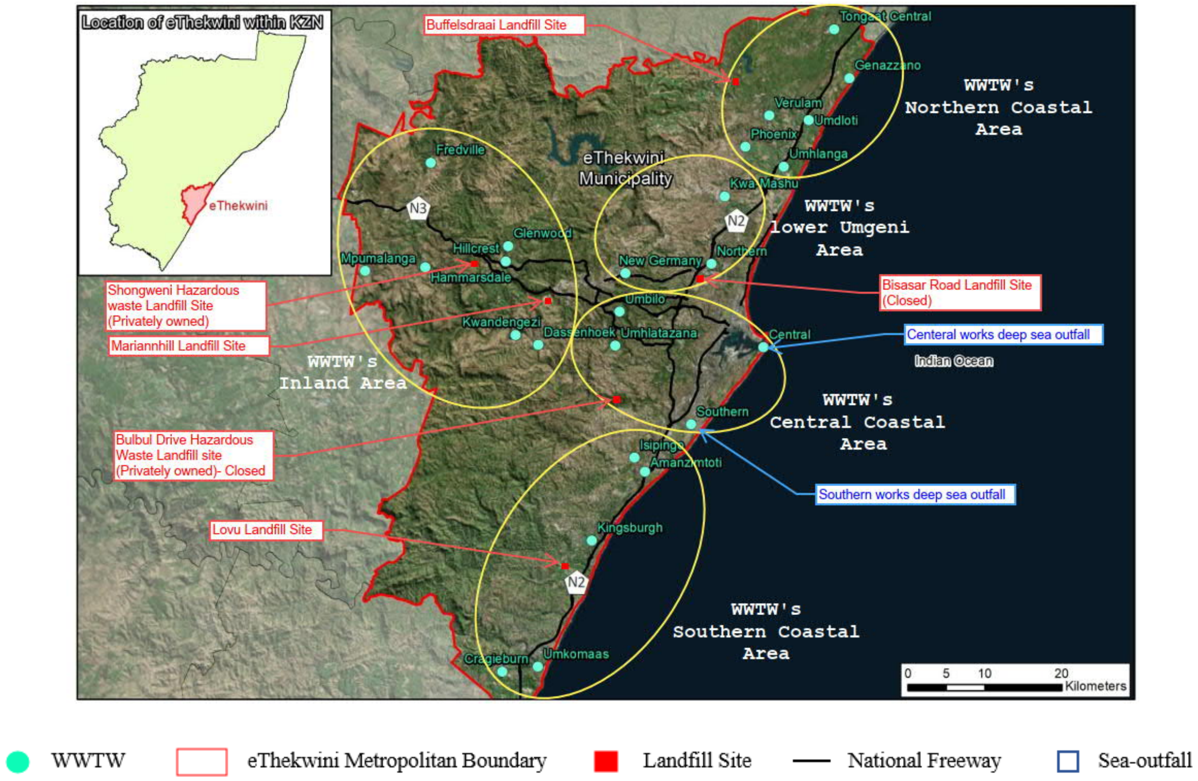


Figure 4-1 eThekwini WWTW's Locations Relative to Landfill Sites and Sea-Outfalls

Most local municipalities still view sewage sludge disposal as the default option, despite the waste management hierarchy prioritizing waste diversion techniques such as waste avoidance, reuse, recovery, and recycling over disposal (WC- Sewage Sludge status Quo Report, 2020/21). Considering the current sludge treatment and disposal trends and difficulties within eThekwini municipality, the need arises to study the available handling and disposal methods and highlight the most cost-effective, environmentally acceptable, and technically feasible method(s) for Sewage sludge management within the municipality.

While the sludge treatment processes have diversified and developed significantly in the last decades, there are still only three primary ultimate disposal methods for processed sewage sludge: land application, landfill and marine disposal. Some may consider the thermal oxidation processes such as incineration as an ultimate disposal method. However, by-products such as ash still need to be disposed of safely or beneficially utilised. Generally, none of these methods are essentially good or bad; each is merely more or less suited for a specific situation.

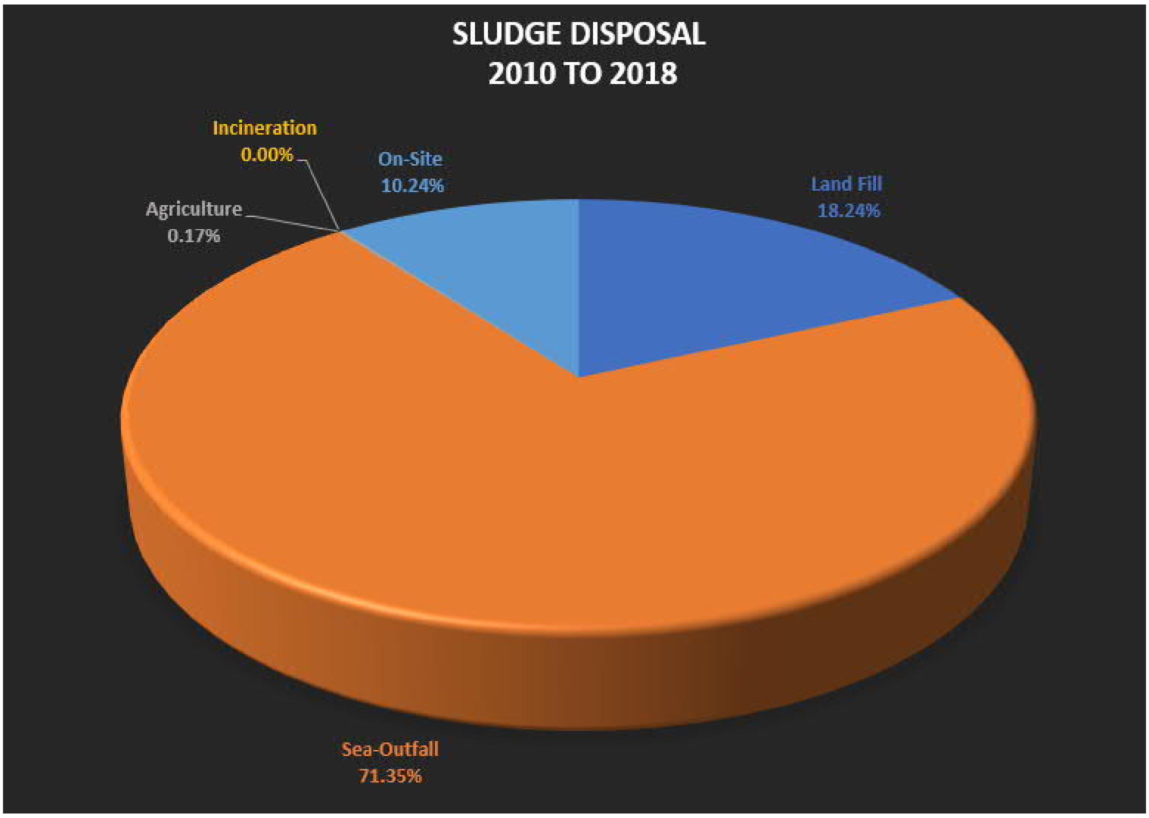


Figure 4-2 Sewage sludge disposal methods employed between 2010 and 2018

Table 4-1 Quantity of Sludge Disposed through Different Disposal Methods Employed by eThekwini Municipality Between 2010 and 2018 (Appendix 1)

	Lower Umgeni Area m^3	Southern Coastal Area m^3	Inland Area m^3	Northern Coastal Area m^3	Central Coastal Area m^3	TOTAL m^3
Land Fill	0	3,012	1,796,044	42,267	34,202	1,875,525
Sea-Outfall	19,116	410,368	0	0	6,907,226	7,336,709
Agriculture	17,610	0	0	0	0	17,610
Incineration	283	0	0	0	0	283
On-Site	250,001	70,034	652,844	80,321	0	1,053,199
	287,010	**483,414**	**2,448,888**	**122,588**	**6,941,428**	**10,283,326**

The choice of a sludge management solution is not immune to popular trends, and this may introduce non-scientific selection criteria as opposed to having the choice based on a scientific evaluation of the needs of each specific project (Campbell, 2000). We must ensure that our attempts to promote one sludge management option do not create additional barriers for other options (Campbell, 2000). It must also be noted that optimising sludge management is a complex task involving a variety factors and professional skills and it should not be oversimplified (Bertanza et al., 2016). Typically, this is a work of a team of specialists. This research is an attempt to analyse available sludge management alternatives to identify the most suited combination methods for treatment, processing, disposal and beneficial use of sewage sludge produced from 24 WWTW within the eThekwini municipality area. Sludge treatment processes in use by the municipality and other possible alternatives were considered and evaluated.

4.3 Validation of the collected data

The data quality assessment results are presented in Table 4-2. The results are measured on an average and percentage basis.

Table 4-2 Results of the Data Quality Assessment

Parameter	DQA1	DQA2	DQA3	DQA4	DQA5	DQA6	Average	Data Quality %
Sludge quantity	3	2	1	2	1	1	1.7	83%
Dry Solids	1	2	2	2	1	1	1.5	88%
Volatile solids	1	2	3	4	1	1	2.0	75%
Fixed Solids	1	2	3	4	1	1	2.0	75%
pH	1	2	2	2	1	1	1.5	88%
Volatile acids	1	2	3	4	1	1	2.0	75%
Moisture content	2	2	2	2	1	1	1.7	83%
Heavy metals	1	2	3	2	1	1	1.7	83%
Nutrients	1	2	2	2	1	1	1.5	88%
Microbial properties	1	2	2	2	1	1	1.5	88%

The above results show a score between 1.5 and 2, representing a data quality percentage between 75% and 88%.

4.3.1 Sludge quantity ;

Sludge quantity scored between 1 and 3 on the five-point scale with an average of 1.7 and a percentage of 83%. The lowest score of 3 was given on the reliability of the data source since sludge production for some months are missing, and an empirical formula was developed to calculate it as explained under section 4.2.

4.3.2 Dry solids, pH, Nutrients and Microbial properties;

Dry solids, pH, nutrients and microbial properties scored between 1 and 2 on the five-point scale with an average of 1.5 and a percentage of 88%.

4.3.3 Volatile solids and fixed solids;

Volatile solids and fixed solids scored between 1 and 4 on the five-point scale with an average of 2 and a percentage of 75%. The lowest score of 4 was given on the representativeness of the year since the data collected was from 2007 and 2019. In addition, they scored 3 in the credibility of data since the collection duration was limited to specific monitoring and studies performed within 2007 (monitoring) and 2019 (Classification study performed in 2019: “Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality”).

4.3.4 Moisture content;

Moisture content scored between 1 and 3 on the five-point scale with an average of 1.8 and a percentage of 79%. The lowest score of 3 was given on the reliability of the data source data since the collection duration was limited to specific monitoring and studies performed within 2007 (monitoring) and 2019 (Classification study performed in 2019: “Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality”).

4.3.5 Heavy metals;

Heavy metals scored between 1 and 3 on the five-point scale with an average of 1.7 and a percentage of 83%. The lowest score of 3 was given on the reliability of the data source data since the collection duration was limited to specific monitoring and studies performed within 2007 (monitoring) and 2019 (Classification study performed in 2019: “Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality”).

In conclusion, the results indicated that the data collected is of high quality and can be used to satisfy the objectives of this thesis.

4.4 Processes performance

4.4.1 Thickening;

eThekwini municipality's primary thickening processes are gravity thickeners and dissolved air-flotation (DAF). There is no data collected to confirm the performance of these units. On the other hand, these units are out of service or not performing most of the time. Two reasons have been identified for the low performance of these processes. First, it’s due to mechanical issues and the unavailability of spare parts. Second, these units are used as sludge storage rather than thickening units since sludge is not disposed of regularly from the works. Figure 4-3 and Figure 4-4 show the gravity thickeners and DAF thickeners at two of the largest treatment works, Northern WWTW and KwaMashu WWTW.

Figure 4-3 Northern WWTW (2020) - Left: DAF Thickening Unit, Right: Gravity Thickening Unit

Figure 4-4 KwaMashu WWTW (2020) - Left: Gravity Thickening Unit, Right: DAF Thickening Unit

Based on the scoring system developed for this thesis, considering the above presented operational facts, the thickening process scores -2 for sludge volume and weight reduction compared to other sludge handling processes. However, it should be noted that the low performance is a result of operational issues. For pollutant reduction/removal, pathogen reduction/elimination and stabilisation, thickening units have little to no effect on these parameters; for this reason, it scores -2.

4.4.2 Mechanical Dewatering;

The mechanical dewatering equipment eThekwini municipality uses are Belt-presses, Screw-presses and Centrifuges. Figure 4-5 illustrate the percentage of sludge processed by different dewatering processes employed by eThekwini municipality on a volume percentage basis, 65% of the sludge does not undergo dewatering, 22% of the sludge undergo mechanical dewatering, where 10% is dewatered using Belt filter presses, 9% is dewatered using screw presses, and 3% is dewatered using centrifuges. Figure 4-6 illustrate the number of treatment works on a percentage basis that uses mechanical dewatering. Screw presses are used at 14% of the treatment works, the same as Belt filter press 14%, followed by centrifuges 7%. This concludes that 35% of the works use mechanical dewatering, and it dewaters only 22% of the overall volume of the produced sludge. The sources of sludge to the dewatering units are WAS or thickened WAS or thickened primary or digested sludge or a combination. Figure 4-7 illustrate the average dry solids concentration in the feed and dewatered sludge cake. The average dry solid concentration in the feed sludge is 1.2% for centrifuges, 2.4% for Belt filter presses, and 1.9% for the screw press. The average dry solids concentration in the dewatered cake is 14.6% for Belt filter presses, 12.4% for Screw-presses and 10% for centrifuges. However, the nature, composition and dry solid concentration of the feed sludge will affect the dewaterability; another primary reason for such low dry solids content in the lack of conditioning chemicals (i.e. polymer). Almost all operators confirmed that conditioning chemicals are not always available.

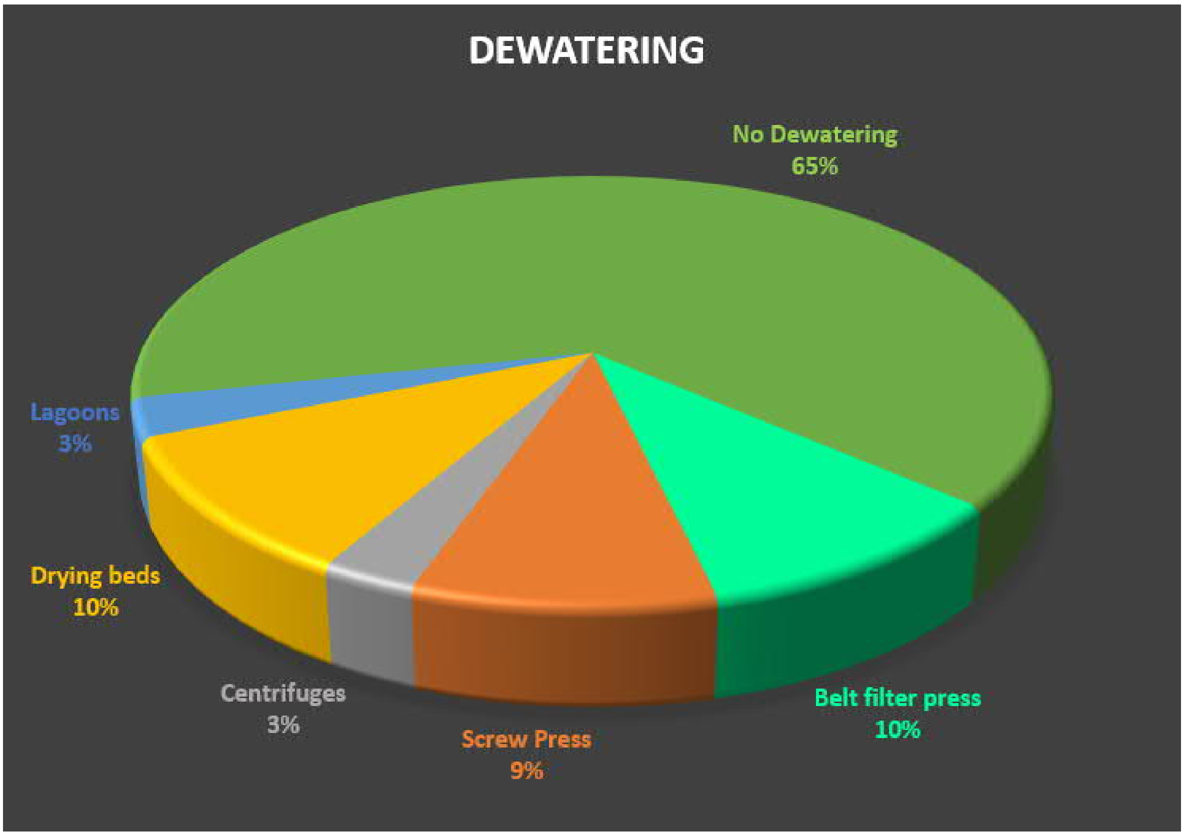


Figure 4-5 Percentage (Volume Basis) of Sludge Processed by Different Dewatering Processes Employed by eThekwini Municipality

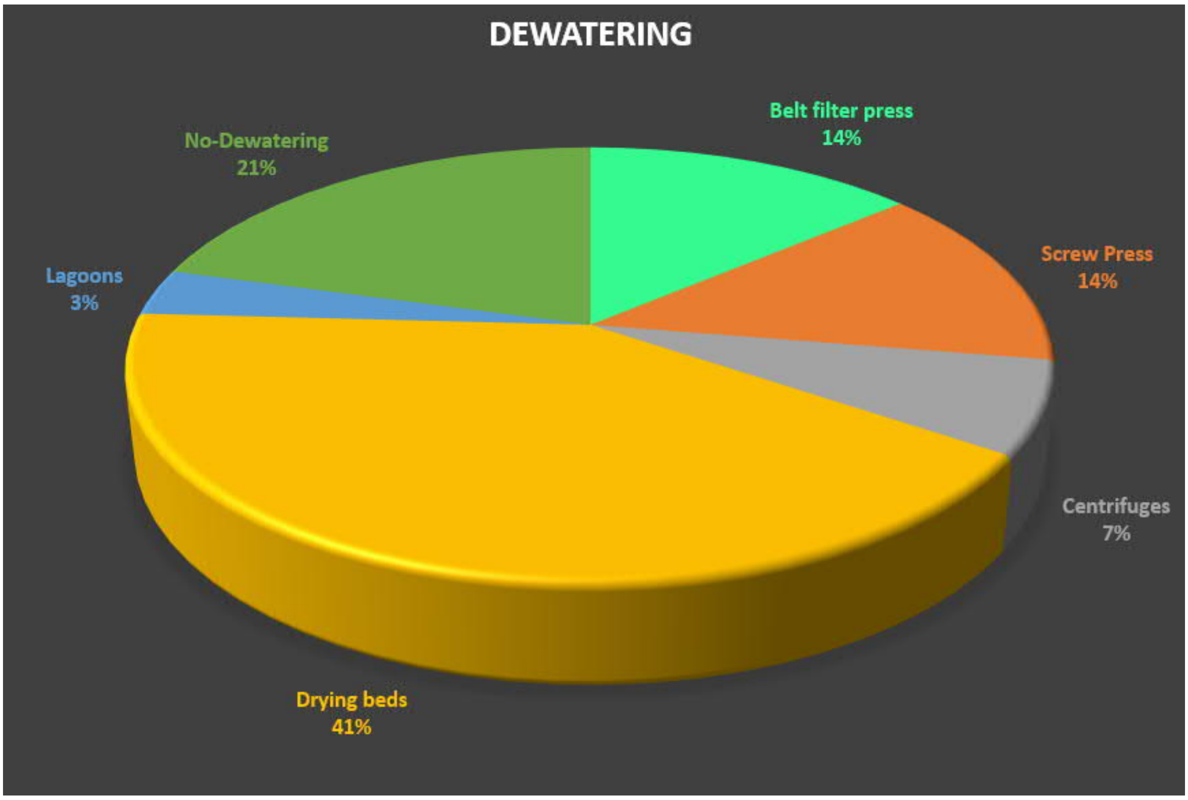


Figure 4-6 Number of Plants That Uses Dewatering Processes on a Percentage Basis

Based on the scoring system developed for this thesis, and considering the above presented operational facts, the mechanical dewatering scores -1 for sludge volume and weight reduction; however, it should be noted that the low-performance is a result of operational issues. For pollutant reduction/removal, pathogens reduction/elimination and stabilisation, mechanical dewatering units have little to no effect on these parameters; for this reason, it scores -2.

4.4.3 Air Drying (Natural drying);

eThekwini municipality uses drying beds and drying lagoons as a means of air drying (natural dewatering). Eight of the WWTW utilise drying beds, and two WWTW utilise sludge drying lagoons. Figure 4-6 illustrate the number of treatment works on a percentage basis that uses natural dewatering. Drying beds are used at 41% of the treatment works, followed by Drying lagoons 3%. On the other hand, Figure 4-5 illustrates the natural dewatering processes on a volume percentage basis. 13% of the produced sludge undergo natural dewatering, where 10% are dewatered using drying beds, and 3% are dewatered using sludge lagoons. This concludes that 44% of the treatment works use natural dewatering, and it dewaters only 13% of the overall volume of the produced sludge.

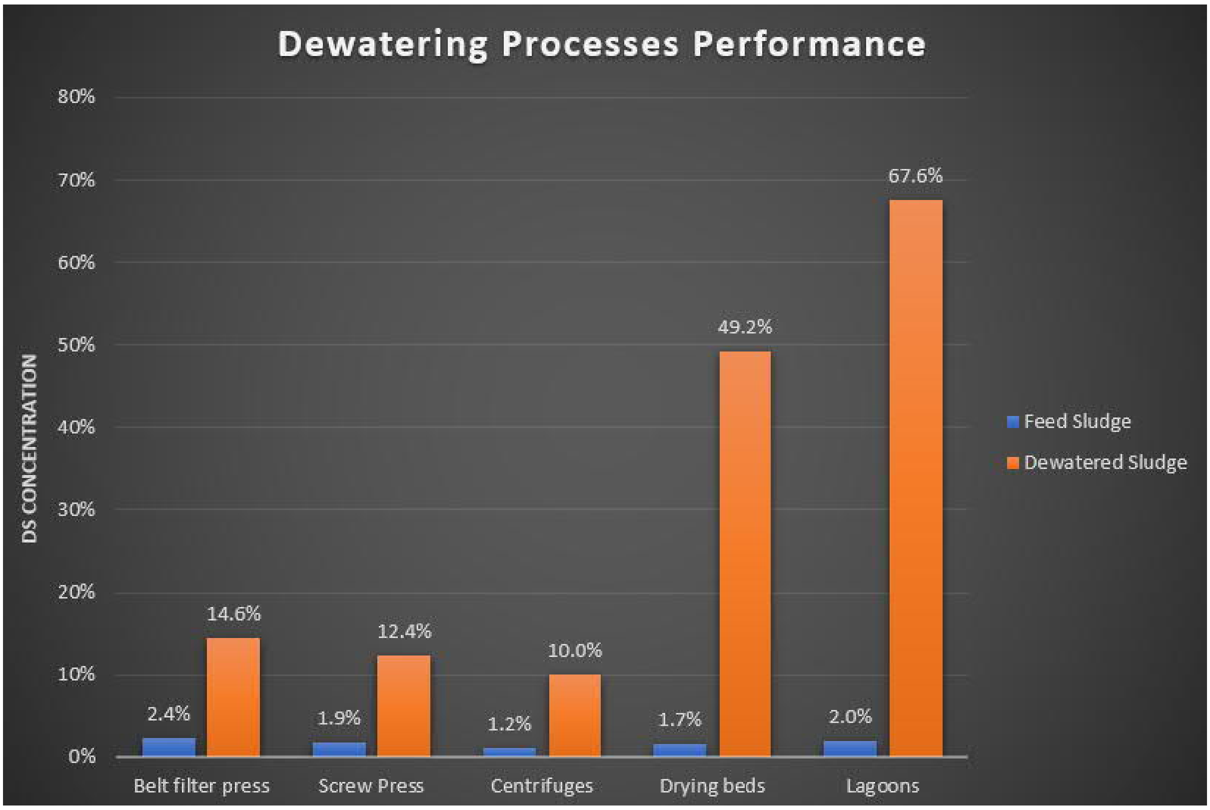


Figure 4-7 Dewatering Processes Performance

The average dry solid concentration in the feed sludge varies between 1.7% for drying beds and 2% for sludge lagoons. However, the average dry solids concentration in the dewatered cake vary between 49.2% for drying beds and 67.6% for sludge lagoons. The performance of the drying beds and sludge lagoons is exceeding the expected performance of these types of natural dewatering systems. The explanation of the unexpected performance is due to the sludge disposal challenges eThekwini municipality is facing. The sludge drying lagoons are not operated correctly, and sludge is not removed as per the design operation cycle; on the contrary, it's used as sludge storage, giving the sludge a very long time to concentrate. Drying beds; the collected samples are taken from the stockpiles that might have been on site for weeks or even months, explaining the unexpectedly high performance. The available data does not represent the actual effectiveness of these dewatering processes. Based on the scoring system developed for this thesis, and considering the above presented operational facts, the natural (air) dewatering scores -1 for sludge volume and weight reduction; Since the high dry solids in the naturally dries sludge may not be an actual representation of performance as explained above. For pollutant reduction/removal, pathogens reduction/elimination and stabilisation, mechanical dewatering units have little to no effect on these parameters (except if lime is used for conditioning, a degree of pathogen reduction and stabilisation will be achieved, which is not the case); for this reason, it scores -2.

4.4.4 Anaerobic digestion;

Nine out of twenty-four treatment works utilise anaerobic digesters for sludge stabilisation. However, Sludge treatment at Southern works is not operational. The efficiency of the anaerobic digesters is measured in terms of percentage reduction of volatile solids calculated using O'Shaunessy's formula. The volatile solids reduction varies between 9% at Northern WWTW and 65% at Isipingo WWTW, with average compliance of 63% of the samples; details can be found in Appendix 3. According to The Guidelines for the Utilisation and Disposal of Wastewater Sludge, 38% is the minimum acceptable volatile solid reduction for stabilisation and minimising of vector attraction. Figure 4-8 illustrate that six-treatment works comply with the acceptable volatile solid reduction in the guidelines. However, only Northern WWTW and KwaMashu WWTW do not comply with the guidelines, with Northern WWTW being the worst performing WWTW with 0% compliance and an average volatile solids reduction of 9%. All the anaerobic digesters operate in the mesophilic temperature range (30–38°C), which should reduce the pathogen count. The data collected does not directly measure pathogens (i.e. faecal coliform and helminth ova) in the feed and digested sludge. However, the pathogens count was measured in the dewatered sludge. Table 4-3 present the microbiological classification of the dewatered sludge for all eight WWTW's. The collected microbiological classification ca not be related to the performance of the digesters for the following reasons;

- There are no data reported on the feed and digested sludge microbiological characteristics.
- The reported pathogen concentration in literature for untreated sludge (Fecal coliform: 8×10^6 CFU/gm, Helminth ova: $10 - 1.4 \times 10^3$ CFU/Kg) is very close to the detected range in the dewatered sludge as reported in Appendix 2.

Table 4-3 Microbiological Classification for The Wastewater Treatment Works Utilising Anaerobic Digestion (Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019))

Wastewater Treatment Work	Microbiological Classification
Amanzimtoti WWTW	C
Isipingo WWTW	B
Mpumalanga WWTW	B
KwaNdengezi WWTW	B
KwaMashu WWTW	B
Phoenix WWTW	B
Umbilo WWTW	C
Northern WWTW	B

Based on the scoring system developed for this thesis, and considering the above presented operational facts, the anaerobic digester scores +1 for sludge volume and weight reduction. For pollutant reduction/removal, it scores -2 as it has little to no effect. However, for pathogens reduction/elimination, Anaerobic digester scores 0. And for stabilisation, it scores +1.

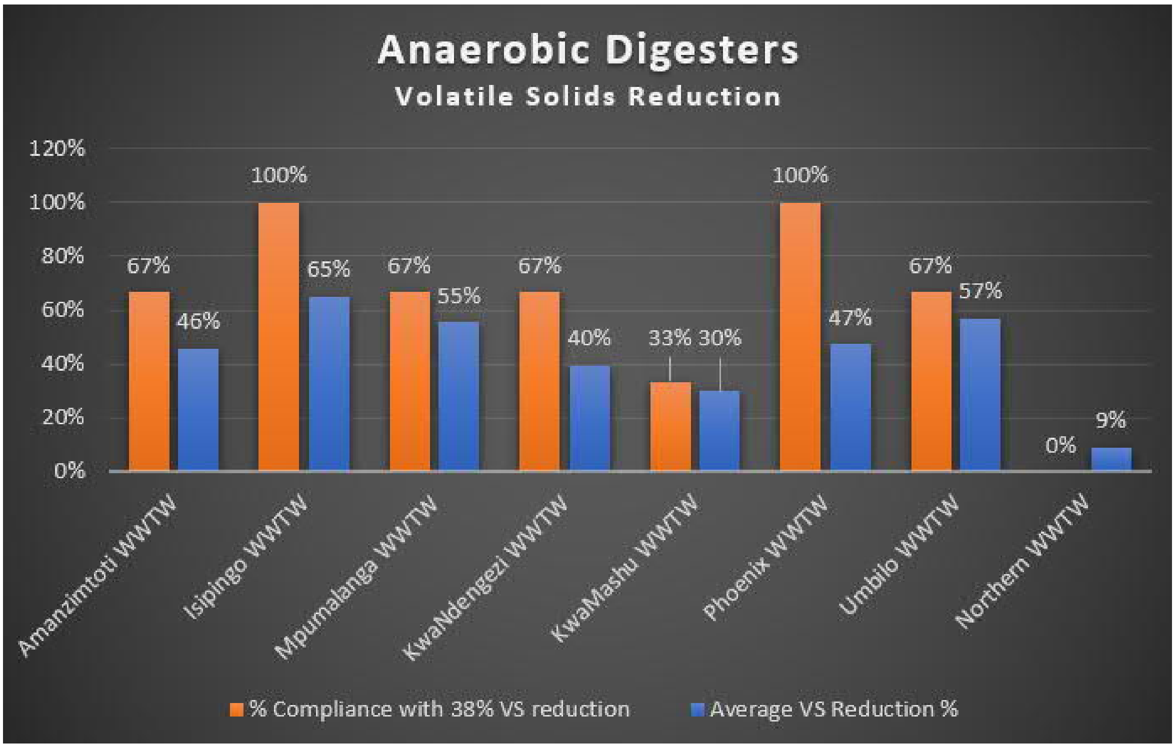


Figure 4-8 Anaerobic Digesters – Performance and Compliance in Terms of Volatile Solids Reduction

4.4.5 Thermal drying;

Thermal drying is not a technology currently in use by eThekwini municipality. However, it has been given serious consideration internationally in recent years since thermally dried sludge has high reuse potential as a fertilizer, soil conditioner and fuel source (Turovskiy and Mathai, 2006, Qasim et al., 2018). The use of dried sludge as a fertilizer is assessed under Agriculture. Here, the sludge was evaluated for reuse as a fuel source. Heat value (calorific value), autogenous combustion, ash content, volatile solids content and heavy metals content are the primary characteristics to evaluate the use of sewage sludge as a fuel source (Andreoli et al., 2007, Qasim et al., 2018). The calorific value of the sewage sludge produced by twenty-one plants is calculated. However, four WWTW did not have enough data to perform the calculations, and these treatment works are KingSburgh WWTW, Dassenjoek WWTW, Glenwood WWTW and Umdloti WWTW. Fair et al. (1966) empirical formula and Vesilind (1997) empirical formula was used to calculate the fuel value. The detailed estimates are presented in Appendix 4. Figure 4-9 and Figure 4-10 present the calculated fuel value for the sludge produced by 21 wastewater treatment works using Fair et al. (1966) empirical formula and Vesilind (1997) empirical formula. The minimum, maximum and average heat values are given in Table 4-4. For comparison, the typical calorific values of sewage sludge and other alternative fuels are shown in Table 4-5. The comparison shows that the average estimated heating values of the sewage sludge produced from the twenty-one WWTW are very much comparative with the typical calorific value for other fuels.

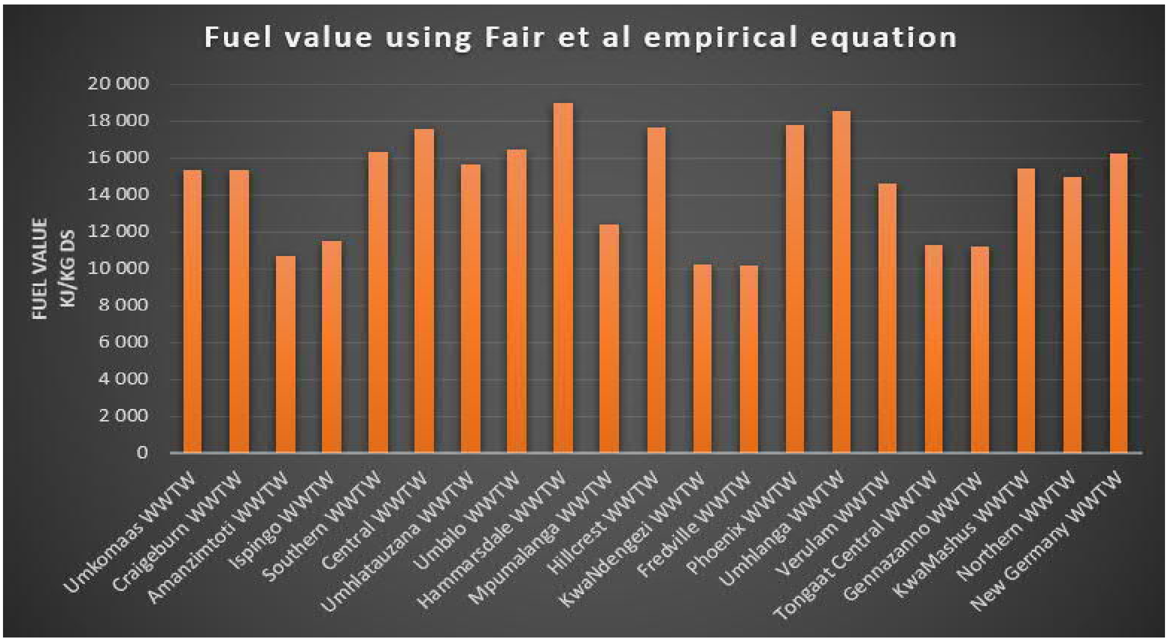


Figure 4-9 Sludge Fuel Value Calculated Using Fair et al. (1966) Empirical Formula

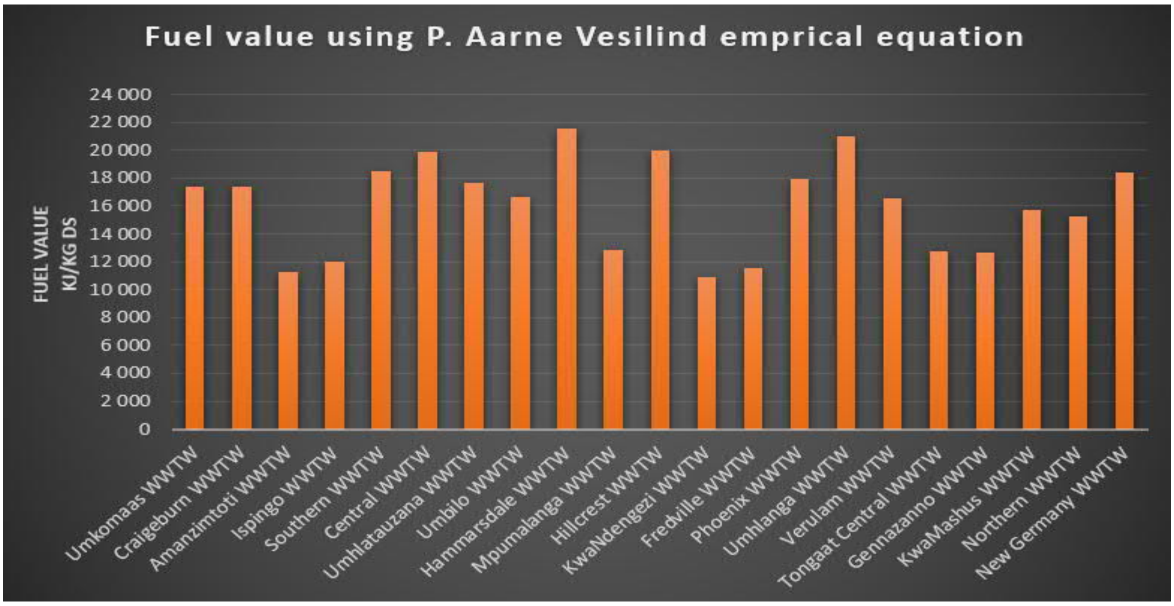


Figure 4-10 Sludge Fuel Value Calculated Using Vesilind (1997) Empirical Formulas

Table 4-4 Summary of the Minimum, Maximum and Average Sludge Calorific Value

	Minimum Calorific Value KJ/Kg	Maximum Calorific Value KJ/Kg	Average Calorific Value KJ/Kg
Fair et al. (1966)	10 193	19 009	14 693
Vesilind (1997)	10 869	21 580	16 101

The average volatile solids concentration was found to be 54% with 43% minimum and 81% maximum which contribute to the good calorific values obtained. It was also found that the average dry solid concentration is 34% which is suitable for thermal drying as it will aid in decreasing the amount of auxiliary fuel required by the dryers.

Table 4-5 Comparison of Alternative Fuels Calorific Value

Fuel Type	Calorific Value KJ/Kg
Coal	14 600 – 26 700
Plastics, wood, paper, rags, garbage	17 600 – 20 000
Wood	16 000 –20 000
Sewage sludge	12 000 – 20 000
Natural gas	38 000
Synthetic coal gas	10 800
Black liquor	12 500 – 15 000
Coke-oven gas	19 000 – 22 000

Since the combustion is only autogenous when the dry solids concentration is higher than 35%, thermal dryers can achieve a moisture content as low as 5% (95% dry solids), supporting autogenous combustion of dried sludge if used as fuel.

The heavy metals concentration in the data collected meets class “a” pollutant level as per the guidelines for utilisation and disposal of sludge (DWAF Report TT261/06) except for three wastewater treatment works (Mpumalanga WWTW, Glenwood WWTW and Umbilo WWTW) it’s classified as “c”. Such concentration of pollutants will limit the emission of heavy metals in the exhaust gases of the thermal dryers and when used as a fuel source.

The ash content of the fuel significantly impacts combustion characteristics by decreasing the combustion reaction rate. The range of ash content found in the literature within which the dry sludge exhibits a good combustion behaviour is 15% to 40% for mixed primary/secondary/digested. The collected data shows an acceptable ash content, with an average of 38%, minimum of 19%, maximum of 56%, and a standard deviation of 12%. It is essential to note that the moisture content of the feed solids to the dryer partially dictates the required capacity and affects decisions on the conveyance technologies and the amount of auxiliary fuel to be used for drying. The collected data shows an average dry solids concentration of mechanically dewatered sludge between 10 and 15%. The performance of the mechanical dewatering units needs to be improved to produce at least 20 to 25% concentration which is a typically acceptable dryness for thermal dryers feed sludge. On the other hand, the reported sludge dryness from natural dewatering (air drying) processes may not be an actual representation of the processes performance. More importantly, 65% of the sludge volume produced from the 25 wastewater treatment works is not dewatered. Thermal drying will also reduce the volume and weight of the feed sludge significantly, as it reduces moisture by as much as 85 to 95% (w/w) without destroying the organic matter content of the sludge. Based on the scoring system developed for this thesis, considering that the produced sludge have the quality to be used as a fuel source after being dried, the thermal drying scores +2 for sludge volume and weight reduction, and +2 for pathogens reduction/elimination and +2 for stabilisation. However, for pollutant reduction/removal, it has almost no effect, and scores -2.

4.4.6 Transportation;

Transportation is an essential support method in the sludge reuse and disposal route. The sludges can be transported by pipeline, barge, rail or trucks. Within eThekwini municipality the sludge transportation by trucks and tankers is the most widespread method used. The selection between trucks and tankers depends mainly on the dryness of the sludge being transported. In addition to the conventional evaluation of transportation methods using solids concentration, the rheological characteristics are a helpful tool to evaluate other alternatives of transport, mainly pumping. However, transportation has no impact on the performance in reducing weight, volume pathogens and pollutants. For this reason, the transportation scores -2.

4.4.7 Landfill;

on-site and off-site disposal of sewage sludge is being practised in eighteen WWTW out of twenty-five WWTW owned and operated by eThekwini municipality. However, only seven wastewater treatment works practice landfill disposal. Landfill (Off-site) disposal is the option investigated under this thesis due to land constraints and lack of on-site disposal good practice at the existing wastewater treatment plant sites. Generally, the landfill is not a good practice from a beneficial use perspective of sewage sludge. The sludge data collected does not include test results for the minimum requirements (explosiveness, flammability, corrosiveness, reactivity radioactivity and toxicity) that govern hazardous waste disposal or any hazardous rating. The average dry solid content of mechanically dewatered sludge is between 10 to 15% which is on the lower end of the acceptable concentration (20% DS) by landfill. On the other hand, natural dewatering reaches a high dry solid content between 49% to 67%; however, it may not be representable as samples were collected from stockpiles that may have been on site for very long. The heavy metals concentration in the data collected meets class "a" pollutant level as per the guidelines for utilisation and disposal of sludge, which improves the hazardous rating of the sludge. The pH varies between 4.73 and 8.6, with an average of 6.8 and a standard deviation of 0.7, which will not prevent metals' leaching. Sludge organic and nutrient content are enough to support the production of landfill methane gas. Volatile solids content vary between 44% and 62%, with a standard deviation of 12%. Nitrogen and phosphorus content vary between 0.13 to 2.69% and 0.05 to 1.7%, with a standard deviation of 0.75% and 0.32% respectively. Collected data details are presented in Appendix 2. The above data indicate that landfill is a good alternative for sludge disposal. However, the lack of available hazardous landfill sites, potential high transportation cost, the fact that 65% of the sludge by volume is not dewatered and the municipality emphases on beneficial use, all these reasons go against the utilisation of landfill as ultimate disposal method.

Based on the scoring developed for this thesis, the use of landfill as a final disposal method has no impact on the sludge volume/weight reduction, pathogens reduction/elimination, pollutant reduction/removal and stabilisation within the treatment works; for these reasons, it scores -2.

4.4.8 Composting;

The goal of composting is to produce a final product that is stable, free of pathogens, and can be beneficially applied to land as a fertilizer or soil conditioner. The sewage sludge quality affecting composting and the utilisation of the compost are moisture, pH, nutrient concentration,
volatile solids, and heavy metals concentration.

The optimum moisture content for composting is between 40% to 60%. The pH for composting mixture should be between 6 to 9, with carbon to nitrogen ratio of 35 to 1. Carbon represents the energy source for composting, while nitrogen is necessary for the reproduction of bacteria (protein synthesis). The balance between these two parameters assures the effectiveness of the process. Sewage sludge (raw, digested and dewatered) typically contains 1% to 6% of nitrogen-DS; and 22-30% of carbon. The data collected, presented in Table 4-6, shows a nitrogen concentration between 0.13% and 5.37%, with an average of 2.69%; on the other hand, no data on the carbon content was found. However, the volatile solids concentration of an average of 62% and standard deviation of 12% can be used as an indicator for sufficient organic content. Composting decreases the sludge volume and weight as 20 to 30% of the volatile solids will decompose during the composting process.

For the unrestricted use of the compost, the heavy metals concentration must meet class “a” pollutant level as per the guideline for utilisation and disposal of sludge (DWAF Report TT261/06). The heavy metals concentration in the data collected for twenty-two plants meets class “a” pollutant level as per the guidelines. Only three WWTW (Glenwood package plant, Mpumalanga WWTW and Umbilo WWTW) are class “C”. Finally, the moisture content and pH are operational parameters that can be readily adjusted at the composting site. Based on the scoring system developed for this thesis, and considering the above presented operational facts, Composting scores 0 for sludge weight and volume reduction. For sludge stabilisation and pathogenic reduction/elimination, it scores 0. Pollutant reduction/removal, composting scores -2 as it has little to no effect on reducing and removing pollutants.

4.4.9 Agriculture;

For the sewage sludge to be used for agriculture purposes, its characteristics must comply with the guidelines for utilisation and disposal of sludge (DWAF Report TT262/06). According to the guidelines, fertilizer can only be classified as an organic fertilizer if it contains less than 20% ash and 40% water. However, it can be used as a soil conditioner. The average ash content on dry bases in the collected data is 38%, with a minimum of 19%, a maximum of 56% and a standard deviation of 12%. Heavy metals and pathogens could compromise the beneficial use of the sewage sludge due to its potential negative impact on soil, plants and humans. Volatile solids are essential as a source of organic matter; however, they pose a risk due to their potential to generate odour and attract vectors. The following is found by comparing the sewage sludge data collected to the guidelines; the heavy metal concentration in the sludge produced from twenty-two WWTW meets pollutant class “a”. Only two WWTW’s produced sludge with pollutants class “c” (Glenwood WWTW & Umbilo WWTW) and one WWTW produce sludge with pollutant class “b” (Mpumalanga WWTW). The produced sludge from twenty-two WWTW’s has a problem with elevated pathogens (Faecal coliform and Helminth ova). These WWTWs produce sewage sludge with microbiological class “B” and “C”. However, only three WWTW’s (Dassenhoek WWTW, Verulam WWTW and Umbilo WWTW) meet the pathogen limits producing sludge with microbiological class “A”. The volatile solids content in the sludge produced from twenty-one WWTW’s meets stability class “3”. Only sludge produced from four WWTW’s (Ispingo WWTW, Dassenhoek WWTW, Verulam WWTW and Phenix WWTW) meets stability class “1”. As the produced sludge can not be used for agriculture as a final disposal method due to it’s characteristics and since agriculture will have no effect on the sludge volume/weight reduction, pollutant reduction/removal, pathogens reduction/elimination and stabilisation; for these reasons, it scores -2.

4.4.10 Sea-outfall (Marine disposal);

Sewage sludge may bring pathogens, toxic organic compounds, and metals that can negatively impact the marine environment. The typical parameters of operation control and effectiveness of sea-Outfall are listed in Table 3-3. Measuring the concentrations of the control parameters in the sludge is a step toward determining its potential harms and toxicity. However, measuring the concentration alone is inadequate to regulate sludge discharges to the marine environment for several reasons. It is nearly impossible to measure for the estimated 10 000 chemical substances in regular use globally and potentially found in sewage sludge. Most of these chemicals have no associated toxicity information. To validate the use of outfall, a comprehensive monitoring program is required to monitor the residue dispersion dynamics, organic matter decomposition rate, transport of toxic elements and pathogenic organisms, the composition of benthic fauna and production of aquatic wildlife in the marine environment. These types of monitoring programs are costly and typically inconclusive. The failure of such monitoring programs can lead to an environmental catastrophe. These arguments show that marine disposal is an expensive alternative in terms of monitoring whose ecological effects cannot be easily measured and controlled. Most if not all the first world counties baned sewage and sludge marine disposal (sea outfalls). Two deep-sea outfalls at Southern wastewater treatment work and Central wastewater treatment work are owned and operated by eThekwini municipality; both outfalls are in operation with a valid permit. However, both outfalls have exceeded their design loads. Based on the scoring system developed for this thesis, the sea-outfall as a final disposal method has no impact on the sludge volume/weight reduction, pollutant/removal, pathogens reduction/elimination and stabilisation within the treatment works; for these reasons; it scores -2.

4.4.11 Incineration;

Incineration is not a current disposal method practised by eThekwini municipality. The primary evaluated characteristics of the feed sludge to consider the incineration process as an ultimate disposal method was (Turovskiy and Mathai, 2006, Andreoli et al., 2007 , Qasim et al., 2018) ; (1) the calorific value (fuel value), (2) dry matter and (3) autogenous combustion. Heavy metals content is also of importance for the selection of air pollution control systems (Turovskiy and Mathai, 2006). The calorific value of the sewage sludge produced by twenty-one plants is calculated. However, four WWTW did not have enough data to perform the calculations, and these treatment works are KingSburgh WWTW, Dassenjoek WWTW, Glenwood WWTW and Umdloti WWTW. Fair et al. (1966) empirical formula and Vesilind (1997) empirical formula were used to calculate the fule value. The detailed estimates are presented in Appendix 4. Figure 4-9 and Figure 4-10 present the calculated fuel value for the sludge produced by 21 wastewater treatment works using Fair et al. (1966) empirical formula and Vesilind (1997) empirical formula. The minimum, maximum and average heat values are given in Table 4-4.

The comparison shows that the estimated heating value of the sewage sludge produced by twenty-one WWTW is very much comparative with the typical calorific value of other fuels.

The sludge moisture content is essential because of the thermal load it imposes on the incineration process, in addition to its consequent effects on autogenous behaviour and self-sustained combustion of the sludge. The concentration of volatile solids in the sludge supports the sludge's autogenous behaviour. However, the combustion is only autogenous and self-sustained when dry solids concentration is higher than 35%. The collected data shows an average dry solids concentration of mechanically dewatered sludge between 10 and 15%. The performance of the mechanical dewatering units needs to be improved to produce at least 35% concentration which is a typically acceptable dryness for incinerators feed sludge.

On the other hand, the reported sludge dryness from natural dewatering (air drying) processes may not be an actual representation of the processes performance, as the samples were collected from stockpiles that may have been on site for a very long period. More importantly, 65% of the sludge volume produced from the 25 wastewater treatment works is not dewatered. The ash content is also an essential element to investigate to determine the combustion behaviour of sewage sludge. The ash content of the fuel significantly impacts combustion characteristics by decreasing the combustion reaction rate. The range of ash content found in the literature within which the dry sludge exhibits a good combustion behaviour is 15% to 40% for mixed primary/secondary/digested. The collected data shows an acceptable ash content, with an average of 38%, minimum of 19%, maximum of 56%, and a standard deviation of 12%.

The data collected shows that The heavy metals concentration in the sludge meets class “a” pollutant level as per the guidelines for utilisation and disposal of sludge (DWAF Report TT261/06) except for three wastewater treatment works it’s classified as “c”. Such concentration of pollutants will lead to a lower concentration of heavy metals in the combustion gases of the incinerators. However, it is reported that the toxicity of the combustion gases can be controlled, and most of the heavy metals in particulates carried out with the combustion gases can be captured by particle collection devices except Mercury (Hg). Based on the concentration of Mercury in the collected data, the mercury emission may create an issue and should be evaluated against the allowable environmental emission value. A thermal drying step may be needed to decrease the moisture content of the sludge in preparation for complete incineration. Based on the scoring system developed for this thesis, and considering the above presented operational facts, the incineration process decreases the sludge volume and weight (reported weight reduction 62% to 96%); for these reasons, it scores +2. However, pollutants reduction/removal scores -2 as most pollutants will be contained in the Ash. For pathogens reduction elimination and stabilisation, incineration scores +2.

Table 4-6 Data Collected on Sewage Sludge Characteristics that Influence Composting and Agriculture- on a Dry Solids Basis

Parameter	Unit	Min	Max	Average
Moisture content	% m/m	3%	99%	63%
pH	-	4.73	8.60	6.86
Total Dry Solids	% m/m	1%	97%	31%
Fixed Solid content (Ash)	% m/m	19%	56%	38%
Volatile solids	% m/m	44%	81%	62%
Total Nitrogen - N	mg/Kg DS	1 333.33	53 716.67	26 889.65
Total Nitrogen - N	%	0.13%	5.37%	2.69%
Phosphorus - P	mg/Kg DS	465.00	17 283.33	5 611.07
Phosphorus - P	%	0.05%	1.7%	0.6%
Potassium - K	mg/Kg DS	28.15	2 767.56	1 122.34
Potassium - K	%	0.003%	0.28%	0.12%
Arsenic	mg/kg DS	2.00	15.33	4.79
Cadmium	mg/kg DS	1.00	63.54	11.99
Chromium	mg/kg DS	10.62	2 367.78	150.10
Copper	mg/kg DS	19.63	1 503.00	199.15
lead	mg/kg DS	3.00	1 160.92	77.86
Mercury	mg/kg DS	0.48	156.17	11.42
Nickle	mg/kg DS	2.18	1 104.22	78.11
Zinc	mg/kg DS	35.67	4 033.56	558.56
Faecal coliform	CFU/gm DS	854	33 774 079	4 604 419
Viable Helminth	Ova/gm DW	0.33	226.33	14.79

4.4.12 Pyrolysis;

is not a current disposal method practised by eThekwini municipality. The characteristics to evaluate the effectiveness of sewage sludge for pyrolysis are almost the same as those to evaluate the incineration process. The differences between the two processes are in the manner the thermal decomposition of sewage sludge takes place (Wang et al., 2008, Yurtsever et al. 2009). The thermal decomposition of sewage sludge in the incineration process takes place in the presence of oxygen (Wang et al., 2008, Yurtsever et al. 2009). However, the pyrolysis process takes place in the absence of oxygen or in lower than stoichiometric oxygen atmospheres (Wang et al., 2008, Yurtsever et al. 2009). The other significant differences of pyrolysis over incineration are (Wang et al., 2008, Yurtsever et al. 2009); (1) the production of three potentially useful end products: gas (primary methane), a liquid (tar and/or oil), and char; (2) the use of less auxiliary fuel for the same moisture content and (3) Higher feed capacity (requires less air, so that more sludge can be processed). High moisture content can be an advantage to the pyrolysis process as it favours the generation of hydrogen-rich fuel gas. However, limited information has been found on using high moisture (>75%) sewage sludge as pyrolysis feedstock and its effect on the process energy consumption and performance. Based on the scoring system developed for this thesis, and considering the above presented operational facts, the pyrolysis process decreases the sludge volume and weight (reported weight reduction 63%); for these reasons, it scores +2. However, pollutants reduction/removal scores -2 as most pollutants will be contained in the pyrolysis products. For pathogens reduction elimination and stabilisation, pyrolysis scores +2.

4.5 The risk of adverse effects on the environment

The environmental impact was assessed using ten critical criteria listed in the literature (Turovskiy and Mathai, 2006, Wang et al., 2008, Qasim et al., 2018) and presented in Table 4-7. The scoring has been developed so that the higher the average scoring, the less the adverse impact percentage. Figure 4-11, a summary of the potential environmental impact results under the assumption of normal operation. The landfill and marine (sea-outfall) disposal scored the highest for potential risk of adverse effect on the environment, with 67% and 64%, respectively, followed by agriculture at 56%. Thickening is the lowest among the treatment and handling processes at 19%, followed by mechanical dewatering and anaerobic digestion at 22%. Natural dewatering 39% has a higher adverse risk impact than mechanical dewatering because of its higher adverse impact on odour, vector attraction, surface water/groundwater contamination, and soil/subsoil contamination. All thermal oxidation processes assessed scored 28%. Composting scored 44%, which is less than agriculture as it poses a lower risk of adverse impact on soil/subsoil contamination, surface water/groundwater contamination, eutrophication, and depreciation of nearby areas. Finally, transportation scored the lowest adverse impact by 11%.

4.6 Operation simplicity

The typical perception of operation simplicity may give natural dewatering (air-drying) an advantage over thickening and mechanical dewatering. However, the effect of climate conditions on the natural dewatering and labour-intensive cake removal process influences its operation simplicity and put the thickening and mechanical dewatering at the same operation simplicity level (Turovskiy and Mathai, 2006, Gurjar et al., 2017). In addition, eThekwini municipality operators are very familiar with such processes; for these reasons, all three processes score +2.

Anaerobic digester is a technology in use by eThekwini municipality. However, in practice, operating anaerobic digesters is more demanding in terms of sensitivity to the feed sludge quality and quantity and maintaining optimum operation parameters such as temperature and pH and the operational requirements of the sludge recycling and heating units as well as biogas storage. For this reason, it has been given a score of +2. The thermal drying technology is considered a complex process in terms of operation and control. System complexity is also supported by the fact that thermal dryer is typically followed by air pollution control devices and systems that alter the form of the dried sludge. Thermal dryers are not currently used by eThekwini municipality and will require intensive training and a significant learning curve for the operators. For these reasons, it scored -2.

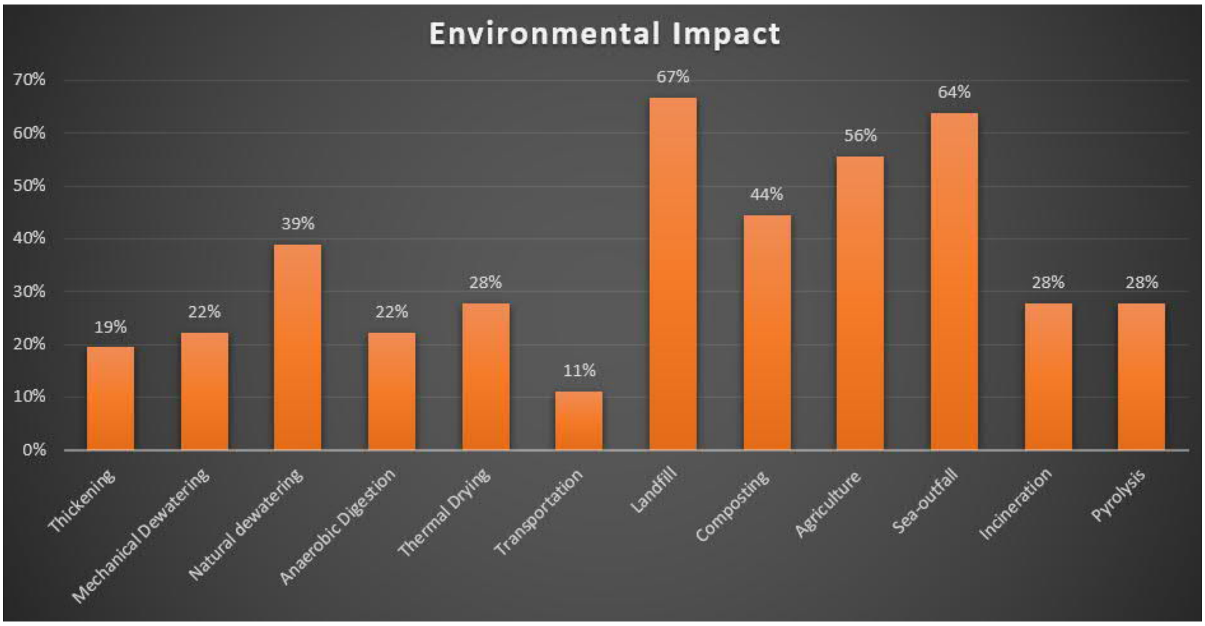


Figure 4-11 Adverse Effects of Environmental Impact of Sludge Treatment and Disposal Methods

eThekwini municipality involvement in the landfill, composting, and agriculture as a final disposal method is limited to transportation. The municipality is not involved in the actual operation of these disposal methods; for this reason, they scored +2.

However; The municipality operates the Sea-out falls as a final disposal method; it only requires pumping and transportation, which are simple processes to operate. For this reason, it scored +2.

Incineration is similar to thermal drying in its operational complexity. Air pollution control devices typically follow both technologies. The high operating temperature (400 – 800 °C) required by the incineration process reduce equipment reliability and require a complex control system. The incineration process is not currently in use by the eThekwini municipality and will require intensive training and a significant learning curve for the operators. For these reasons, it scored -2.

Pyrolysis involves heating the sludge without oxygen, which eliminates air pollution and the need for air pollution control devices and systems. However, it produces combustible gases that require collection systems for beneficial use or flaring, which adds complexity to the system operation. It is also not currently in use by the municipality. For these reasons, it scored -2. The above operation simplicity scoring is summarised in Table 4-13.

4.7 Reuse potential

Table 4-8 and Figure 4-12 summarise and illustrate the potential reuse assessment results for the treatment and disposal methods discussed under this thesis. The high average score represents a high reuse potential. The results of Pollutants, pathogens and stabilisation were discussed in detail under section 4.2 Process performance. The results of energy recovery potential and revenue potential are discussed hereafter.

4.7.1 Thickening;

energy ca not be recovered from thickening processes. On the other hand, for thickened sludge to be used as a solid conditioner or a fertiliser, it should meet the required guidelines classifications. The collected data for dewatered sludge shows that it does not meet the guidelines' requirements, primarily the microbiological classifications, reflecting that thickened sludge ca not be reused as a fertiliser or soil conditioner. If the sludge quality improves to meet the guidelines, the thickened sludge has a high moisture content of up to 95%, significantly impacting transportation costs and reducing or eliminating possible revenue. For these reasons, thickening score -2 for revenue potential and energy recovery potential, with an overall reuse potential of 0%.

4.7.2 Mechanical dewatering and Natural dewatering;

Energy recovery is not possible from both processes. Utilising the dewatered sludge as a solid conditioner or a fertiliser is not possible as it does not meet the guidelines classifications, primarily the microbiological classifications. If the sludge quality improves to meet the guidelines, the dewatered sludge will be transported at a lower cost compared to thickened sludge due to the low moisture content. However, the transportation cost will still be subject to quantity and transport distance. For these reasons, dewatering processes score -2 for revenue potential and energy recovery potential, with an overall reuse potential of 0%.

4.7.3 Anaerobic digestion;

It offers the possibility of energy recovery through the use of the biogas (65% methane) produced (Turovskiy and Mathai, 2006, Qasim et al., 2018). In most cases, the amount of biogas produced exceeds the amount required to maintain the digestion process temperature (Turovskiy and Mathai, 2006, Qasim et al., 2018). Excess biogas can be used to generate electricity to run some of the treatment work equipment. Currently, the biogas produced at the eight WWTW that utilise anaerobic digestion is only used to heat the feed sludge, and the excess is flared. Utilising the biogas for heating feed sludge reduces the operation cost; however, flaring the excess is a waste of a valuable resource. Biogas can produce heat and electricity for use in engines, microturbines, and fuel cells (Turovskiy and Mathai, 2006, Qasim et al., 2018). Biogas can also be upgraded into biomethane, also called renewable natural gas, and injected into natural gas pipelines or used as a vehicle fuel (Turovskiy and Mathai, 2006, Metcalf & Eddy/AECOM, 2014, Qasim et al., 2018). However, all these potential reuse options require further investigation to determine the optimal alternative considering the required infrastructure and the excess biogas quantity and quality. For these reasons, anaerobic digestion scores +1 for revenue potential and energy recovery potential, with an overall reuse potential of 75%.

4.7.4 Thermal dryers;

Thermal dryers produce marketable sludge with almost 95% dryness, easy to be packaged and transported, stabilised and almost free of pathogens (Metcalf & Eddy/AECOM, 2014, Qasim et al. 2018). The thermal dried sludge can also be used as an auxiliary fuel during the drying process or sold as a fuel source to other industries such as cement and coal power plants (Metcalf & Eddy/AECOM, 2014, Qasim et al. 2018). However, creating a market for these products may be the limiting factor. For these reasons, Thermal dryers score +1 for revenue potential and energy recovery potential, with an overall reuse potential of 75%.

4.7.5 Transportation;

Transportation has no potential for energy recovery nether revenue potential for eThekwini municipality. For this reason, transportation scores -2 revenue potential and energy recovery potential, with an overall reuse potential of 0%.

4.7.6 Landfill;

Landfill has no potential for energy recovery nether revenue potential primarily for eThekwini municipality. For this reason, transportation scores -2 revenue potential and energy recovery potential, with an overall reuse potential of 0%.

4.7.7 Composting;

Composting has no potential for energy recovery. However, it has high revenue potential. Composting will improve the sludge microbiological quality to meet the guidelines. It will also convert the sludge into a stable end product that is easy to handle, store and use as a soil conditioner or a fertiliser. The foreseen challenges are; (1) the availability of composting sites, (2) the transportation of sludge from the wastewater treatment plants to the composting sites and (3) the availability of a market to consume the massive amount of produced compost from sludge. For these reasons, composting scores -2 for energy recovery potential and +2 for revenue potential with an overall reuse potential of 50%.

4.7.8 Agriculture;

Agriculture has no potential for energy recovery. For sludge to be used as a solid conditioner or a fertiliser, it should meet the required guidelines classifications, which is not the case for the thickened and dewatered sludge produced by the 25 WWTW. As mentioned previously, transportation cost may be a limiting factor for excellent revenue even if the sludge quality is improved to meet the guidelines. However, if the sludge is thermally dried or composted, the transportation cost will be reduced dramatically, and its quality will meet the guidelines classifications. For these reasons, For these reasons, agriculture scores -2 for energy recovery potential and +2 for revenue potential with an overall reuse potential of 50%.

Table 4-7 Environmental Impact Assessment Scoring

	Odour	Vector Attraction	Noise	Air-contamination	Soil/Sub-soil contamination	Surface water /Groundwater contamination	Eutrophication potential	Depreciation of nearby areas	Annoyance to Affected populations	Average Score	Impact %
Thickening	+1	+1	+2	+2	+2	+2	+1	+1	-1	+1.2	19%
Mechanical Dewatering	+1	+1	+1	+2	+2	+2	+1	+1	-1	+1.1	22%
Natural Dewatering	0	0	+2	+2	0	0	0	+1	-1	+0.4	39%
Anaerobic Digestion	0	+2	+2	+1	+2	+2	+1	+1	-1	+1.1	22%
Thermal Drying	0	+2	+1	-1	+2	+2	+2	+1	-1	+0.9	28%
Transportation	+1	+2	0	+1	+2	+2	+2	+2	+2	+1.6	11%
Landfill	-1	-1	0	0	-1	-1	0	-1	-1	-0.7	67%
Composting	-1	-1	+1	+1	0	0	+2	+1	-1	+0.2	44%
Agriculture	-1	-1	+2	+1	-1	-1	-1	0	0	-0.2	56%
Sea-outfall	-1	0	0	0	+2	-2	-2	-1	-1	-0.6	64%
Incineration	0	+2	+1	-1	+2	+2	+2	+1	-1	+0.9	28%
Pyrolysis	0	+2	+1	-1	+2	+2	+2	+1	-1	+0.9	28%

+2 No risk of adverse impact / +1 low risk of adverse impact / 0 moderate risk of negative impact / -1 High risk of adverse impact / -2 Very high risk of adverse impact

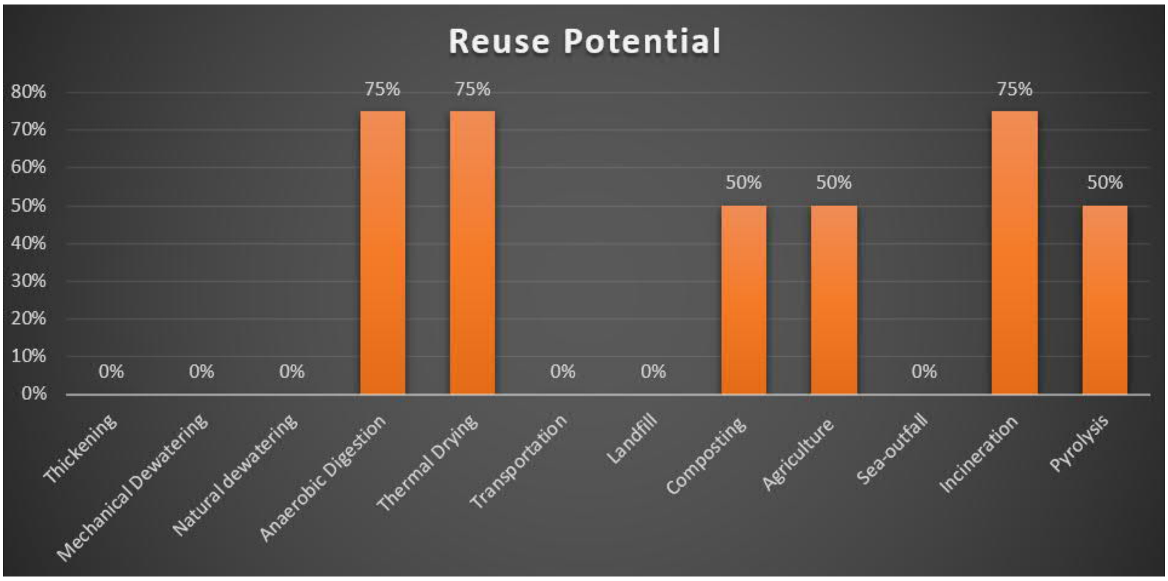


Figure 4-12 Reuse Potential of Sludge Treatment and Disposal Methods

4.7.9 Marine disposal (Sea-Outfall) ;

Marine disposal has no potential for energy recovery nether revenue potential for eThekwini municipality. For this reason, marine disposal scores -2 revenue potential and energy recovery potential, with an overall reuse potential of 0%.

4.7.10 Incineration;

Incineration has a relatively high potential for energy recovery through heat. The energy produced in the incineration process can be used to dry the dewatered sludge cake before the incineration process or can be used to produce electricity. The infrastructure required to recover the heat and produce energy may be a limiting factor, and its feasibility needs to be investigated further. However, incineration of sludge is currently applied worldwide more and more in combination with energy recovery, mainly on a large scale. For large-scale incineration within eThekwini municipality, a centralised incineration plant may be required, and sludge transportation will contribute to higher operating costs and possibly less revenue. The produced ash is also a marketable product; since it can be used to manufacture clay in sintered bricks, tiles and pavers, and as a raw material for manufacturing lightweight aggregate (Ukwatta et al., 2016, Moreno et al., 2016). Ash has also been used to form high-density glass-ceramics. Phosphate and heavy metals can also be extracted from ashes (Evans, 2016). However, the lack of such facilities to work with ashes and creating a market for the incineration process products are limiting factors. For these reasons, incineration score +1 for revenue potential and energy recovery potential, with an overall reuse potential of 75%.

4.7.11 Pyrolysis;

the by-products (gases, oil, tar, and char) of the pyrolysis process are marketable and typically used as a fuel source. However, their heating value is sometimes considered low compared with other fuel sources. There are also certain limitations associated with the physical and chemical properties of these oils, which prevent them in most cases from being used as a direct substitute for conventional fossil fuels without pre-treatment. The availability of a market al.so plays a significant role in generating revenue. For these reasons, pyrolysis score 0 for revenue potential and energy recovery potential, with an overall reuse potential of 50%.

Table 4-8 Reuse Potential Assessment Scoring

Technology	Potential for Energy Recovery	Revenue Potential	Average Score	Reuse potential %
Thickening	-2	-2	-2.00	0%
Mechanical Dewatering	-2	-2	-2.00	0%
Natural dewatering	-2	-2	-2.00	0%
Anaerobic Digestion	+1	+1	+1.00	75%
Thermal Drying	+1	+1	+1.00	75%
Transportation	-2	-2	-2.00	0%
Landfill	-2	-2	-2.00	0%
Composting	-2	+2	0	50%
Agriculture	-2	+2	0	50%
Sea-outfall	-2	-2	-2.00	0%
Incineration	+1	+1	+1.00	75%
Pyrolysis	0	0	0	50%

4.8 Amount of sludge/by-products produced and requires disposal after each process and method

The three primary final disposal methods, (1) landfill, (2) marine disposal, and (3) agriculture, scored +2 since all sludge or by-products are disposed of or utilised. Composting and thermal drying produce a large amount of sludge to be utilised, hence scored -1. Incineration and pyrolysis scored +2 since a small quantity of by-products such as ash and liquid are still to be disposed of or utilised. Digestion, thickening, and dewatering produce a large amount of sludge for further disposal or utilisation; for this reason, all scored -2. The results are summarised in Table 4-13.

4.9 Reliability and robustness

The scoring of reliability and robustness is shown in Table 4-9. Figure 4-13, illustrate the reliability and robustness percentage of sludge treatment and disposal methods studied under this thesis. Natural dewatering scored the highest percentage with 94%, followed by agriculture at 88%, this is primarily due to the simplicity of operation of these methods. Mechanical dewatering scores 81%; since it requires a higher operation experience and equipment control compared to natural dewatering. During site visits to few wastewater treatments works, it was evident that the mechanical dewatering units are not operational due to lack of conditioning chemicals or spare parts. Landfill scores 69%; however, hazardous landfill sites are not owned or operated by the eThekwini municipality. Thickening scores 69% since it operates 24h/day; however thickening equipment is frequently out of order or underperforming due to a lack of proper operation and maintenance. Sea-outfall scores 69% because it is simply pumping equipment to operate and control. Composting scores 63%, as it requires higher operators experience and moderate equipment control when compared to final disposal methods such as agriculture. Anaerobic digestion scores 50% due to operating hours and the required moderate operator experience. The data collected confirms that six out of the eight anaerobic digesters are performing well. Thermal drying scores a low percentage of 25% due to the relatively high equipment and control requirements, high operating temperature, and the high level of operator experience required. Incineration and pyrolysis score the lowest reliability and robustness percentage at 13% due to the relatively high requirements for equipment control, high operating temperature, and high level of operator experience required.

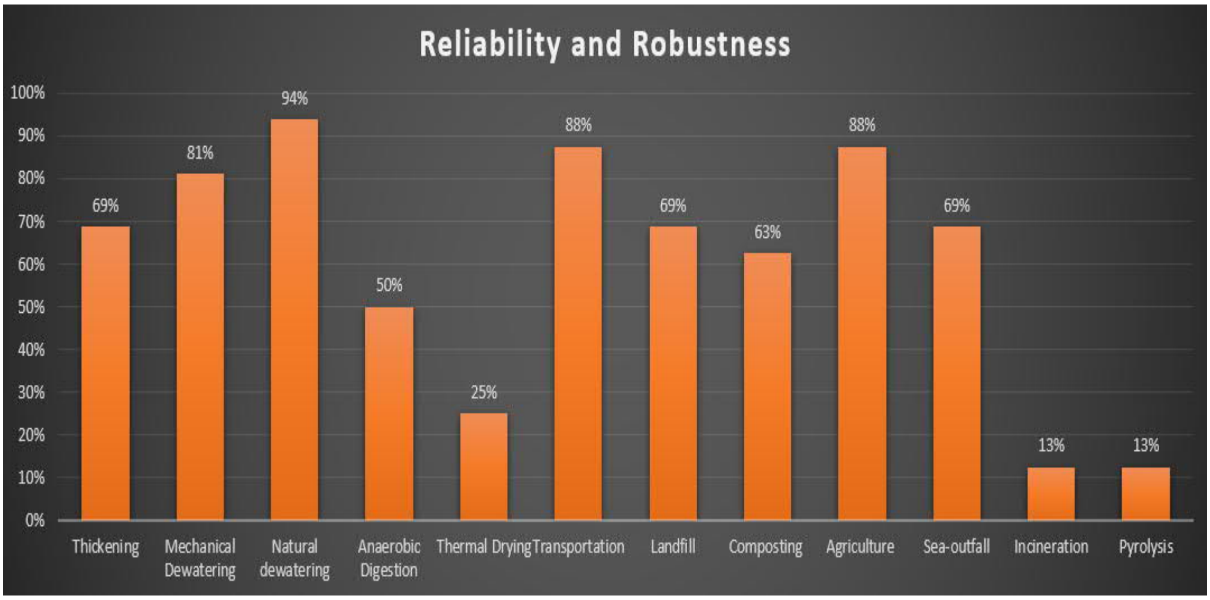


Figure 4-13 Reliability and Robustness of Sludge Treatment and Disposal Methods

Table 4-9 Reliability and Robustness Assessment Scoring

Technology	Operating hours	Equipment and control intensity	Operating temperature	required level of operators' experience	Average Score	Reliability and Robustness %
Thickening	-2	+1	+2	+1	+0.5	63%
Mechanical Dewatering	+1	+1	+2	+1	+1.3	81%
Natural Dewatering	+1	+2	+2	+2	+1.8	94%
Anaerobic Digestion	-2	0	+1	+1	0.0	50%
Thermal Drying	-1	-1	-1	-1	-1.0	25%
Transportation	0	+2	+2	+2	+1.5	88%
Landfill	-2	+1	+2	+2	+0.8	69%
Composting	0	0	+1	+1	+0.5	63%
Agriculture	0	+2	+2	+2	+1.5	88%
Sea-outfall	-2	0	+2	+2	+0.5	63%
Incineration	-1	-1	-1	-2	-1.3	19%
Pyrolysis	-1	-1	-1	-2	-1.3	19%

4.10 Performance sensitivity to feed sludge characteristics deterioration and quantity overload

The scoring of the sludge treatment and disposal methods performance sensitivity to feed sludge characteristics deterioration and quantity overload is presented in Table 4-10. The performance sensitivity results are also illustrated in Figure 4-14.

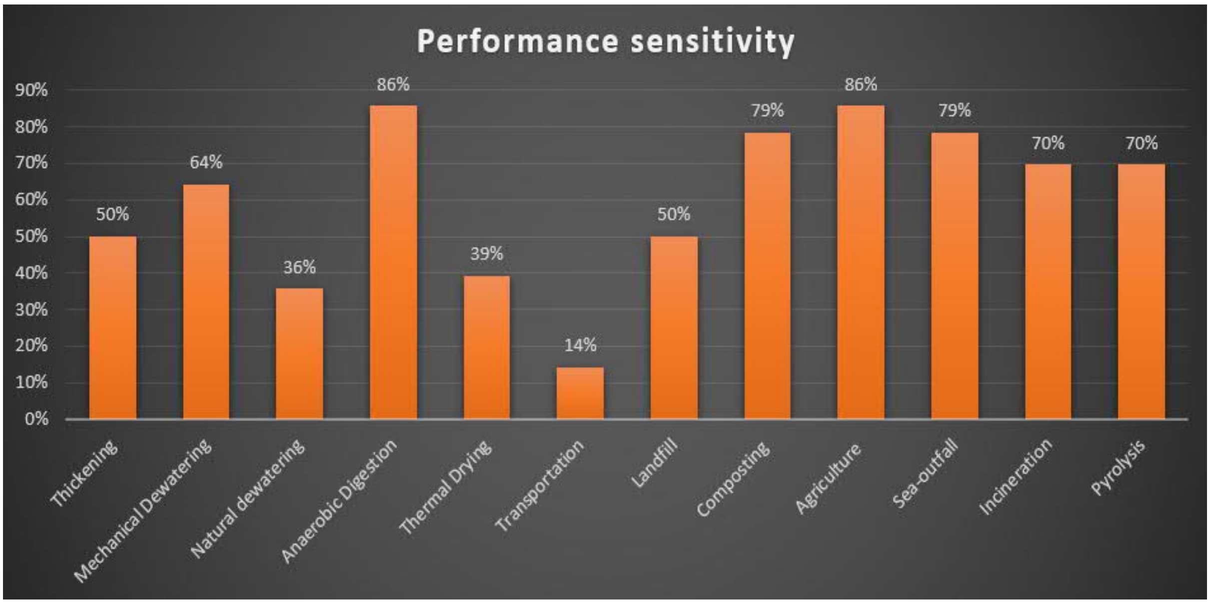


Figure 4-14 Scoring of the performance sensitivity to feed sludge characteristics deterioration and quantity overload

4.10.1 Thickening;

The results reveal that thickening is 50% sensitive to changes in feed sludge characteristics deterioration and quantity overload. Since thickeners are physical and chemical treatment units, performance is typically affected by changes in dry solids concentration, solid loading, moisture content, temperature, pH, oil & grease, hydraulic load and solids load. As reported in the literature and from experience, the deterioration of these parameters may significantly affect the performance of the process; for these reasons all of these above parameters scored -2 (significantly high impact on performance). It should also be noted that pH indirectly affects the thickener's performance if chemical conditioning is utilised. As the pH affects the solids' surface charge, which influences the selection of the polymer type. The effect of oil and grease is more adverse in gravity and mechanical thickening than flotation thickening. In thickening, especially gravity thickening, the effect of these changes can be mitigated to a certain degree. However, the degree of changes in performance will depend on the degree of changes in the feed sludge and thickener design. From literature and experience, a well-designed thickening process typically can tolerate moderate deterioration in feed sludge characteristics and quantity, which is well represented by the results.

4.10.2 Mechanical dewatering;

The main parameters that affect the performance of the mechanical dewatering process are dry solids concentration, moisture content, temperature, pH, oil & grease, hydraulic load and solids load. As stated in literature and from experience, the deterioration of these parameters may significantly affect the performance of the process; for these reasons a score of -2 (significantly high impact on performance) was given. Same as in thickening, change in pH affects the solids' surface charge, which influences the selection of the polymer type. However, in mechanical dewatering, chemical conditioning is essential. Typically, a well-designed dewatering unit can tolerate a small to moderate deterioration in feed sludge characteristics and quantity, which is well represented by the 64% performance sensitivity.

4.10.3 Natural Dewatering;

The main parameters that affect the performance of the Natural dewatering process are dry solids concentration, moisture content, oil & grease, hydraulic load and solids load. As reported in literature and from experience, the deterioration in these parameters may significantly affect the performance of the process; for these reasons a score of -2 (significantly high impact on performance) was given. Natural dewatering is typically restricted to well-digested or stabilised sludge because raw sludge is odorous, attracts insects, and does not dry/evaporate satisfactorily. Although the natural dewatering overall performance sensitivity score is 36%, Natural-drying performance deterioration due to the change in feed sludge characteristics has no easy or practical way to mitigate the change.

4.10.4 Anaerobic digestion;

Since the anaerobic microorganisms are susceptible to the characteristics deterioration and quantity overload of the feed sludge, the anaerobic digester performance can quickly deteriorate. Anaerobic digestion is one of the processes with the highest number of parameters influencing its performance compared to other processes being evaluated under this thesis. The feed sludge parameters that affect the performance of the anaerobic digesters are dry solid concentration, volatile solids concentration, moisture content, biological inhibiting substances, heavy metals, pH, temperature, Ash content, oil & grease, nutrients concentration, hydraulic load and solid load. As reported in the literature and from experience, the deterioration of these parameters may significantly affect the performance of the process; for these reasons a score of -2 (significantly high impact on performance) was given. The anaerobic digestion has scored the highest performance sensitivity of 86%, supporting the high operation vulnerability reported in the literature. However, a well monitored and operated anaerobic digester can perform satisfactorily.

4.10.5 Thermal drying;

The principal parameters that influence the performance of thermal drying is temperature, moisture content, dry solids concentration, hydraulic load and solids load. In reality, moisture content and dry solids concentration are inversely proportional to each other. As reported in literature and from experience, the deterioration of these parameters may significantly affect the performance of the process; for these reasons a score of -2 (significantly high impact on performance) was given . Heavy metals have an indirect effect on the drying process. As heavy metals concentration increases, the quality of dried sludge and the exhaust gas deteriorate, leading to an inferior quality of the dried solids for reuse as a fertiliser and a low performance of the exhaust gas treatment system. For this reason, heavy metals scored 0 (moderate impact on performance). Volatile solids and ash content do not directly influence the thermal drying process performance; however, their concentration significantly influences the dried sludge quality and reuse potential either as a fertiliser or fuel. Since the evaluation is for the parameters that directly affect the process performance, volatile solids and ash content scored +2 (no impact on performance). Thermal drying has scored a performance sensitivity of 39%, supporting the moderate performance sensitivity reported in the literature.

4.10.6 Transportation;

Transportation is split into two modes (1) tankers and (2) pumping. For tankers, a change in moisture content and dry solids concentration will significantly impact the number of truckloads. For pumping, the rheological characteristics of the sludge will change with the change of moisture content and dry solids concentration, influencing the pumping selection, efficiency, capital cost and operation cost. For both modes of transportation, the change in moisture content and dry solids concentration will significantly influence the performance of the transportation mode. For these reasons, both parameters scored -2 (significantly high impact on performance). Transportation scored a performance sensitivity of 14%.

4.10.7 Landfill;

Since the landfill sites are not operated by eThekwini municipality, the evaluation covered the parameters that influence the applicability of sludge disposal to landfill sites as an approach to measure the disposal method's performance. The principal parameters are; volatile solid concentration, moisture content, dry solids content, heavy metals concentration, oil & grease and pH. As reported in the literature, legislation and from experience, the deterioration of these parameters may significantly affect the acceptance of landfill sites to the sludge; for these reasons, a score of -2 (significantly high impact on performance) was given. The hazardous rating of the sludge impacts the selection of the landfill site. The sludge quantity is also important when the landfill is utilised as a final disposal method since it significantly influences the transportation cost and landfill fees. The landfill scored a performance sensitivity of 50%.

4.10.8 Composting;

Composting is one of the processes with the highest number of parameters influencing its performance compared to other processes being evaluated under this thesis. The feed sludge parameters that affect the performance of the composting process are dry solid concentration, volatile solids concentration, moisture content, biological inhibiting substances, heavy metals, pH, temperature, Ash content, oil & grease, nutrients concentration, hydraulic load and solid load. As reported in the literature and from experience, the deterioration of these parameters may have a high to a significantly high impact on the process performance; for these reasons a score of -1 (high impact on performance) & -2 (significantly high impact on performance) were given as presented in Table 4-10. The deterioration of the sludge quality will deteriorate the quality of the compost as an end product. It also can lead to the sludge and the compost been classified as unfit for agriculture purposes. Composting scored an overall performance sensitivity of 79%, supporting the high-performance sensitivity reported in the literature as a biological process. It is also an indication of

4.10.9 Agriculture;

is one of the final disposal methods with the highest number of parameters influencing its utilisation. The sludge parameters that affect the utilisation of agriculture as a final disposal method are dry solid concentration, volatile solids concentration, moisture content, biological inhibiting substances, heavy metals, pH, temperature, Ash content, oil & grease, nutrients concentration, hydraulic load and solid load. Hydraulic load and solids load are a representation of the application rate. As reported in the literature, the deterioration of these parameters may have a high to a significantly high impact on the utilisation of sludge in agriculture as a final disposal method. For these reasons, a score of -1 (high impact on performance) & -2 (significantly high impact on performance) were given as presented in Table 4-10. Agriculture scored an overall performance sensitivity of 86%, supporting that utilisation of agriculture as a final disposal method depends on the sludge characteristics and application rate.

4.10.10 Incineration and Pyrolysis;

The principal parameters that influence incineration and pyrolysis performance are; volatile solids concentration, Ash content, dry solids concentration, moisture content, calorific value, temperature, heavy metal concentration, oil & grease, hydraulic load and solids load. As reported in the literature and from experience, the deterioration of these parameters may have a high to a significantly high impact on the performance of both processes. For these reasons, a score of -1 (high impact on performance) & -2 (significantly high impact on performance) were given as presented in Table 4-10. Incineration and Pyrolysis scored an overall performance sensitivity of 70%, supporting the high-performance sensitivity reported in the literature for such processes, primarily that they operate at very high temperatures.

4.11 Capital cost (CAPEX)

The capital cost scoring of the sludge treatment and disposal methods researched under this thesis is presented in Table 4-11. Figure 4-15 illustrates the capital cost scoring scale on a percentage basis.

4.11.1 Thickening;

Thickening scored 13%, which is one of the lowest percentages. Such a low percentage indicates that thinking is one of the least expensive sludge treatment and disposal processes. The thickening process is the most commonly employed sludge treatment process, with a small footprint, simple to construct, low equipment cost and relatively low construction cost of structures or buildings. The construction cost will differ between the thickening processes (gravity thickening, flotation thickening and mechanical thickening). Gravity thickening and flotation thickening are the most employed by eThekwini municipality.

4.11.2 Mechanical dewatering;

Mechanical dewatering scored 13%. Such a low percentage indicates that mechanical dewatering is also one of the least expensive sludge treatment and disposal processes studied under this thesis. Dewatering is one of the most commonly employed sludge treatment processes. The high average score and low percentage are a result of a small footprint, simple construction, relatively low equipment cost and low construction cost of structures or buildings. The equipment cost will differ between the mechanical dewatering processes (belt filter press, filter press, centrifuge, Etc.). However, footprint and construction cost may relatively be the same. Belt filter press, centrifuges, and screw press are the most employed by eThekwini municipality.

	Dry Solids concentration	**Volatile solids concentration**	**Moisture content**	**Biological Inhibiting substance**	**Heavy metals**	**pH**	**Temp.**	**Ash Content**	**Oil & Grease**	**Calorific Value**	**Nutrients concentration**	**Pathogens concentration**	**Hydraulic load**	**Solids Load**	**Average Score**	**Performance Sensitivity %**
Thickening	-2	+2	-2	+2	+2	-2	-2	+2	-2	+2	+2	+2	-2	-2	0.00	50%
Mechanical Dewatering	-2	-2	-2	+2	+2	-2	-2	-2	-2	+2	+2	+2	-2	-2	-0.57	64%
Natural Dewatering	-2	+2	-2	+2	+2	+2	+2	+2	-2	+2	+2	+2	-2	-2	+0.57	36%
Anaerobic Digestion	-2	-2	-2	-2	-2	-2	-2	-2	-2	+2	-2	+2	-2	-2	-1.43	86%
Thermal Drying	-2	+2	-2	+2	0	+2	-2	+2	+2	+2	+2	+2	-2	-2	+0.43	39%
Transportation	-2	+2	-2	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2	+2	+1.43	14%
Landfill	-2	-2	-2	+2	-2	-2	+2	-2	-2	+2	+2	+2	+2	+2	0.00	50%
Composting	-1	-2	-1	-2	-2	-2	-2	-1	-2	+2	-1	+2	-2	-2	-1.14	79%
Agriculture	-2	-2	-2	-2	-2	-2	+2	-2	-2	+2	-2	-2	-2	-2	-1.43	86%
Sea-outfall	+2	-2	+2	-2	-2	-2	-2	-2	-2	+2	-2	-2	-2	-2	-1.14	79%
Incineration	-2	-2	-2	+2	-1	+2	-2	-2	-2	-2	+2	+2	-2	-2	-0.79	70%
Pyrolysis	-2	-2	-2	+2	-1	+2	-2	-2	-2	-2	+2	+2	-2	-2	-0.79	70%

Table 4-10 Scoring of The Performance Sensitivity of Sludge Treatment and Disposal Methods to Feed Sludge Characteristics Deterioration and Quantity Overload

4.11.3 Natural dewatering;

Natural dewatering scored 19%. However, the natural dewatering process is more commonly used compared to mechanical dewatering, but it can be more expensive only because of its footprint and land cost. The score reflects a relatively large footprint, simple construction, low equipment cost and low construction cost of structures or buildings. Since natural dewatering requires a relatively large footprint, it is commonly employed when land is available at a low cost. Land availability and cost can be determinant factors to eliminate this dewatering alternative. Drying beds and sludge lagoons are used by eThekwini municipality; however, drying beds are more utilised.

4.11.4 Anaerobic digestion;

Anaerobic digestion scored 50%, reflecting a moderate capital cost due to a moderate footprint, moderate construction complexity, moderate equipment cost, and moderate construction cost of structures or buildings. Anaerobic digestion is the only stabilisation method used by the eThekwini municipality.

4.11.5 Thermal drying;

Thermal drying scored 63%, reflecting a relatively high capital cost due to a relatively small footprint, relatively high construction complexity, relatively high equipment cost, and relatively high construction cost of structures or buildings.

4.11.6 Transportation;

there is no capital cost associated with transportation as it is typically outsourced service.

4.11.7 Landfill;

Landfill scored 56%, reflecting a moderate to relatively high capital cost due to large footprint, moderate construction complexity, moderate equipment cost, and relatively low construction cost of structures or buildings. The availability and cost of land are significant determinants that may lead to a high capital cost. It should be noted that eThekwini municipality does not own a hazardous landfill site and may not be interested in constructing one since landfill disposal defies the reuse potential of sludge.

4.11.8 Composting;

Composting scored 19%, reflecting a relatively low to low capital cost due to a moderate footprint, relatively low construction complexity, low equipment cost, and low construction cost of structures or buildings. The availability and cost of land are significant determinants that may lead to a high capital cost.

4.11.9 Agriculture;

There is no capital cost associated with the use of sludge in agriculture since the sludge is sold dewatered or dried to farmers. Unless eThekwini municipality decides to utilise the sludge in other land applications such as forest enhancement or land reclamation, the cost will be limited to operational cost.

4.11.10 Sea-outfall;

Sea-outfall scored 56%, reflecting a moderate capital cost due to a moderate footprint, relatively high construction complexity, moderate equipment cost, and relatively high construction cost of structures or buildings.

4.11.11 Incineration;

Incineration scored 81%, reflecting a high capital cost due to a relatively small footprint, high construction complexity, high equipment cost, and high construction cost of structures or buildings.

4.11.12 Pyrolysis;

Pyrolysis scored 81%, reflecting a high capital cost due to a relatively small footprint, high construction complexity, high equipment cost, and high construction cost of structures or buildings.

Table 4-11 Capital Cost Assessment Scoring

	Footprint	**Construction complexity**	**Equipment Cost**	**Structures and/or buildings Cost**	**Average Score**	**CAPEX %**
Thickening	+1	+2	+2	+1	+1.5	13%
Mechanical Dewatering	+1	+2	+1	+2	+1.5	13%
Natural Dewatering	-1	+2	+2	+2	+1.3	19%
Anaerobic Digestion	0	0	0	0	0.0	50%
Thermal Drying	+1	-1	-1	-1	-0.5	63%
Transportation	+2	+2	+2	+2	+2.0	0%
Landfill	-2	0	0	+1	-0.3	56%
Composting	0	+1	+2	+2	+1.3	19%
Agriculture	+2	+2	+2	+2	+2.0	0%
Sea-outfall	0	-1	0	0	-0.3	56%
Incineration	+1	-2	-2	-2	-1.3	81%
Pyrolysis	+1	-2	-2	-2	-1.3	81%

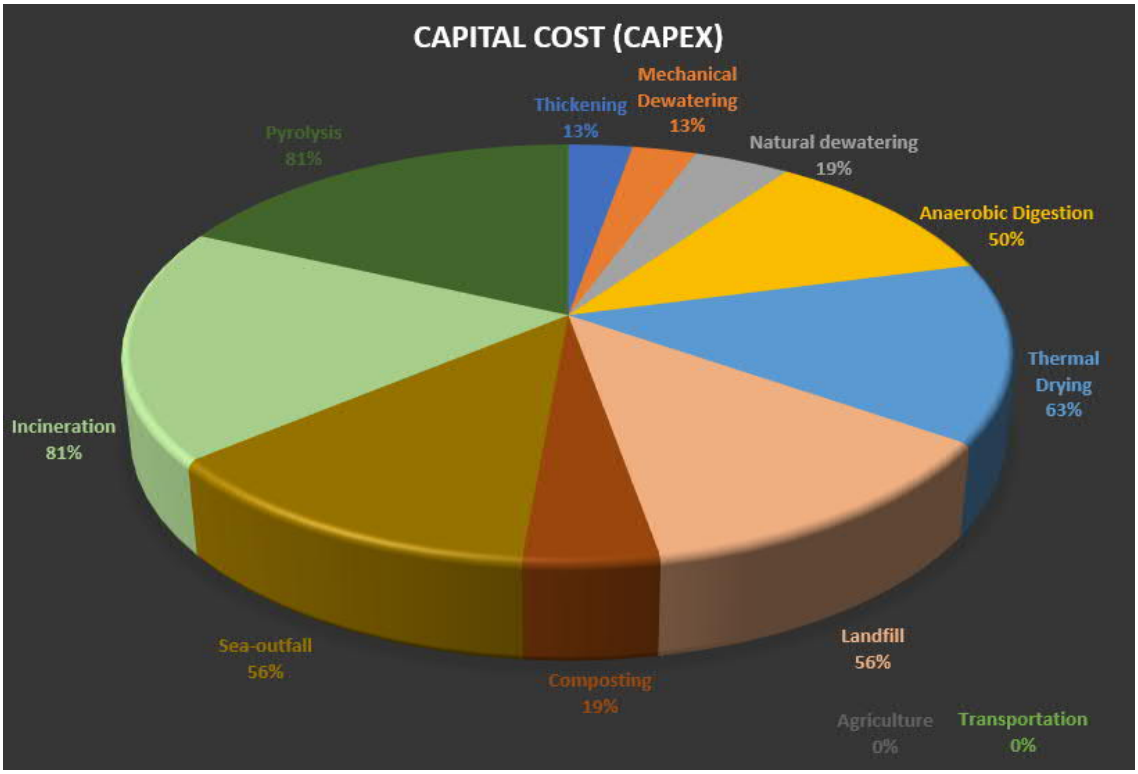


Figure 4-15 Capital Cost Scoring Percentage

4.12 Operating cost (OPEX)

The operational cost scoring of the sludge treatment and disposal methods studied under this thesis is presented in Table 4-12. Figure 4-16 illustrates the operational cost scoring scale on a percentage basis.

4.12.1 Thickening;

Thickening scored 8%, reflecting a low operating cost due to the low personal requirements for operation, relatively low chemical consumption (flocculants and/or coagulants are typicaly used with DAF and mechanical thickening, however, it can be used with gravity thickening. Chlorine is also occasionally used with gravity thickening to prevent septicity), no auxiliary fuel, relatively low electricity consumption, low maintenance and no other miscellaneous cost.

4.12.2 Mechanical dewatering;

Mechanical dewatering scored 25%, reflecting a relatively low operating cost due to the low personal requirements for operation, relatively high chemical consumption, no auxiliary fuel, moderate electricity consumption, relatively low maintenance and no other miscellaneous cost.

4.12.3 Natural dewatering;

Natural dewatering scored 13%, reflecting a low operating cost due to the moderate personal requirements for operation, low to no chemical consumption, no auxiliary fuel, no electricity consumption, low maintenance and relatively low miscellaneous cost.

4.12.4 Anaerobic digestion;

Anaerobic digestion scored 21%, reflecting a relatively low operating cost due to the relatively low personal requirements for operation, low to no chemical consumption, no auxiliary fuel, moderate electricity consumption (mainly for recycling and mixing), moderate maintenance and low miscellaneous cost.

4.12.5 Thermal drying;

Thermal drying scored 67%, reflecting a relatively high operating cost due to the relatively high personal requirements for operation (not only in number but also in qualification, which requires a higher pay), low to no chemical consumption, high auxiliary fuel requirements, high electricity consumption, high maintenance and high miscellaneous cost.

4.12.6 Transportation;

since sludge transport is typically outsourced to a transportation contractor, the only encountered operation cost is the cost paid to the contractor. In addition, transportation forms an integral part of sludge treatment and disposal management. The transportation cost depends on the sludge volume, dry solids concentration and distance to be transported. For example, transporting 1000 m^3 thickened sludge (4 to 6% DS) for 100 Km (approximately three hours round trip) requires 50 trips of 20 m^3 vacuum truck, with an hourly rate of R750/h; the total cost is R112 500. The transportation cost would be more if thickening was not utilised. On the other hand, if the same volume of sludge is dewatered before transportation to achieve 35% dry solids. The total volume to be transported will be 170 m^3. With a 20 tonne (approximately 20 m^3) closed truck, a total of 9 trips are required, at a rate of R450/h; the total cost for the same distance will be R12 150. The above approximation illustrates the power of thickening and dewatering of sludge in reducing transportation cost and reducing the size and cost of any process units that may be utilised after them. In conclusion, operation costs for transportation should not be assessed in isolation from the complete sludge treatment and disposal management scheme. Considering that the current primary disposal methods are sea-outfall (71.35% by volume) and the landfill (18.24% by volume), the travel distance between the WWTW’s and the final disposal sites, the non-dewatered quantity of the produced sludge (65%), transportation cost is expected to be significant. For these reasons and considering the current situation at the eThekwini municipality, transportation is given a relatively high score of 50%.

4.12.7 Landfill;

Landfill scored 25%, reflecting a relatively low operating cost due to the relatively low personal requirements for operation, low/to no chemical consumption, no auxiliary fuel requirements, low electricity consumption, moderate maintenance and relatively low miscellaneous cost. The score represents the landfill operation cost, but it does not include transportation from WWTW's. Since the eThekwini municipality does not own or operate hazardous landfill sits, in addition to the sludge quantities and transportation distance to the current available hazardous landfill site (Shongweni landfill site), transportation cost is expected to be significant.

4.12.8 Composting;

Composting scored 17%, reflecting a relatively low operating cost due to the moderate personal requirements for operation, low/to no chemical consumption, no auxiliary fuel requirements, low electricity consumption, relatively low maintenance and relatively low miscellaneous cost. The transportation cost of sludge to composting sites is a major determinant factor for this utilisation route since the composting companies will pay for the transportation, influencing the final product price.

4.12.9 Agriculture;

Agriculture scored 13%, reflecting a relatively low operating cost due to the moderate personal requirements for operation, low/to no chemical consumption, no auxiliary fuel requirements, no electricity consumption, low maintenance and relatively low miscellaneous cost. Similarly, to composting, the transportation cost of sludge to the farms is a major determinant factor for this utilisation route since the farmers will pay for the transportation. This utilisation route may also require additional monitoring by the municipality to prevent any adverse effects on the environment.

4.12.10 Sea-outfall;

Sea-outfall scored 46%, reflecting a moderate operating cost due to the moderate personal requirements for operation, low chemical consumption, no auxiliary fuel requirements, moderate electricity consumption, moderate maintenance and high miscellaneous cost. The high miscellaneous cost reflects the high transportation cost paid by the municipality since the out-falls are owned and operated by the municipality.

4.12.11 Incineration;

Incineration scored 67%, reflecting a relatively high operating cost due to the relatively high personal requirements for operation (not only in number but also in qualification, which requires a higher pay), low/to no chemical consumption, high auxiliary fuel requirements, high electricity consumption, high maintenance and high miscellaneous cost.

4.12.12 Pyrolysis;

Pyrolysis scored 67%, reflecting a relatively high operating cost due to the relatively high personal requirements for operation (not only in number but also in qualification, which requires a higher pay), low/to no chemical consumption, high auxiliary fuel requirements, high electricity consumption, high maintenance and high miscellaneous cost.

4.13 Overall results

Table 4-13 presents a summary of the scoring results. In addition, the results are illustrated in Figure 4-17.

4.13.1 Thermal drying and composting;

Thermal drying and composting scored 52.4%. Part of achieving this score is because their performance was assessed based on literature, not actual performance, as they are not currently in use processes by eThekwini municipality. However, these processes are best suited for sludge reuse in agriculture (composting & thermal drying) or as a fuel source (thermal drying) since the final product is safe, stable, easy to package and transport. The collected data supports this selection since the sludge pollutants content is acceptable and mainly requires stabilisation and pathogen reduction, which can be achieved using these processes. However, the reasons for shutting down the Kwamashu incineration and drying plant must be further investigated. Thickening and dewatering are typically required prior to thermal drying and compositing. Transportation to the composting site(s) may also be required.

Table 4-12 Operating Cost Assessment Scoring

	Personal	Chemicals	Auxiliary Fuel	Electricity	Maintenance	Miscellaneous	Average Score	OPEX %
Thickening	+2	+1	+2	+1	+2	+2	+1.7	8%
Mechanical Dewatering	+2	-1	+2	0	+1	+2	+1.0	25%
Natural dewatering	0	+2	+2	+2	+2	+1	+1.5	13%
Anaerobic Digestion	+1	+2	+2	0	0	+2	+1.2	21%
Thermal Drying	-2	+2	-1	-1	-1	-1	-0.7	67%
Transportation							-1.0	75%
Landfill	+1	+2	+2	+2	0	-1	+1.0	25%
Composting	0	+2	+2	+2	+1	+1	+1.3	17%
Agriculture	0	+2	+2	+2	+2	+1	+1.5	13%
Sea-outfall	0	+1	+2	0	0	-2	+0.2	46%
Incineration	-2	+2	-1	-1	-1	-1	-0.7	67%
Pyrolysis	-2	+2	-1	-1	-1	-1	-0.7	67%

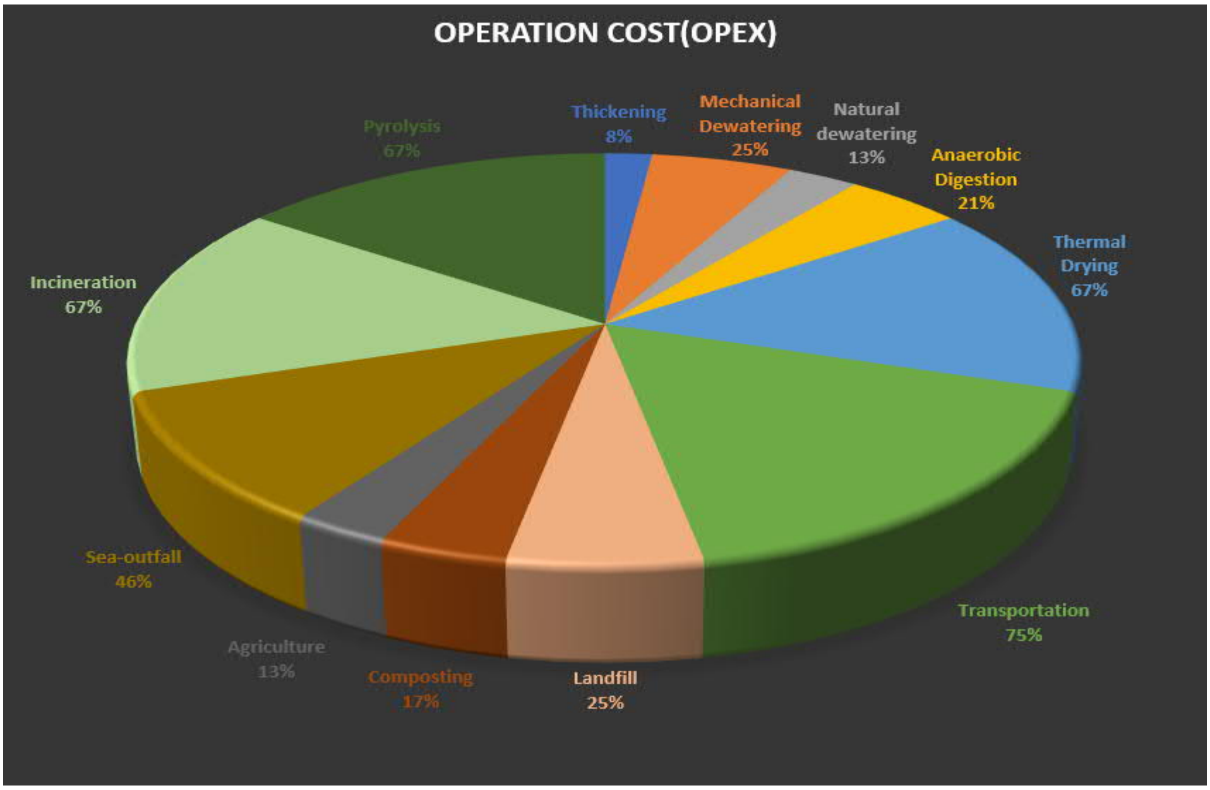


Figure 4-16 Operating Cost Scoring Percentage

4.13.2 Anaerobic digestion;

Anaerobic digestion scored 51.8%, six of the existing anaerobic digesters are performing satisfactorily, one is out of service (Southern WWTW), and two have operational issues as explained above. Overall anaerobic digestion is best suited for energy recovery through the biogas; in addition, digested sludge is stabilised, easy to dewater and can be used as a fertiliser. Thickening is typically required prior to anaerobic digestion.

4.13.3 Incineration and pyrolysis;

Incineration and pyrolysis scored 51.4% and 49.3%, respectively. Incineration and pyrolysis achieved different scores for reuse potential, which influenced the final percentage. Part of achieving this score is because their performance was assessed based on literature, not actual performance, as they are not currently in use processes by eThekwini municipality. However, these processes are best suited for energy recovery and by-products reuse. In addition, the incineration ash can be disposed of if the reuse market is unavailable. The collected data and calculations presented in the appendices support this selection. The reasons for shutting down the Kwamashu incineration and drying plant must be further investigated. Thickening/dewatering or thickening/dewatering/thermal drying is typically required prior to Incineration and pyrolysis.

4.13.4 Agriculture;

Agriculture scored 48.6%, which is a relatively high percentage compared to other treatment and disposal methods. Operation simplicity, being a final disposal method, reliability and robustness, CAPEX and OPEX are the main criteria that affected the final overall scoring for agriculture. Thickening, dewatering, thermal drying or combination may be utilised to enhance sludge quality and reduce transportation costs.

4.13.5 Mechanical and natural dewatering;

Mechanical and natural dewatering scored 40.2% and 42.7%, respectively. Environmental impact, reliability & robustness, performance sensitivity, CAPEX and OPEX were the determinant factors for each process's score. The dewatering step is typically an integral part of most sludge treatment. It can be the final processing after which the sludge can be utilised or disposed. However, the cost of transport to utilisation or disposal site is a determinant factor. Both processes are in use by eThekwini municipality, and their performance is evaluated accordingly. Thickening is typically required prior to dewatering.

4.13.6 Transportation

Transportation scored 40.6%. Transportation has a significant impact on reuse and disposal costs and directly depends on sludge moisture content. The relatively high score achieved for environmental impact, operation simplicity, reliability & robustness, performance sensitivity and CAPEX resulted in a final percentage comparable to that achieved by treatment and disposal methods. Transportation is an essential part of any sludge management plan. OPEX is a vital issue since farmers do not pay for sludge transportation, and eThekwini municipality covers the cost. It also covers sludge transportation costs to the landfill site and sea-outfall sites.

4.13.7 Thickening

Thickening scored 39.9%; thickening is an essential step in any sludge management plan. Gravity or mechanical thinking is typically the first step in the sludge treatment process. The gravity and flotation thickeners at most wastewater treatment works owned and operated by eThekwini municipality are not performing. The relatively high score achieved for environmental impact, operation simplicity, reliability & robustness, CAPEX and OPEX, resulted in a final percentage comparable to that achieved by other treatment and disposal methods.

4.13.8 Landfill and sea-outfall

Landfill and sea-outfall scored 39.2% and 35.4%, respectively. Both are final (ultimate) disposal methods and scored the same or almost the same under most of the criteria evaluated. Since the hazardous landfill sites are not owned either operated by eThekwini municipality, no beneficial utilisation (ex. Landfill Biogas production process) of the sludge is possible after disposal. Sea-outfall as a final disposal method does not offer any beneficial utilisation of the sludge. In reality, the associated cost with landfill disposal is transportation and landfill site fees. The challenge with this method is the availability of hazardous landfill sites, transportation costs and wasting of a valuable resource such as sludge. The sea-out fall almost faces the same challenges; available outfalls are reaching their maximum capacity, transportation cost, and wasting a valuable resource such as sludge. Dewatering is typically required prior to landfill; however, it's not required prior to sea disposal.

After obtaining the final scoring of each individual treatment process and disposal method, eight scenarios for treatment, beneficial utilisation and disposal were examined, as illustrated in Table 4-14. The average scoring for all scenarios were calculated with mechanical and natural dewatering.

The results are arranged in descending order, from the highest score (Green) to the lowest score (Red).

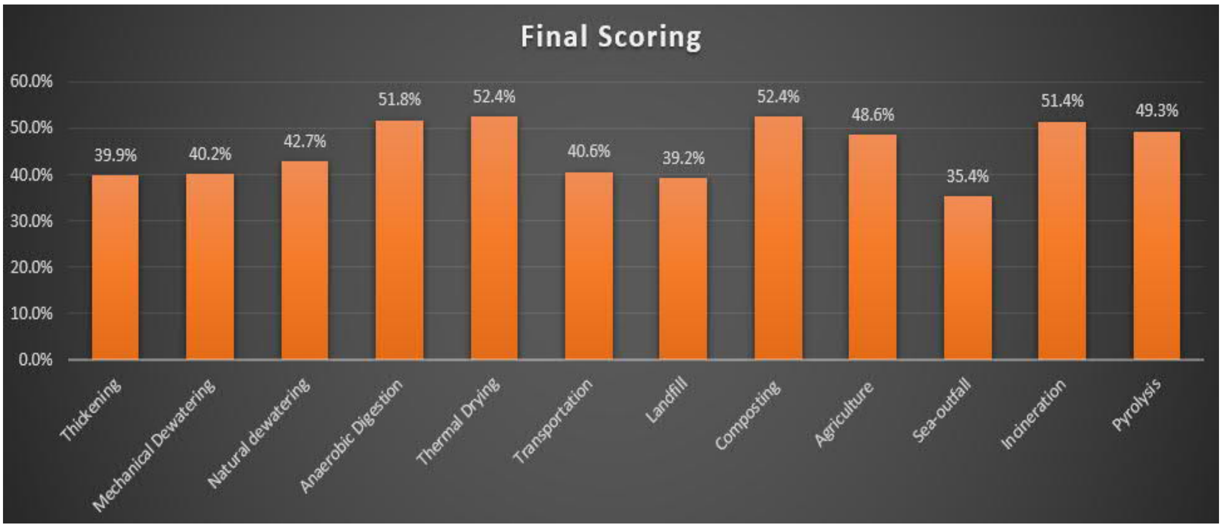


Figure 4-17 Final Scorings for Sludge Treatment Processes and Disposal Methods

Thickening and/or dewatering are common treatment steps in all scenarios. Considering the sludge characteristics (Stabilisation and microbiological class) produced from all the wastewater treatment works studied under this thesis, scenarios for beneficial use without drying, stabilisation or pathogen reduction were not considered.

The top four scenarios are for beneficial use as a fertiliser and/or soil conditioner either through composting as in scenario one or direct agriculture use as in scenarios two and three. Scenarios one and four also represent energy recovery through the production of Biogas in the anaerobic digestion step. Scenarios five and six represent energy recovery either through heat as in incineration and pyrolysis or beneficial use of by-products as a fuel source as in pyrolysis. The landfill step for scenarios four and five is for the disposal of the ashes.

Scenario seven covers sludge preparation through thickening, dewatering and thermal drying for other beneficial use such as fuel source.

Scenario eight is for direct disposal to landfill after thickening and dewatering; the dewatering step is crucial to achieving the level of dryness required for landfill. Scenario nine is also for direct disposal but to the marine environment through the available outfalls.

The results have revealed that the semi-qualitative method used in this thesis is limited in ranking the importance and interaction of the feasibility factors. For example, the same score for transportation had to be used in all scenarios regardless of the transported sludge dryness level. The same for the landfill step in scenarios four and five should have less score than the landfill step in scenario eight since the quantity of ashes is much less than the quantity of dewatered sludge to be disposed of. The same agriculture score had to be considered regardless if the sludge is thermally dries, composted or dewatered. All scenarios scored more with natural dewatering than mechanical dewatering; however, with the importance of the feasibility factors not being considered, a factor such as land requirements, availability and cost can result in mechanical dewatering being the preferred option.

Table 4-13 Scoring summary of sludge treatment and disposal methods

Technology	**Performance**				**Environmental Impact**	**Operation simplicity**	**Reuse potential**	**Amount of sludge or by-products after each process**	**Reliability and robustness**	**Performance Sensitivity to feed sludge quality deterioration and quantity overload**	**CAPEX**	**OPEX**	**Average Score**	**%**
	Sludge volume/weight reduction	**Pollutant reduction or removal**	**Pathogens reduction or elimination**	**Stabilisation**										
Thickening	-2.0	-2.0	-2.0	-2.0	+1.2	+2.0	-2.0	-2.0	+0.8	0.0	+1.5	+1.7	-0.41	**40%**
Mechanical dewatering	-1.0	-2.0	-2.0	-2.0	+1.1	+2.0	-2.0	-2.0	+1.3	-0.6	+1.5	+1.0	-0.39	**40%**
Natural dewatering	-1.0	-2.0	-2.0	-2.0	+0.4	+2.0	-2.0	-2.0	+1.8	+0.6	+1.3	+1.5	-0.29	**43%**
Anaerobic Digestion	+1.0	-2.0	0.0	+1.0	+1.1	+1.0	+1.0	-2.0	0.0	-1.4	0.0	+1.2	+0.07	**52%**
Thermal Drying	+2.0	-2.0	+2.0	+2.0	+0.9	-2.0	+1.0	-1.0	-1.0	+0.4	-0.5	-0.7	+0.10	**52%**
Transportation	-2.0	-2.0	-2.0	-2.0	+1.6	+2.0	-2.0	-2.0	+1.5	+1.4	+2.0	-1.0	-0.38	**41%**
Landfill	-2.0	-2.0	-2.0	-2.0	-0.7	+2.0	-2.0	+2.0	+0.8	0.0	-0.3	+1.0	-0.43	**39%**
Composting	0.0	-2.0	0.0	0.0	+0.2	+2.0	0.0	-1.0	+0.5	-1.1	+1.3	+1.3	+0.10	**52%**
Agriculture	-2.0	-2.0	-2.0	-2.0	-0.2	+2.0	0.0	+2.0	+1.5	-1.4	+2.0	+1.5	-0.05	**49%**
Sea-outfall	-2.0	-2.0	-2.0	-2.0	-0.6	+2.0	-2.0	+2.0	+0.8	-1.1	-0.3	+0.2	-0.59	**35%**
Incineration	+2.0	-2.0	+2.0	+2.0	+0.9	-2.0	+1.0	+1.0	-1.5	-0.8	-1.3	-0.7	+0.06	**51%**
Pyrolysis	+2.0	-2.0	+2.0	+2.0	+0.9	-2.0	0.0	+1.0	-1.5	-0.8	-1.3	-0.7	-0.03	**49%**

Table 4-14 Sludge Treatment, Utilisation and Disposal Scenarios

Sludge Management Scenarios	Treatment, Beneficial Reuse and Disposal						Average Score			
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	1*		2*	
Scenario 1	Thickening	Anaerobic digestion	Dewatering	Composting	Transportation	Agriculture	-0.18	45.6%	-0.16	46.0%
Scenario 2	Thickening	Dewatering	Composting	Transportation	Agriculture		-0.23	44.3%	-0.21	44.9%
Scenario 3	Thickening	Dewatering	Thermal Drying	Transportation	Agriculture		-0.23	44.3%	-0.21	44.8%
Scenario 4	Thickening	Anaerobic digestion	Dewatering	Transportation	Agriculture		-0.23	44.2%	-0.21	44.7%
Scenario 5	Thickening	Dewatering	Thermal Drying	Incineration	Transportation	Landfill	-0.24	44.0%	-0.22	44.4%
Scenario 6	Thickening	Dewatering	Thermal Drying	Pyrolysis	Transportation	Landfill	-0.26	43.6%	-0.24	44.0%
Scenario 7	Thickening	Dewatering	Thermal Drying	Transportation	* *		-0.27	43.3%	-0.24	43.9%
Scenario 8	Thickening	Dewatering	Transportation	Landfill			-0.40	40.0%	-0.38	40.6%
Scenario 9	Thickening	Transportation	Sea-Outfall				-0.46	38.6%	-0.46	38.6%

*1: Mechanical dewatering / 2: Natural dewatering

** Other penfecial use (i.e. Fuel Source)

5. Conclusion

This thesis identified the optimum alternatives for the sewage sludge treatment processes and disposal methods for eThekwini municipality through a semi-quantitative analysis of several feasibility factors.

An optimisation of sludge management includes the utilisation of several different sludge treatment processes or technologies. It is clear from this study that there is a wide range of treatment processes to select from, also the future of the development of these treatment processes. Some of these processes have been widely in use for a long time and have shown to be effective, including but not limited to thickening and dewatering. These processes typically do not have a lot of room for development, and efficiency mainly depends on design and operation.

On the other hand, other processes have already been implemented in practice, but there is still room for development, including but not limited to thermal drying, incineration and pyrolysis.

Sludge management must increasingly focus on beneficial use and developing markets for the treated sludge and its by-products to reduce net costs. Sludge management can also be integrated into other industrial operations or waste treatment processes, which can reduce net costs. However, direct sludge disposal to the marine environment or landfill is a waste of a valuable resource and will not reduce the overall management cost. This has been proved in this thesis where the sludge management scenarios with beneficial use scored the highest; however, the scenarios with direct disposal scored the lowest.

It is also evident that there is no such thing as a most sustainable system. Each case may necessitate a unique solution that is best suited to a particular location or a wastewater treatment work. Because of the many factors that influence the long-term viability of a sludge management system, it should be viewed as a dynamic activity, with the goal of always finding the most efficient and long-term solution at the concerned location and within the current and future boundary conditions.

The sludge management scenarios with the highest score, positions 1 to 4, promote agriculture as a final disposal method. However, the current sludge produced from twenty-two WWTW's do not meet the microbiological class "A", and sludge produced from twenty-one WWTW's do not meet the stabilisation class "1". The stability class and microbiological class can be optimised to meet the guidelines through the treatment steps selected. On the other hand, the pollutants level will have to be controlled at the source for the two identified WWTW's that produce sludge with pollutants class "c" (Glenwood WWTW & Umbilo WWTW) and the WWTW that produce sludge with pollutant class "b" (Mpumalanga WWTW).

Treatment scenarios that include thermal oxidation processes (incineration and pyrolysis) came in the 5th and 6th positions. However, the sludge management scenario through the thermal dryer for other beneficial uses than agriculture came in the 7th position; this scenario may score a higher position once the markets for beneficial use of dried sludge are evaluated. Market availability for beneficial use was not assessed under this thesis, and it will have a significant impact on the final selection of the optimum sludge management scenario.

Scenarios with direct disposal to landfill and marine environment (sea-outfall) scored the last two positions 8th and 9th respectively.

The semi-quantitative analysis performed (Likert-type five-point scale, Cartmell et al., 2006, Teoh et al., 2020) in this thesis has a limitation in ranking the importance of the feasibility factors and their interaction compared to methods such as the multi-criteria decision analysis. The challenges remain in comparing feasibility factors across the treatment processes and disposal methods without being biased. The differences in choices of the evaluation method, feasibility factors and other parameters influence the significance of the factors and their impact potentials, even for the same sludge treatment and disposal method. Future studies could propose alternative scenarios, feasibility factors, weighing procedures, etc, to remove such biases as much as possible, or include sensitivity analyses to investigate how the results may change if the parameters are assumed differently.

The developed scale is available for the municipality engineers as a useful tool to aid sludge treatment and disposal decision making, especially by engaging multiple stakeholders with different prospective.

6. Recommendations

Several points were identified that are relevant to the optimisation and selection of sludge management scenarios;

Record keeping: It is critical to determine the quantity and location of sludge for successful management. Sewage sludge quantities and quality reporting within eThekwini municipality need to improve; see section 3.1 . A standardised and simplified form to be developed for all wastewater treatment works. The form should include the daily quantity of the WAS produced in cubic meters and dry tonne. The sludge quantity and dry solids content after and before each treatment step. The amount of supernatant and filtrate produced and returned to the treatment work. The final sludge quantity disposed and the disposal method. The form must be submitted on a weekly basis to a centralised information centre, where it's logged into a centralised record by a professional. Ensure data is received and logged on a weekly basis.

Limit the number of authorised employees logging the weekly data received from the wastewater treatment works. Do not allow trainees or students to enter the data at the plant or in the centralised records.

Sludge quality: Perform frequent testing on the sludge to establish its microbiological parameters (faecal coliforms, helminth ova), physical and stability parameters (pH, TS, VS, VFA) as well as chemical characteristics (nutrients, metals, organic pollutants), as these parameters are essential in determining some treatment units performance such as anaerobic digesters and the final treated sludge beneficial utilisation as per the guidelines values.

Condition assessment: Conduct a condition assessment for the sludge treatment and handling processes and equipment for all wastewater treatment works. Ensure that the current sludge treatment processes and equipment are operational and well maintained. Stock chemicals and common spare parts to avoid long periods of treatment unit's shutdown.

Reducing sludge production: Explorer other strategies to reduce sludge production at the wastewater treatment works such as enzymatic hydrolysis, mechanical disintegration, ultrasonic disintegration, chemical and thermochemical hydrolysis, etc., or upgrade to low F/M systems such as MBR.

Future studies:

The following studies are recommended:

- A Multi-criteria Decision Analysis study to overcome the limitation of the semi-quantitative method used in this thesis and to determine the sustainability of each sludge management scenario investigated.

- A long term effect study on the use of sludge on agricultural land and the fate of pollutants and its toxicity potential considering local conditions such as soil type, climate , application rate, and type of crops.
- A feasibility study for a centralised sludge treatment facility.
- Market study to establish the possibilities of sludge beneficial use and stimulate business interest in using sludge.

7. References

Andreoli, C. V. , Von Sperling, M. and Fernandes, F. (2007). *Sludge Treatment and Disposal*. London, United Kingdom: IWA Publishing.

ANSW (2019). *Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality. Durban, South Africa*: eThekwini Water and Sanitation Unit

Arabi, S. , Newman, B. , Weerts, S. , Pillay, S. and Blair, A . (2012) . *Sea disposal of sewage: environmental surveys in the Durban outfalls region.* Report No 30 : Surveys made in 2011. CSIR Report . *Coastal Systems Research Group* , Durban , South Africa.

Bailey, T. (2000). *Durban Metro: Deep sea sewage outfalls*. Paper presented at the *WISA Conference*, Sun City , South Africa.

Bertanza, G., Baroni, P. and Canato, M. (2016). *Ranking sewage sludge management strategies by means of Decision Support Systems: A case study*. *Resources, Conservation and Recycling, 110* , 1-15.

Bertanza, G., Canato, M., Laera, G., Tomei, M. C. (2015). Methodology for technical and economic assessment of advanced routes for sludge processing and disposal, Environ Sci Pollut Res 22, 7190-7202.

Bosch Munitech (2016). *eThekwini Municipality Integrated Waste Management Plan* 2016 - 2021. Project No. 4024-022.

Botha, M. F. , Biyela, S. L. , Fry, M. R. and Paladh, R. (2011). *Sewage-sludge incineration in South Africa using a fluidized-bed reactor. In: Proceedings of a conference on fluidization,* Johannesburg, South Africa: 315-323.

Brewster, W. J. , Connell, A. D. ,De Decker, R. H. , Du Toit, M. , Fijen, A. P. M. , Grundlingh, M. J. , Hennig, H. F-K. O. , Hunter, I. T. , Jordaan, J. M. , Largier, J. L. , Livingstone, D. J. , Lusher, J. A. , Moldan, A. G. S. , McGlashan, J. E. , Russell, K. S. , Toms, G. and Woodborne, M. W. (1992). Guide for the marine disposal of effluents through pipelines. *Water Research Commission*, Pretoria, South Africa.

Bridgwater A. V. (2003) Renewable fuels and chemicals by thermal processing of biomass. Chemical Engineering Journal 91, 87–102.

Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K., and Astaraie-Imani, M. (2014). A new approach to urban water management: Safe and *SuRe*, Elsevier, Bari, Italy.

Campbell, H. W. (2000). Sludge management-future issues and trends. *Water Science Technology (2000) 41 (8): 1–8.* [Online] Available: https://iwaponline.com/wst/article-pdf/41/8/1/39073/1.pdf

Cartmell, E., Gostelow, P., Aridell-Black, D., Simms, N., Oakey, J., Morris, J., Jeffrey, P.,Howsam, P. and Pollard, S.J. (2006). *Biosolids - A fuel or a waste? An integrated appraisal of five co-combustion scenarios with policy analysis.* Environmental Science & Technology 40, 649-658. [Online] Available: https://pubs.acs.org/doi/pdf/10.1021/es052181g

Christensen, M. L. , Keiding, K. , Nielsen, P. H. and Jorgensen, M. K. (2015). *Dewatering in biological wastewater treatment: A review. Water Research* , 1-11.

Dangtran K., Mullen J. F., Mayrose D. T. (2000). *A comparison of fluid bed and multiple hearth biosolids incineration. In: 14th Annual Residuals and Sludge Management Conference*, Boston.

Davis, M. L. (2020). *Water and wastewater engineering, Design principles and practice, 2nd edition.* New York, NY: McGraw-Hill

Evans, T. D. (2016). *Sewage sludge: Operational and environmental issues*. Foundation for Water Research, Marlow, United Kingdom.

Fair, G.M., Geyer, J.C., and Okun, D.A., (1966). *Water and wastewater engineering.* New Work, John Wiley.

Girovich, M. J. (1996). Biosolids Treatment and Management Processes for Beneficial *Use*. New York, Marcel Dekker Inc.

Gurjar, B. R. and Tyagi, V. K. (2017). *Sludge Management.* London, United Kingdom: Taylor & Francis Group.

Hair, J. F., Anderson, R. E., Tatham, R. L., & Black, W. C. (1998). *Multivariate data analysis.* Upper Saddle River, NJ: Prentice Hall.

Hasson, R. N. D. and Arnetz, B. B. (2005). *Validation and findings comparing VAS vs. Likert Scales for Psychosocial measurement*. International Journal of Health Education. 8, 178-192.

Haug, R. T. (1993). *The practical handbook of compost engineering*. Florida, CRC Press LLC.

Herselman, J. E. , Burger, L.W. and Moodley, P. (2009) . *Guidelines for the utilization and disposal of wastewater sludge, Volume 5: Requirements for thermal sludge management practices and for commercial products containing sludge.* Water Research Commission, Gezina, Pretoria

Herselman, J. E. and Moodley, P. (2009). *Guidelines for the utilization and disposal of wastewater sludge, Volume 4: Requirements for the beneficial use of sludge at high loading rates.* Water Research Commission, Gezina, Pretoria.

Hung, Y. , Wang, L. K. and Shammas N. K. (2014). *Handbook Of Environment And Waste Management, Volume 2: Land and Groundwater Pollution Control.* Singapore, World Scientific Publishing Co. Pte. Ltd.

Kelessidis, A. and Stasinakis, A. S. (2012). *Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Management ,32,* 1186-1195.

Kim, Y-J. , Kang, H-O. and Qureshi, T. I. (2005) . *Heating value characteristics of sewage sludge: A comparative study of different sludge types.* Journal of Chemical Society of Pakistan, 27(2), 124-128.

Krol, K . , Iskra, K. , Ferens, W. and Miodonski, J. M. (2019). *Testing properties of sewage sludge for energy use*. Environment Protection Engineering ,45(4), 61-72.

Lewis-Beck, M. S., Bryman, A., & Liao, T. F. (Eds.). (2004). *The Sage encyclopaedia of social science research methods (3rd ed.).* Thousand Oaks, California: Sage Publications Inc.

Likert, R. A. (1932). *Technique for the Measurement of Attitudes*. New York; McGraw-Hill.

Lindfors, L.-G. (1995). *Nordic guidelines on life-cycle assessment.* Copenhagen: Nordic Council of Ministers.

McFarland, M. (2001). *Biosolids Engineering.* New York : McGraw-Hill Companies.

Moodley, L. (2012). *Sludge Classification Guidelines – eThekwini Municipality's Planning Tool For Sludge*. In : Proceedings of 2012 WISA conference, [Online] Available: https://wisa.org.za/wp-content/uploads/2018/12/WISA2012-P064.pdf

Moreno, W.; Gómez, A. (2016). *Biosolids and Biosolid Ashes as Input for Producing Brick-Like Construction Materials.* Tecciencia, 11(21), 45-51.

Musangu, L. M. and Kekwaletswe, R. M. (2012). *Comparison of likert scale with visual analogue scale for strategic information systems planning measurements: a preliminary study.* Faculty of ICT, Tshwane University of Technology. Pretoria, South Africa

Naidoo, K. (2004). *The performance of KwaMashu wastewater sludge incinerator and dryer plant. In: Proceedings of the 2004 Water Institute of Southern Africa (WISA) Biennial Conference.* Cape Town, South Africa.

Paul, E. and Liu, Y. (2012). *Biological Sludge Minimization and Biomaterials/Bioenergy Recovery Technologies.* Hoboken, New Jersey: John Wiley & Sons Publishers.

Qasim, S. R. and Zhu, Guang (2018). *Wastewater Treatment and Reuse Theory and Design Examples Volume 1 and 2.* New York , CRC Press, Taylor & Francis Group, LLC.

Robert, P. J. W., Salas, H. J., Reiff, F. M., Libhaber, M., Labbe, A. and Thomson, J. C. (2010). *Marine Wastewater Outfalls and Treatment Systems*. London, IWA Publishing.

Snyman, H. G. and Herselman, J.E. (2006) . *Guidelines for the utilization and disposal of wastewater sludge, Volume 1: Selection of Management options.* Water Research Commission, Gezina, Pretoria.

Snyman, H. G. and Herselman, J.E. (2006) . *Guidelines for the utilization and disposal of wastewater sludge, Volume 2: Requirements for the agricultural use of wastewater sludge.* Water Research Commission, Gezina, Pretoria.

Snyman, H. G. and Herselman, J.E. (2009) . *Guidelines for the utilization and disposal of wastewater sludge, Volume 3: Requirements for the on-site and off-site disposal of sludge*. Water Research Commission, Gezina, Pretoria.

Sperling, M. (2007). *Wastewater Characteristics, Treatment and Disposal.* London, UK: IWA Publishing.

Teoh, S. K. and Li, L. Y. (2020). *Feasibility of alternative sewage sludge treatment methods from a lifecycle assessment (LCA) perspective.* Journal of Cleaner Production, 247 .

Turovskiy, I. S. and Mathai, P. K. (2006). *Wastewater Sludge Processing.* Hoboken, New Jersey: John Wiley & Sons Publishers.

U.S. Environmental Protection Agency (1985). *Estimating sludge management costs, EPA 625/6-85/010.* Center for Environmental Research Information, Cincinnati, Ohio.

U.S. Environmental Protection Agency (1979). *Process Design Manual for Sludge Treatment and Disposal, EPA 625/1-79-011.* Center for Environmental Research Information, Cincinnati, Ohio.

Vesilind, P.A. (1997). *Treatment and Disposal of Wastewater Sludges, 2nd ed.* Ann Arbor Science Publishers.

Wang, L. K. , Shammas, N.K. and Hung, Y-T. (2007). *Biosolids Treatment Processes.* Totowa, New Jersey: Humana Press.

Wang, L. K. , Shammas, N.K. and Hung, Y-T. (2008). *Biosolids Engineering and Management.* Totowa, New Jersey: Humana Press.

Wang, Q . , Wei, W. , Gong, Y. , Yu, Q. , Li, Q. , Sun, J. and Yuan, Z. (2017). *Technologies for reducing sludge production in wastewater treatment plans: State of the art.* Science of the Total Environment, 510-521.

Task Force of the Water Environment Federation and the American Society of Civil Engineers/ Environmental and Water Resources Institute, *Design of Municipal Wastewater Treatment Plant, WEF Manual of Practice No. 8* and ASCE Manuals and Reports on Engineering Practice No. 76, 5th ed. (2010). McGraw-Hill, New York, NY.

Ukwatta, A.; Mohanjerani, A.; Eshtiaghi, N.; Setunge, S. (2016). *Variation in Physical and Mechanical Properties of Fired-Clay Bricks Incorporating ETP Biosolids*. J. Cleaner Prod., 119, 76-85

Wang, X., Liu, J. X., Ren, N. Q., Yu, H. Q., Lee, D. J., & Guo, X. S. (2012). *Assessment of multiple sustainability demands for wastewater treatment alternatives: A Refined evaluation scheme and case study.* Environmental Science and Technology, 46(10), 5542–5549.

Western Cape Government, Environmental Affairs & Development Planning (2020/21). *Sewage Sludge Status Quo Report 2020/21.* [Online] Available: https://www.westerncape.gov.za/eadp/files/atoms/files/Sewage%20Sludge%20Status%20Quo_12032021.pdf

Von Sperling, M. (2007). Biological wastewater Treatment series, Volume one. *Wastewater Characteristics, Treatment and Disposal.* London, UK: IWA Publishing.

Zanoni, A. E. and Mueller, D. L. (1982). *Calorific Value of Wastewater Plant Sludges.* J. Environ. Eng. Di., ASCE, 108(EE1).

8. Appendices

Appendix 1 - eThekwini municipality monthly sludge production 2010 – 2018

eThekwini municipality Sludge records 2010

Sludge quantities are reported in m^3/Year		Sludge production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,921	58,172	145,002	11,576			2.1%	16%				1,895		11,576
2	Kwa Mashu	4,285	86,830		17,250			3.5%	15%			11,468	8,725		5,784
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,713	17,420	76,819								17,420			
5	Craigieburn	5,824	6,496							6,496	649				
6	Umkomaas	4,097	2,465							2,465	175				
7	Amanzimtoti	5,110	44,578									44,578			
8	Isipingo		5,860							5,860					5,860
Inland Area															
9	Hammersdale	5,597	118,440	539,918			1,088	1.1%	9%		1,088				
10	Mpumalanga		2,473							2,473					2,473
11	Hillcrest	5,266	4,772			408		3.0%	9%		408				
12	Kwandengezi		52,929							52,929					52,929
13	Dassenhoek	5,725	42,425							42,425					42,425
14	Fredville	5,282	318,879							318,879					318,879
Northern Coastal Area															
15	Phoenix	4,390	70,447	120,079	7,450			0.6%	9%		4,496				2,954
16	Umdloti	6,389	3,734							3,734					3,734
17	Umhlanga	3,398	1857				922		9%						922
18	Verulam	6,380	25,880			3,106		2.5%	9%						2,102
19	Gennazzanno	3,727	451							451					451
20	Tongaat Central	6,789	17,710			2,439		0.88%	9%		2,439				
Central Coastal Area															
21	Southern		344,886	693,948								344,886			
22	Central		169,541									169,541			
23	Umhlatuzana	4,004	151,200									151,200			
24	Umbilo	6,088	28,321		10,752			2.6%	17%		10,752				
	TOTAL		1,575,765		54,991					435,712	20,007	739,092	10,620	0	450,089

eThekwini municipality Sludge records 2011

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,772	35,779	100,048	6,107			4.25%	19%				2,490		6,107
2	Kwa Mashu	4,219	64,269		9,877			3.2%	19%			4,250	3,780	283	5,627
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	6,142	15,460	81,158								15,460			
5	Craigieburn	3,860	6,216							6,216	616				
6	Umkomaas	3,617	2,869							2,869	154				
7	Amanzimtoti	7,055	48,010									48,010			
8	Isipingo		8,603							8,603					8,603
Inland Area															
9	Hammersdale		152,085	186,367			932,257		10%	17,000	931,956				
10	Mpumalanga		1,933							1,933					1,933
11	Hillcrest	4,858	7,761			581		1.3%	9%		581				
12	Kwandengezi		3,363							3,363					3,363
13	Dassenhoek	5,419	20,840							20,840					20,840
14	Fredville	3,537	385							385					385
Northern Coastal Area															
15	Phoenix	4,946	92,161	153,653	8,790			1.1%	12%		4,456				4,334
16	Umdloti	6,500	272							272					272
17	Umhlanga	3,357	591				289		8%						289
18	Verulam	6,413	40,026			4,725		1.82%	10%						1,973
19	Gennazzanno		499							499					499
20	Tongaat Central	5,516	20,104			1,957		0.82%	10%		1,957				
Central Coastal Area															
21	Southern		519,469	657,526								519,469			
22	Central		124,977									124,977			
23	Umhlatuzana														
24	Umbilo	3,765	13,080		2,414			3.1%	14%		2,414				
	TOTAL		1,178,751		966,997					61,979	942,134	712,166	6,270	283	54,224

eThekwini municipality Sludge records 2012

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,849	25,841	163,710	6,079			3.5%	17%				360		6,079
2	Kwa Mashu	3,626	137,869		21,305			3.2%	15%			3,398	360		12,276
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,952	19,931	95,397								19,931			
5	Craigieburn	3,732	9,426							9,426	66				
6	Umkomaas	3,692	4,696							4,696	28				
7	Amanzimtoti	7,033	56,226									56,226			
8	Isipingo		5,118							5,118					5,118
Inland Area															
9	Hammersdale		146,440	208,939			858,315		9%		854,015				
10	Mpumalanga		2,245							2,245					2,245
11	Hillcrest	4,478	10,161			189		1.0%	9%		189				
12	Kwandengezi		1,493							1,493					1,493
13	Dassenhoek	4,682	47,136							47,136					47,136
14	Fredville	2,956	1,463							1,463					1,463
Northern Coastal Area															
15	Phoenix	5,219	70,779	144,360	12,808				13%		4,484				8,324
16	Umdloti	6,500	3,951							3,951					3,951
17	Umhlanga	3357	8895				2,220	0.6%	9%						2,220
18	Verulam	6,360	49,356			10,828		1.4%	9%						4,803
19	Gennazzanno		864							864					864
20	Tongaat Central	5,441	10,515			768		1.3%			768				
Central Coastal Area															
21	Southern		607,120	700,306								607,120			
22	Central		83,777									83,777			
23	Umhlatuzana	3,744													
24	Umbilo	3,408	9,409		1,134			3.0%	16%		1,134				
	TOTAL		1,312,711		913,646					76,393	860,684	770,452	720	0	95,973

eThekwini municipality Sludge records 2013

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,849	24,943	141,588	97,314			2.9%	15%						97,314
2	Kwa Mashu	3,626	116,645		20,081			3.0%	16%						8,595
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,952	25,565	111,350								25,565			
5	Craigieburn	3,732	6,202							6,202	22				
6	Umkomaas	3,692	4,347							4,347	8				
7	Amanzimtoti	7,033	66,819									66,819			
8	Isipingo		8,417							8,417					8,417
Inland Area															
9	Hammersdale		163,140	230,875			1,177		10%	3,000	1,177				
10	Mpumalanga		1,896							1,896					1,896
11	Hillcrest	4,478	8,158					1.4%							
12	Kwandengezi		6,303							6,303					6,303
13	Dassenhoek	4,682	49,107							49,107					49,107
14	Fredville	2,956	2,272							2,272					2,272
Northern Coastal Area															
15	Phoenix	5,219	72,479	147,863	7,651			4.1%	10%		3,698				3,953
16	Umdloti	6,500	768							768					768
17	Umhlanga	3357					1,736								1,736
18	Verulam	6,360	46,732			7,131		2.3%	9%						4,091
19	Gennazzanno		678							678					678
20	Tongaat Central	5,441	27,206			2,869		1.2%	10%		2,869				
Central Coastal Area															
21	Southern		661,870	942,304								661,870			
22	Central		263,639									263,639			
23	Umhlatuzana														
24	Umbilo	3,408	16,795		8,201			3.1%	15%		8,201				
	TOTAL		1,573,979		146,160					82,989	15,975	1,017,892	0	0	185,129

* MLSS is not measured, the recoreds is the same as 2012

eThekwini municipality Sludge records 2014

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,849	40,934	183,167	62,153			2.3%	16%						62,153
2	Kwa Mashu	3,626	142,233		22,399			3.0%	17%						16,265
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,952	19,360	81,375								19,360			
5	Craigieburn	3,732	8,624							8,624	16				
6	Umkomaas	3,692	4,090							4,090					
7	Amanzimtoti	7,033	40,882									40,882			
8	Isipingo		8,419							8,419					8,419
Inland Area															
9	Hammersdale		154,990	202,371			1,719	1.0%	10%		1,719				
10	Mpumalanga		1,450							1,450					1,450
11	Hillcrest	4,478	6,673			75		1.9%	9%		75				
12	Kwandengezi									0					0
13	Dassenhoek	4,682	38,166							38,166					38,166
14	Fredville	2,956	1,092							1,092					1,092
Northern Coastal Area															
15	Phoenix	5,219	49,020	134,768	7,777				14%		4,194				3,583
16	Umdloti	6,500	882							882					882
17	Umhlanga														0
18	Verulam	6,360	54,403			7,184		1.9%	10%						2,777
19	Gennazzanno		797							797					797
20	Tongaat Central	5,441	29,666			2,394		1.1%	11%		2,394				
Central Coastal Area															
21	Southern		629,265	672,801								629,265			
22	Central		17,656									17,656			
23	Umhlatuzana														
24	Umbilo	3,408	25,880		6,021			2.9%	15%		6,021				
	TOTAL		1,274,482		109,722					63,520	14,419	707,163	0	0	135,584

* MLSS is not measured, the recoreds is the same as 2012

eThekwini municipality Sludge records 2015

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,849	32,302	42,611	4,219			3.5%	21%						4,219
2	Kwa Mashu	3,626	10,309		1,706			3.0%	19%						1,706
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,952	17,746	77,526								17,746			
5	Craigieburn	3,732	6,420							6,420	150				
6	Umkomaas	3,692	3,152							3,152	72				
7	Amanzimtoti	7,033	38,371									38,371			
8	Isipingo		11,837							11,837					11,837
Inland Area															
9	Hammersdale		53,140	109,665			461	1.4%	13%	16,500	461				
10	Mpumalanga		2,688							2,688					2,688
11	Hillcrest	4,478	9,542			267		1.0%	12%		267				
12	Kwandengezi		165							165					165
13	Dassenhoek	4,682	44,016							44,016					44,016
14	Fredville	2,956	113							113					113
Northern Coastal Area															
15	Phoenix	5,219	9,390	115,292	1,194			1.7%	13%		660				534
16	Umdloti	6,500	738							738					738
17	Umhlanga	3357	15550												
18	Verulam	6,360	55,695			5,850		2.2%	10%						3,594
19	Gennazzanno		648							648					648
20	Tongaat Central	5,441	33,271			204		1.0%	14%		204				
Central Coastal Area															
21	Southern		615,382	634,741								615,382			
22	Central											0			
23	Umhlatuzana														
24	Umbilo	3,408	19,359		2,544			2.8%	14%		2,544				
	TOTAL		979,835		16,445					86,278	4,358	671,499	0	0	70,259

* MLSS is not measured, the recoreds is the same as 2012

eThekwini municipality Sludge records 2016

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,849	9,840	9,840	1,640			3.7%	16%						1,640
2	Kwa Mashu				0			1.5%							0
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,952	5,265	21,175						5,265					
5	Craigieburn	3,732	2,449							2,449	176				
6	Umkomaas	3,692	6,201							6,201	176				
7	Amanzimtoti											0			
8	Isipingo		7,260							7,260					7,260
Inland Area															
9	Hammersdale		42,150	54,328			220		16%	22,500	220				
10	Mpumalanga									0					0
11	Hillcrest	4,478	8,841			524		1.1%	14%		524				
12	Kwandengezi									0					0
13	Dassenhoek	4,682	3,337							3,337					3,337
14	Fredville									0					0
Northern Coastal Area															
15	Phoenix	5,219	18,780	45,466	2,388				13%		660				1,728
16	Umdloti									0					0
17	Umhlanga														
18	Verulam	6,360	9,029			1,122		2.0%	12%						780
19	Gennazzanno		1,188							1,188					1,188
20	Tongaat Central	5,441	16,469			204		0.6%	13%		204				
Central Coastal Area															
21	Southern		598,290	942,330								598,290			
22	Central											0			
23	Umhlatuzana	3,744	341,055									341,055			
24	Umbilo	3,408	2,985		448			3.1%	13%		448				
	TOTAL		1,073,139		6,546					48,200	2,408	939,345	0	0	15,933

* MLSS is not measured, the recoreds is the same as 2012

eThekwini municipality Sludge records 2017

	Sludge quantities are reported in m^3/Year	Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
	Lower Umgeni Area														
1	Northern	3,849	59,040	59,040	9,840				16%						9,840
2	Kwa Mashu				0										0
3	New Germany														
	Southern Coastal Area														
4	Kingsburgh	5,952	5,740	21,650						5,740					
5	Craigieburn	3,732	2,449							2,449	176				
6	Umkomaas	3,692	6,201							6,201	176				
7	Amanzimtoti											0			
8	Isipingo		7,260							7,260					7,260
	Inland Area														
9	Hammersdale		44,400	100,608			220		16%	24,750	220				
10	Mpumalanga									0					0
11	Hillcrest	4,478	52,871			3,144		2.0%	14%		3,144				
12	Kwandengezi									0					0
13	Dassenhoek	4,682	3,337							3,337					3,337
14	Fredville									0					0
	Northern Coastal Area														
15	Phoenix	5,219	112,680	186,266	14,328			3.0%	13%		7,920				6,408
16	Umdloti									0					0
17	Umhlanga														
18	Verulam	6,360	52,839			5,874		2.0%	12%						2,268
19	Gennazzanno		1,188							1,188					1,188
20	Tongaat Central	5,441	19,559			204		0.8%			204				
	Central Coastal Area														
21	Southern		548,585	906,915								548,585			
22	Central											0			
23	Umhlatuzana	3,744	341,055									341,055			
24	Umbilo	3,408	17,275		2,688			2.8%	13%		2,688				
	TOTAL		1,274,479		36,298					50,925	14,528	889,640	0	0	30,301

* MLSS is not measured, the recoreds is the same as 2012

eThekwini municipality Sludge records 2018

Sludge quantities are reported in m^3/Year		Sludge Production									Sludge Disposal				
					Dewatering										
		Average MLSS (mg/l)	Feed to Dewatering / Disposal	Total per Area	Belt Press (cake)	Screw Press (cake)	Centrifuge (cake)	Average Feed Sludge DS%	Average Cake DS% (Mechanical Dewatering)	Drying Beds/Lagoon	Land Fill	Outfall	Agriculture	Incineration	On-Site
Lower Umgeni Area															
1	Northern	3,849	4,920	4,920	820			3.3%	16%						820
2	Kwa Mashu				0			3.3%							0
3	New Germany														
Southern Coastal Area															
4	Kingsburgh	5,952	5,640	21,550						5,640					
5	Craigieburn	3,732	2,449							2,449	176				
6	Umkomaas	3,692	6,201							6,201	176				
7	Amanzimtoti											0			
8	Isipingo		7,260							7,260					7,260
Inland Area															
9	Hammersdale		24,750	28,087			0			24,750	0				
10	Mpumalanga									0					0
11	Hillcrest					0		0.8%			0				
12	Kwandengezi									0					0
13	Dassenhoek	4,682	3,337							3,337					3,337
14	Fredville									0					0
Northern Coastal Area															
15	Phoenix	5,219	9,390	43,665	1,194				13%		660				534
16	Umdloti									0					0
17	Umhlanga														
18	Verulam	6,360	26,907			3,504		2.3%	12%						2,568
19	Gennazzanno		1,188							1,188					1,188
20	Tongaat Central	5,441	6,180			0		2.9%			0				
Central Coastal Area															
21	Southern		548,405	889,460								548,405			
22	Central											0			
23	Umhlatuzana	3,744	341,055									341,055			
24	Umbilo				0			3.6%			0				
	TOTAL		987,682		5,518					50,825	1,012	889,460	0	0	15,707

* MLSS is not measured, the recoreds is the same as 2012

eThekwini municipality sludge production summary 2010 - 2018

	WWTW	m^3/year									TOTAL/PLANT m^3/year
		2010	2011	2012	2013	2014	2015	2016	2017	2018	
Lower Umgeni Area											
1	Northern	58,172	35,779	25,841	24,943	40,934	32,302	9,840	59,040	4,920	291,771
2	Kwa Mashu	86,830	64,269	137,869	116,645	142,233	10,309	0	0	0	558,155
3	New Germany	0	0	0	0	0	0	0	0	0	0
Southern Coastal Area											
4	Kingsburgh	17,420	15,460	19,931	25,565	19,360	17,746	5,265	5,740	5,640	132,127
5	Craigieburn	6,496	6,216	9,426	6,202	8,624	6,420	2,449	2,449	2,449	50,731
6	Umkomaas	2,465	2,869	4,696	4,347	4,090	3,152	6,201	6,201	6,201	40,222
7	Amanzimtoti	44,578	48,010	56,226	66,819	40,882	38,371	0	0	0	294,886
8	Isipingo	5,860	8,603	5,118	8,417	8,419	11,837	7,260	7,260	7,260	70,034
Inland Area											
9	Hammersdale	118,440	152,085	146,440	163,140	154,990	53,140	42,150	44,400	24,750	899,535
10	Mpumalanga	2,473	1,933	2,245	1,896	1,450	2,688	0	0	0	12,686
11	Hillcrest	4,772	7,761	10,161	8,158	6,673	9,542	8,841	52,871	0	108,779
12	Kwandengezi	52,929	3,363	1,493	6,303	0	165	0	0	0	64,253
13	Dassenhoek	42,425	20,840	47,136	49,107	38,166	44,016	3,337	3,337	3,337	251,701
14	Fredville	318,879	385	1,463	2,272	1,092	113	0	0	0	324,203
Northern Coastal Area											
15	Phoenix	70,447	92,161	70,779	72,479	49,020	9,390	18,780	112,680	9,390	505,126
16	Umdloti	3,734	272	3,951	768	882	738	0	0	0	10,345
17	Umhlanga	1,857	591	8,895	0	0	15,550	0	0	0	26,893
18	Verulam	25,880	40,026	49,356	46,732	54,403	55,695	9,029	52,839	26,907	360,867
19	Gennazzanno	451	499	864	678	797	648	1,188	1,188	1,188	7,501
20	Tongaat Central	17,710	20,104	10,515	27,206	29,666	33,271	16,469	19,559	6,180	180,680
Central Coastal Area											
21	Southern	344,886	519,469	607,120	661,870	629,265	615,382	598,290	548,585	548,405	5,073,272
22	Central	169,541	124,977	83,777	263,639	17,656	0	0	0	0	659,589
23	Umhlatuzana	151,200	0	0	0	0	0	341,055	341,055	341,055	1,174,365
24	Umbilo	28,321	13,080	9,409	16,795	25,880	19,359	2,985	17,275	0	133,104
	TOTAL/YEAR	1,575,765	1,178,751	1,312,711	1,573,979	1,274,482	979,835	1,073,139	1,274,479	987,682	11,230,824

Appendix 2 - Sludge physical, chemical, and microbiological quality

PLANT NAME:	Kingsburgh WWTW
WWTW AREA:	Southern Coastal Area
SLUDGE SOURCE:	Drying Beds

		REMARKS	UNIT	OBSERVED VALUES					ESTIMATES	
				Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			Min.	Max.	Summary Statistics	
				Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day									
	Primary Sludge		kg DS/day							
	Secondary Sludge		kg DS/day							
	Tertiary Sludge		kg DS/day							
	Thickened Sludge		kg DS/day							
	Dewatered Sludge		kg DS/day							
	Physical Characteristics									
	Colour		Hazan							
	Odour									
	Specific Gravity									
	Moisture content		% m/m	51%	46%	36%	36%	51%	44%	7.6376%
	Drainability		Time to dry							
	Fuel value (thermal content)		Kj/Kg DS							
	Compressibility									
	Viscosity		Kg/m sec							
	Specific Resistance		S^2/g							
	Chemical Characteristics									
COMPU-LSORY	pH			8.5	8.5	8.8	8.5	8.8	8.6	0.1732
	Total Dry Solids		% m/m	49%	54%	64%	49%	64%	56%	7.64%
	Volatile solids		% m/m							
	Fixed Solid content		% m/m							
	Alkalinity ($CaCO_3$)		mg/l							
	COD		mg/l							
	BOD		mg/l							
	SOUR		mg/hr/gm							
	Grease and Fats		% m/m							
	Protein		% m/m							
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	23000	26000	32000	23000	32000	27000	4582.58
	Total Nitrogen - N		% m/m	2.30%	2.60%	3.20%	2.30%	3.20%	2.70%	0.458%
	Phosphorus - P		mg/Kg DS	16570	15140	20140	15140	20140	17283.33	2575.20
	Phosphorus - P		% m/m	1.657%	1.514%	2.014%	1.514%	2.014%	1.73%	0.2575%
	Potassium - K		mg/Kg DS	1090	1497	1558	1090	1558	1381.67	254.43
	Potassium - K		% m/m	0.109%	0.150%	0.156%	0.109%	0.156%	0.14%	0.0254%
	Potash (K_2O)		% m/m							
	Cellulose		% m/m							
	Volatile Acids		mg/l							
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS							
	METALS									
COMPULSORY	Arsenic		mg/kg DS	4	4	4	4	4	4	0.00
	Cadmium		mg/kg DS	2	2	2	2	2	2	0.00
	Chromium		mg/kg DS	29	35	37	29	37	33.7	4.16
	Copper		mg/kg DS	171	161	203	161	203	178.3	21.94
	lead		mg/kg DS	23	30	33	23	33	28.67	5.13
	Mercury		mg/kg DS	1.21	1.26	1.27	1.21	1.27	1.25	0.03
	Nickle		mg/kg DS	14.9	17.6	17.9	14.9	17.9	16.80	1.65
	Zinc		mg/kg DS	323	342	383	323	383	349.33	30.66
RECOMMENDED	Antimony		mg/kg DS							
	Boron		mg/kg DS							
	Barium		mg/kg DS							
	Beryllium		mg/kg DS							
	Cobalt		mg/kg DS							
	Manganese		mg/kg DS							
	Molybdenum		mg/kg DS							
	Selenium		mg/kg DS							
	Strontium		mg/kg DS							
	Thallium		mg/kg DS							
	Vanadium		mg/kg DS							
	Iron		mg/kg DS							
	Tin		mg/kg DS							
	Aluminum		mg/kg DS							
	Magnesium		mg/kg DS							
	Sodium		mg/kg DS							
	Sulpher		mg/kg DS							
	Biological Characteristics									
COMPU-LSORY	Fecal coliform		CFU/gm DS	400	8900	40	40	8900	3113.33	5014.63
	Viable Helminth		Ova/gm DW	0	1	0	0	1	0.33	0.5774
	Total colifom		CFU/gm DS							
	Fecal streptococci		Number/gm DS							
	Salmonella sp.		Number/gm DS							
	Shigella sp.		Number/gm DS							
	Pseudomonas aeruginosa		Number/gm DS							
	Enteric virus		Number/gm DS							
	Parasite ova/cysts		Number/gm DS							

PLANT NAME:	Kingsburgh WWTW
WWTW AREA:	Southern Coastal Area
SLUDGE SOURCE:	WAS

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 03/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Late Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	97.10%	97.52%	97.42%				97.10%	97.52%	97.35%	0.22%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH						6.8	6.6	6.6	6.6	6.8	6.67	0.12
	Total Dry Solids		% m/m	2.90%	2.48%	2.58%				2.48%	2.90%	2.65%	0.22%
	Volatile solids		% m/m	66.03%	65.91%	66.13%				65.91%	66.13%	66.02%	0.11%
	Fixed Solid content		% m/m	33.97%	34.09%	33.87%				33.87%	34.09%	33.98%	0.11%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	57000	60000	56000				56000	60000	57666.67	2081.67
	Total Nitrogen - N		% m/m	5.70%	6.00%	5.60%				5.60%	6.00%	6%	0.21%
	Phosphorus - P		mg/Kg DS	7000	6800	7350				6800	7350	7050.00	278.39
	Phosphorus - P		% m/m	0.70%	0.68%	0.74%				0.680%	0.735%	0.71%	0.03%
	Potassium - K		mg/Kg DS	2867	2566	3785				2566	3785	3072.67	634.99
	Potassium - K		% m/m	0.29%	0.26%	0.38%				0.257%	0.379%	0%	0.06%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	303	210	202				202	303	238.33	5614.56
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	5	0	4	4	4	0	5	2.83	222.86
	Cadmium		mg/kg DS	20	17	14	2	2	2	2	20	9.50	843.21
	Chromium		mg/kg DS	61	78	87	8.15	8.16	8.81	8.15	87	41.85	3761.49
	Copper		mg/kg DS	278	285	364	16	17.6	8.83	8.83	364	161.49	16441.54
	lead		mg/kg DS	2	7.2	48	3.83	3	3	2	48	11.17	1813.10
	Mercury		mg/kg DS	12.52	13.71	9.8	0.62	0.78	0.41	0.41	13.71	6.31	637.61
	Nickle		mg/kg DS	69	79	0	4.54	4.57	4.78	0	79	26.98	3660.13
	Zinc		mg/kg DS	548	732	823	17.4	15	16	15	823	358.57	38544.01
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	137797.64	302565.76	217441.95	530000	1190000	1900000	137797.64	1900000	712967.56	69496457.39
	Viable Helminth		Ova/gm DW	2.47	2.87	2.16	9	50	23	2.16	50	14.92	1894.18
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Umkomaas WWTW
WWTW AREA: Southern Coastal Area
SLUDGE SOURCE: Drying Beds

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 06/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	56.39%	37.41%	20.97%	71%	73%	75%	20.97%	75.00%	55.63%	22.12%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH						8	6.7	7.1	6.7	8	7.27	0.67
	Total Dry Solids		% m/m	43.61%	62.59%	79.03%	29.00%	27.00%	25.00%	25.00%	79.03%	44.37%	22.12%
	Volatile solids		% m/m	65.18%	70.68%	64.40%				64.40%	70.68%	66.75%	3.42%
	Fixed Solid content		% m/m	34.82%	29.82%	35.60%						33.41%	3.14%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm							0	0	#DIV/0!	#DIV/0!
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	50000	45000	57000	10000	25000	15000	10000	57000	33666.67	19612.92
	Total Nitrogen - N		% m/m	5.00%	4.50%	5.70%	1.00%	2.50%	1.50%	1.00%	5.70%	3%	1.96%
	Phosphorus - P		mg/Kg DS	5650	5750	5200	1527	1673	1542	1527	5750	3557.00	2173.47
	Phosphorus - P		% m/m	0.57%	0.58%	0.52%	0.15%	0.17%	0.15%	0.153%	0.575%	0.36%	0.22%
	Potassium - K		mg/Kg DS	1561	1305	1506	657	679	584	584	1561	1048.67	456.80
	Potassium - K		% m/m	0.16%	0.13%	0.15%	0.07%	0.07%	0.06%	0.058%	0.156%	0%	0.05%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	101	76	58				58	101	78.33	2159.48
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	8	9	14	4	4	4	4	14	7.17	402.08
	Cadmium		mg/kg DS	17	15	16	2	2	2	2	17	9.00	769.42
	Chromium		mg/kg DS	204	189	77	13.7	12.4	13.5	12.4	204	84.93	9000.85
	Copper		mg/kg DS	262	322	277	117	106	62	62	322	191.00	10857.26
	lead		mg/kg DS	93	101	41	8.18	8.6	8.61	8.18	101	43.40	4346.38
	Mercury		mg/kg DS	7.25	6.75	0.25	0.85	0.96	0.59	0.25	7.25	2.78	328.56
	Nickle		mg/kg DS	83	0	16	7	6.99	7.28	0	83	20.05	3125.71
	Zinc		mg/kg DS	1230	1344	1487	163	158	136	136	1487	753.00	66308.07
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	458.63	319.51	253.04	400000	92100	50000	253.04	400000	90521.86	15608814.18
	Viable Helminth		Ova/gm DW	2.84	2.67	5.72	2	1	1	1	5.72	2.54	174.67
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Craigeburn WWTW
WWTW AREA:	Southern Coastal Area
SLUDGE SOURCE:	Drying Beds

				OBSERVED VALUES								ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 06/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	56.39%	37.41%	20.97%	67%	65%	99%	20.97%	98.80%	57.60%	26.80%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.2	6	6.3	8.3	8.7	6.5	6	8.7	7.00	1.18
	Total Dry Solids		% m/m	43.61%	62.59%	79.03%	33.00%	35.00%	1.20%	1.20%	79.03%	42.41%	26.80%
	Volatile solids		% m/m	65.18%	70.68%	64.40%				64.40%	70.68%	66.75%	3.42%
	Fixed Solid content		% m/m	34.82%	29.32%	35.60%				29.32%	35.60%	33.25%	3.42%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				293	442	260	260.00	442.00	331.67	96.97
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	27000	19000	39000	12000	9100	1000	1000	39000	17850.00	13616.72
	Total Nitrogen - N		% m/m	2.70%	1.90%	3.90%	1.20%	0.91%	0.10%	0.10%	3.90%	2%	1.36%
	Phosphorus - P		mg/Kg DS	1450	980	3750	2425	2397	472	472	3750	1912.33	1185.94
	Phosphorus - P		% m/m	0.15%	0.10%	0.38%	0.24%	0.24%	0.05%	0.047%	0.375%	0.19%	0.12%
	Potassium - K		mg/Kg DS	958	799	902	525	460	82	82	958	621.00	331.62
	Potassium - K		% m/m	0.10%	0.08%	0.09%	0.05%	0.05%	0.01%	0.008%	0.096%	0%	0.03%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	66	91	50				50	91	69.00	2066.40
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	26	9	16	4	4	4	4	26	10.50	893.87
	Cadmium		mg/kg DS	16	15	14	2	2	2.03	2	16	8.51	714.30
	Chromium		mg/kg DS	41.8	40.7	161	12.8	18.7	14.9	12.8	161	48.32	5666.26
	Copper		mg/kg DS	102	80	101	34	300	43	34	300	110.00	9737.56
	lead		mg/kg DS	13	0	88	7.44	4.08	20	0	88	22.09	3303.96
	Mercury		mg/kg DS	6	6.25	5.27	2.71	2.17	1.33	1.33	6.25	3.96	213.57
	Nickle		mg/kg DS	32	0	30	6.6	7.07	6.02	0	32	13.62	1372.28
	Zinc		mg/kg DS	214	142	216	77	208	28	28	216	147.50	8006.93
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	447.09	260.62	223.12	610000	81600	4200000	223.12	4200000	815421.81	167506910.65
	Viable Helminth		Ova/gm DW	3.8	7.31	19.29	0	0	33	0	33	10.57	1310.77
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Amanzimtoti WWTW
WWTW AREA:	Southern Coastal Area
SLUDGE SOURCE:	Digested Sludge

				OBSERVED VALUES								ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 12/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	91.89%	93.20%	93.60%	91%	91%	91%	90.55%	93.60%	91.98%	1.19%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			7.1	7.2	7	7.7	7.8	7.6	7	7.8	7.40	0.34
	Total Dry Solids		% m/m	8.11%	6.80%	6.40%	9.45%	8.85%	8.52%	6.40%	9.45%	8.02%	1.19%
	Volatile solids		% m/m	49.00%	46.00%	46.00%	45.00%	38.00%	46.00%	38.00%	49.00%	45.00%	3.69%
	Fixed Solid content		% m/m	51.00%	54.00%	54.00%				51.00%	54.00%	53.00%	1.73%
	Alkalinity (CaCO$_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	33000			3800	4400	100	100	33000	10325.00	15235.79
	Total Nitrogen - N		% m/m	3.30%			0.38%	0.44%	0.01%	0.01%	3.30%	1%	1.52%
	Phosphorus - P		mg/Kg DS	6250			866	501	445	445	6250	2015.50	2829.16
	Phosphorus - P		% m/m	0.63%			0.09%	0.05%	0.04%	0.045%	0.625%	0.20%	0.28%
	Potassium - K		mg/Kg DS	1818	1804	1772	185	100	104	100	1818	963.83	914.41
	Potassium - K		% m/m	0.18%	0.18%	0.18%	0.02%	0.01%	0.01%	0.010%	0.182%	0%	0.09%
	Potash (K$_2$O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	218	226	210				210	226	218.00	800.00
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.1	0.1	0.1	0.1	0.1	0.10	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	5	11	5	4	4	4	4	11	5.50	273.86
	Cadmium		mg/kg DS	17	20	17	2	2	2	2	20	10.00	883.18
	Chromium		mg/kg DS	155	110	194	20	15.9	14	14	194	84.82	7930.52
	Copper		mg/kg DS	435	291	571	57	30	60	30	571	240.67	22811.11
	lead		mg/kg DS	82	100	64	9.69	6.45	5.26	5.26	100	44.57	4258.18
	Mercury		mg/kg DS	1	14	13	0.51	0.81	0.39	0.39	14	4.95	663.26
	Nickle		mg/kg DS	208	417	407	29	17.1	16.5	16.5	417	182.43	19210.21
	Zinc		mg/kg DS	2316	1420	2884	444	221	227	221	2884	1252.00	114805.87
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	1232.35	4411.76	3125	24000	14500000	1200	1200	14500000	2422328.19	591683302.41
	Viable Helminth		Ova/gm DW	3.37	2	3	3	8	0	0	8	3.23	263.91
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Isipingo WWTW
WWTW AREA:	Southern Coastal Area
SLUDGE SOURCE:	Drying Beds

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 13/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	12.34%	27.03%	8.51%	62%	30%	62%	8.51%	62.00%	33.65%	23.45%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU- LSORY	pH			6.8	7.2	6.9	7.3	5.9	6.9	5.9	7.3	6.83	0.50
	Total Dry Solids		% m/m	87.66%	72.97%	91.49%	38.00%	70.00%	38.00%	38.00%	91.49%	66.35%	23.45%
	Volatile solids		% m/m	45.73%	49.46%	48.33%				45.73%	49.46%	47.84%	1.91%
	Fixed Solid content		% m/m	54.27%	50.54%	51.67%				50.54%	54.27%	52.16%	1.91%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	29000	30000	31000	2543	1548	989	989	31000	15846.67	15525.08
	Total Nitrogen - N		% m/m	2.90%	3.00%	3.10%	0.25%	0.15%	0.10%	0.10%	3.10%	2%	1.55%
	Phosphorus - P		mg/Kg DS	11150	10900	10000	12100	4127	3008	3008	12100	8547.50	3931.01
	Phosphorus - P		% m/m	1.12%	1.09%	1.00%	1.21%	0.41%	0.30%	0.301%	1.210%	0.85%	0.39%
	Potassium - K		mg/Kg DS	1260	1350	1180	185	100	104	100	1350	696.50	624.00
	Potassium - K		% m/m	0.13%	0.14%	0.12%	0.02%	0.01%	0.01%	0.010%	0.135%	0%	0.06%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	200	193	202				193	202	198.33	472.58
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	5.4	4.12	4	0	5.4	2.25	251.67
	Cadmium		mg/kg DS	16.8	12.4	16.9	2	2	2	2	16.9	8.68	749.94
	Chromium		mg/kg DS	120	89	73	58	43	27	27	120	68.33	3339.26
	Copper		mg/kg DS	324	58	216	153	222	69	58	324	173.67	10147.84
	lead		mg/kg DS	128	48	66	46	30	19.4	19.4	128	56.23	3863.48
	Mercury		mg/kg DS	8.5	3.5	8.25	3.02	2.69	1.45	1.45	8.5	4.57	302.67
	Nickle		mg/kg DS	28	15	1	19.1	14.1	9.5	1	28	14.45	906.70
	Zinc		mg/kg DS	966	148	590	503	408	210	148	966	470.83	29550.93
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU- LSORY	Fecal coliform		CFU/gm DS	0	0	0	67000	3500	330	0	67000	11805.00	2707475.12
	Viable Helminth		Ova/gm DW	25.12	9.99	32.92	1	0	1	0	32.92	11.67	1413.63
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Southern WWTW
WWTW AREA:	Central Coastal Area
SLUDGE SOURCE:	Raw Sludge

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 - (Sample Date: 14/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	92.86%	92.29%	93.39%				92.29%	93.39%	92.85%	0.55%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			4.6	4.7	4.8	4.7	4.8	4.8	4.6	4.8	4.73	0.08
	Total Dry Solids		% m/m	7.14%	7.71%	6.61%				6.61%	7.71%	7.15%	0.55%
	Volatile solids		% m/m	57.65%	58.05%	51.64%	88.00%	84.00%	84.00%	51.64%	88.00%	70.56%	16.41%
	Fixed Solid content		% m/m	42.35%	41.95%	48.36%				41.95%	48.36%	44.22%	3.59%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	29000	30000	31000	1000	1300	1000	1000	31000	15550.00	15842.19
	Total Nitrogen - N		% m/m	2.90%	3.00%	3.10%	0.10%	0.13%	0.10%	0.10%	3.10%	2%	1.58%
	Phosphorus - P		mg/Kg DS	11150	10900	10000	393	288	328	288	11150	5509.83	5680.28
	Phosphorus - P		% m/m	1.12%	1.09%	1.00%	0.04%	0.03%	0.03%	0.029%	1.115%	0.55%	0.57%
	Potassium - K		mg/Kg DS	1260	1350	1180	57	51	82	51	1350	663.33	659.55
	Potassium - K		% m/m	0.13%	0.14%	0.12%	0.01%	0.01%	0.01%	0.005%	0.135%	0%	0.07%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	1907	2039	1884				1884	2039	1943.33	8364.41
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.03	0.03	0.03	0.03	0.03	0.03	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	16.7	15.6	20.1	2	2	2	2	20.1	9.73	860.04
	Chromium		mg/kg DS	92	97	167	7.59	12.7	7.99	7.59	167	64.05	6547.20
	Copper		mg/kg DS	155	167	143	4.55	5.42	3.17	3.17	167	79.69	8284.94
	lead		mg/kg DS	119	145	60	3	7.47	3	3	145	56.25	6305.36
	Mercury		mg/kg DS	6.25	0.25	7	0.2	0.66	0.41	0.2	7	2.46	323.76
	Nickle		mg/kg DS	5	58	66	4.3	5.06	4.33	4.3	66	23.78	2971.34
	Zinc		mg/kg DS	403	426	390	7.75	3.72	2.26	2.26	426	205.46	22036.04
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	177756.63	204918.03	261803.87	74000000	58000000	70000000	177756.63	74000000	33774079.76	3713761260.58
	Viable Helminth		Ova/gm DW	0.93	0.72	0.72	1	0	8	0	8	1.90	301.18
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Centeral WWTW
WWTW AREA: Central Coastal Area
SLUDGE SOURCE: Raw Sludge

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 23/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	99.56%	99.34%	98.96%				98.96%	99.56%	99.29%	0.30%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			5.4	5.4	5.2	4.9	4.9	4.9	4.9	5.4	5.12	0.25
	Total Dry Solids		% m/m	0.44%	0.66%	1.04%				0.44%	1.04%	0.71%	0.30%
	Volatile solids		% m/m	68.18%	81.82%	76.92%				68.18%	81.82%	75.64%	6.91%
	Fixed Solid content		% m/m	31.82%	18.18%	23.08%				18.18%	31.82%	24.36%	6.91%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	61000	62000	61000	1000	1000	1000	1000	62000	31166.67	33047.94
	Total Nitrogen - N		% m/m	6.10%	6.20%	6.10%	0.10%	0.10%	0.10%	0.10%	6.20%	3%	3.30%
	Phosphorus - P		mg/Kg DS	2150	2250	2050	430	261	234	234	2250	1229.17	1012.93
	Phosphorus - P		% m/m	0.22%	0.23%	0.21%	0.04%	0.03%	0.02%	0.023%	0.225%	0.12%	0.10%
	Potassium - K		mg/Kg DS	8.1	7.8	8	83	35	27	7.8	83	28.15	29.25
	Potassium - K		% m/m	0.001%	0.001%	0.001%	0.01%	0.004%	0.003%	0.001%	0.008%	0%	0.00%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	227	304	408				227	408	313.00	9083.50
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.03	0.03	0.03	0.03	0.03	0.03	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	0	0	0	2	2	2	0	2	1.00	109.54
	Chromium		mg/kg DS	14	14	14	12.2	7.79	7.73	7.73	14	11.62	307.02
	Copper		mg/kg DS	191	191	191	100	17.8	2	2	191	115.47	8918.36
	lead		mg/kg DS	40	40	40	6.43	3	3	3	40	22.07	1967.94
	Mercury		mg/kg DS	0.75	0.75	0.75	0.32	0.31	0.2	0.2	0.75	0.51	26.27
	Nickle		mg/kg DS	0	0	0	5.21	4.35	4.34	0	5.21	2.32	255.74
	Zinc		mg/kg DS	389	389	389	71	2.27	2	2	389	207.05	20090.16
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	931818.18	621212.12	394130.77	4300000	7400000	5900000	394130.77	7400000	3257860.18	302613981.94
	Viable Helminth		Ova/gm DW	6.45	6.73	4.35	0	8	4	0	8	4.92	284.54
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Umhlatazana WWTW
WWTW AREA: Central Costal Area
SLUDGE SOURCE: WAS

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 23/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	99.20%	99.22%	98.86%				98.86%	99.22%	99.09%	0.20%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.6	6.5	6.4	7	6.9	7.1	6.4	7.1	6.75	0.29
	Total Dry Solids		% m/m	0.80%	0.78%	1.14%				0.78%	1.14%	0.91%	0.20%
	Volatile solids		% m/m	70.00%	66.67%	66.67%				66.67%	70.00%	67.78%	1.92%
	Fixed Solid content		% m/m	30.00%	33.33%	33.33%				30.00%	33.33%	32.22%	1.92%
	Alkalinity (CaCO$_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	63000	67000	63000	0.1	0.1	0.1	0.1	67000	32166.72	35267.02
	Total Nitrogen - N		% m/m	6.30%	6.70%	6.30%	0.00%	0.00%	0.00%	0.00%	6.70%	3%	3.53%
	Phosphorus - P		mg/Kg DS	5050	5450	5000	119	320	286	119	5450	2704.17	2702.90
	Phosphorus - P		% m/m	0.51%	0.55%	0.50%	0.01%	0.03%	0.03%	0.012%	0.545%	0.27%	0.27%
	Potassium - K		mg/Kg DS	23	24	23	30	68	48	23	68	36.00	18.36
	Potassium - K		% m/m	0.002%	0.002%	0.002%	0.00%	0.007%	0.005%	0.002%	0.007%	0%	0.00%
	Potash (K$_2$O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	81.3	272	126				81.3	272	159.77	9973.35
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.03	0.03	0.03	0.03	0.03	0.03	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	0	0	0	2	2	2	0	2	1.00	109.54
	Chromium		mg/kg DS	59	59	59	7.36	7.64	12.6	7.36	59	34.10	2734.02
	Copper		mg/kg DS	415	415	415	11.4	195	15.2	11.4	415	244.43	19828.01
	lead		mg/kg DS	37	37	37	9.72	3	3	3	37	21.12	1756.79
	Mercury		mg/kg DS	29.97	29.97	29.97	0.6	0.62	0.2	0.2	29.97	15.22	1615.67
	Nickle		mg/kg DS	0	0	0	2.85	4.97	5.26	0	5.26	2.18	252.89
	Zinc		mg/kg DS	843	843	843	6.89	90	12.8	6.89	843	439.78	44267.61
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	87500	384615.38	877.93	540000	780000	9800000	877.93	9800000	1932165.55	386512622.55
	Viable Helminth		Ova/gm DW	3.13	4.33	3.84	42	12	0	0	42	10.88	1575.19
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Umbilo WWTW
WWTW AREA:	Inland Area
SLUDGE SOURCE:	Drying Bids/Belt Press

		REMARKS	UNIT	OBSERVED VALUES											ESTIMATES	
				File : Result of testing 3 (Sample Date: 25/04/2007) (Belt Press)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Belt Press)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Drying Beds)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day															
	Primary Sludge		kg DS/day													
	Secondary Sludge		kg DS/day													
	Tertiary Sludge		kg DS/day													
	Thickened Sludge		kg DS/day													
	Dewatered Sludge		kg DS/day													
	Physical Characteristics															
	Colour		Hazan													
	Odour															
	Specific Gravity															
	Moisture content		% m/m	85.04%	84.50%	87.80%				26%	19%	32%	19.00%	87.80%	55.72%	33.20%
	Drainability		Time to dry													
	Fuel value (thermal content)		Kj/Kg DS													
	Compressibility															
	Viscosity		Kg/m sec													
	Specific Resistance		S^2/g													
	Chemical Characteristics															
COMPU-LSORY	pH			6.5	6.5	6.6	6.9	6.2	6.6	7.5	7.5	7.4	6.2	7.5	6.86	0.49
	Total Dry Solids		% m/m	14.96%	15.50%	12.20%				74.00%	81.00%	68.00%	12.20%	81.00%	44.28%	33.20%
	Volatile solids		% m/m	64.04%	64.52%	64.10%							64.04%	64.52%	64.22%	0.26%
	Fixed Solid content		% m/m	35.96%	35.48%	35.90%							35.48%	35.96%	35.78%	0.26%
	Alkalinity ($CaCO_3$)		mg/l													
	COD		mg/l													
	BOD		mg/l													
	SOUR		mg/hr/gm													
	Grease and Fats		% m/m													
	Protein		% m/m													
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	43000	44000	42000	9000	9300	9000	25000	24000	24000	9000	44000	25477.78	14715.79
	Total Nitrogen - N		% m/m	4.30%	4.40%	4.20%	0.90%	0.93%	0.90%	2.50%	2.40%	2.40%	0.90%	4.40%	3%	1.47%
	Phosphorus - P		mg/Kg DS	8400	8550	8250	6165	2935	3572	11070	21680	21530	2935	21680	10239.11	6925.13
	Phosphorus - P		% m/m	0.84%	0.86%	0.83%	0.62%	0.29%	0.36%	1.11%	2.17%	2.15%	0.294%	2.168%	1.02%	0.69%
	Potassium - K		mg/Kg DS	6.7	6.8	6.7	352	144	215	397	556	632	6.7	632	257.36	240.07
	Potassium - K		% m/m	0.001%	0.001%	0.001%	0.04%	0.01%	0.02%	0.04%	0.056%	0.063%	0.001%	0.063%	0%	0.02%
	Potash (K_2O)		% m/m													
	Cellulose		% m/m													
	Volatile Acids		mg/l	136	140	127							127	140	134.33	665.83
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.1005	0.1005	0.1005	0.1094	0.1094	0.1094	0.1005	0.1094	0.10	0.49
	METALS															
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	5.41	4.08	4.29	0	5.41	2.86	219.30
	Cadmium		mg/kg DS	178	178	178	4.18	2	2.28	5	4.73	19.7	2	178	63.54	8600.46
	Chromium		mg/kg DS	241	241	241	4070	1704	2074	4262	4913	3564	241	4913	2367.78	188716.72
	Copper		mg/kg DS	1360	1360	1360	1241	665	818	2385	2411	1927	665	2411	1503.00	62084.86
	lead		mg/kg DS	1160	1160	1160	392	214	266	1112	1161	881	214	1161	834.00	41946.96
	Mercury		mg/kg DS	35.27	35.27	35.27	1.42	0.71	1.38	2.02	2.42	2.36	0.71	35.27	12.90	1678.41
	Nickle		mg/kg DS	630	630	630	1119	568	689	2024	2014	1634	568	2024	1104.22	62140.70
	Zinc		mg/kg DS	4600	4600	4600	2920	1144	1414	5712	5875	5437	1144	5875	4033.56	178857.26
RECOMMENDED	Antimony		mg/kg DS													
	Boron		mg/kg DS													
	Barium		mg/kg DS													
	Berylium		mg/kg DS													
	Cobalt		mg/kg DS													
	Manganese		mg/kg DS													
	Molybdenum		mg/kg DS													
	Selenium		mg/kg DS													
	Strontium		mg/kg DS													
	Thallium		mg/kg DS													
	Vanadium		mg/kg DS													
	Iron		mg/kg DS													
	Tin		mg/kg DS													
	Aluminum		mg/kg DS													
	Magnesium		mg/kg DS													
	Sodium		mg/kg DS													
	Sulpher		mg/kg DS													
	Biological Characteristics															
COMPU-LSORY	Fecal coliform		CFU/gm DS	66.84	967.74	81.97	1000	1400	22000	100	2	100	2	22000	2857.62	719751.65
	Viable Helminth		Ova/gm DW	0.94	1.3	0.8	0	1	4	0	0	0	0	4	0.89	127.63
	Total colifom		CFU/gm DS													
	Fecal streptococci		Number/gm DS													
	Salmonella sp.		Number/gm DS													
	Shigella sp.		Number/gm DS													
	Pseudomonas aeruginosa		Number/gm DS													
	Enteric virus		Number/gm DS													
	Parasite ova/cysts		Number/gm DS													

PLANT NAME: Hammersdale WWTW
WWTW AREA: Inland Area
SLUDGE SOURCE: Drying Bids/Centrifuge

		REMARKS	UNIT	OBSERVED VALUES											ESTIMATES	
				File : Result of testing 3 (Sample Date: 08/08/2007 & 26/08/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (CENTRIFUGE)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Drying Beds)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day															
	Primary Sludge		kg DS/day													
	Secondary Sludge		kg DS/day													
	Tertiary Sludge		kg DS/day													
	Thickened Sludge		kg DS/day													
	Dewatered Sludge		kg DS/day													
	Physical Characteristics															
	Colour		Hazan													
	Odour															
	Specific Gravity															
	Moisture content		% m/m	89.20%	89.16%	89.18%				70%	88%	87%	70.00%	89.20%	85.42%	7.61%
	Drainability		Time to dry													
	Fuel value (thermal content)		Kj/Kg DS													
	Compressibility															
	Viscosity		Kg/m sec													
	Specific Resistance		S^2/g													
	Chemical Characteristics															
COMPU- LSORY	pH			6.9	6.7	6.7	8.4	8.1	8.3	6.5	7.5	7.6	6.5	8.4	7.41	0.74
	Total Dry Solids		% m/m	10.80%	10.84%	10.82%				30.00%	12.00%	13.00%	10.80%	30.00%	14.58%	7.61%
	Volatile solids		% m/m	81.48%	81.37%	81.52%							81.37%	81.52%	81.46%	0.08%
	Fixed Solid content		% m/m	18.52%	18.63%	18.48%							18.48%	18.63%	18.54%	0.08%
	Alkalinity ($CaCO_3$)		mg/l													
	COD		mg/l													
	BOD		mg/l													
	SOUR		mg/hr/gm				566	290	726						527.33	220.56
	Grease and Fats		% m/m													
	Protein		% m/m													
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	78000	77000	78000	9700	10000	9300	13000	11000	19000	9300	78000	33888.89	32962.99
	Total Nitrogen - N		% m/m	7.80%	7.70%	7.80%	0.97%	1.00%	0.93%	1.30%	1.10%	1.90%	0.93%	7.80%	3%	3.30%
	Phosphorus - P		mg/Kg DS	9800	10350	10200	3075	7731	4092	6939	4679	4945	3075	10350	6867.89	2809.71
	Phosphorus - P		% m/m	0.98%	1.04%	1.02%	0.31%	0.77%	0.41%	0.69%	0.47%	0.49%	0.308%	1.035%	0.69%	0.28%
	Potassium - K		mg/Kg DS	5280	5879	5840	1044	2186	1319	888	1193	1279	888	5879	2767.56	2209.87
	Potassium - K		% m/m	0.528%	0.588%	0.584%	0.10%	0.22%	0.13%	0.09%	0.119%	0.128%	0.089%	0.588%	0%	0.22%
	Potash (K_2O)		% m/m													
	Cellulose		% m/m													
	Volatile Acids		mg/l	912									912	912	912.00	
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00
	METALS															
COMPULSORY	Arsenic		mg/kg DS	2	3	9	4	4	4	4	4	4	2	9	4.22	192.21
	Cadmium		mg/kg DS	0	0	0	2	2	2	2	2	2	0	2	1.33	100.00
	Chromium		mg/kg DS	21	25	22	13	18.9	15.5	22	15.6	22	13	25	19.44	395.35
	Copper		mg/kg DS	77	82	82	105	48	63	180	29	58	29	180	80.44	4335.64
	lead		mg/kg DS	2	4	3	4.53	8.67	5.66	8	6.44	23	2	23	7.26	629.89
	Mercury		mg/kg DS	0.4	0.4	0.4	0.76	0.28	0.5	0.2	0.2	1.22	0.2	1.22	0.48	32.45
	Nickle		mg/kg DS	12	16	8	8.22	12.3	9.57	13.7	9.76	11.6	8	16	11.24	262.53
	Zinc		mg/kg DS	290	306	291	161	242	174	327	144	172	144	327	234.11	7172.42
RECOMMENDED	Antimony		mg/kg DS													
	Boron		mg/kg DS													
	Barium		mg/kg DS													
	Berylium		mg/kg DS													
	Cobalt		mg/kg DS													
	Manganese		mg/kg DS													
	Molybdenum		mg/kg DS													
	Selenium		mg/kg DS													
	Strontium		mg/kg DS													
	Thallium		mg/kg DS													
	Vanadium		mg/kg DS													
	Iron		mg/kg DS													
	Tin		mg/kg DS													
	Aluminum		mg/kg DS													
	Magnesium		mg/kg DS													
	Sodium		mg/kg DS													
	Sulpher		mg/kg DS													
	Biological Characteristics															
COMPU- LSORY	Fecal coliform		CFU/gm DS			4740.15	1000	1400	22000	7100	6000	116000	1000	116000	22605.74	4178258.01
	Viable Helminth		Ova/gm DW				0	1	4	1	1	0	0	4	1.17	147.20
	Total colifom		CFU/gm DS													
	Fecal streptococci		Number/gm DS													
	Salmonella sp.		Number/gm DS													
	Shigella sp.		Number/gm DS													
	Pseudomonas aeruginosa		Number/gm DS													
	Enteric virus		Number/gm DS													
	Parasite ova/cysts		Number/gm DS													

PLANT NAME: Mpumalanga WWTW
WWTW AREA: Inland Area
SLUDGE SOURCE: Drying Beds

				OBSERVED VALUES								ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 27/03/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	42.98%	41.29%	43.10%	6%	37%	10%	6.00%	43.10%	30.06%	17.28%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.9	7	6.9	6.9	7.1	6.8	6.8	7.1	6.93	0.10
	Total Dry Solids		% m/m	57.02%	58.71%	56.90%	94.00%	63.00%	90.00%	56.90%	94.00%	69.94%	17.28%
	Volatile solids		% m/m	51.25%	49.87%	51.10%				49.87%	51.25%	50.74%	0.76%
	Fixed Solid content		% m/m	48.75%	50.13%	48.90%				48.75%	50.13%	49.26%	0.76%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	29000	31000	29000	24000	26000	37000	24000	37000	29333.33	4501.85
	Total Nitrogen - N		% m/m	2.90%	3.10%	2.90%	2.40%	2.60%	3.70%	2.40%	3.70%	3%	0.45%
	Phosphorus - P		mg/Kg DS	18900	17450	17100	8308	6645	18550	6645	18900	14492.17	5500.30
	Phosphorus - P		% m/m	1.89%	1.75%	1.71%	0.83%	0.66%	1.86%	0.665%	1.890%	1.45%	0.55%
	Potassium - K		mg/Kg DS	1356	1345	1332	1250	710	1217	710	1356	1201.67	247.25
	Potassium - K		% m/m	0.136%	0.135%	0.133%	0.13%	0.071%	0.122%	0.071%	0.136%	0%	0.02%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	142	152	185				142	185	159.67	2250.19
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	25	34	21	4	4	4	4	34	15.33	1310.98
	Cadmium		mg/kg DS	0	0	0	2	2	2	0	2	1.00	109.54
	Chromium		mg/kg DS	67	47	50	29	22	37	22	67	42.00	1617.41
	Copper		mg/kg DS	154	149	146	181	100	107	100	181	139.50	3059.90
	lead		mg/kg DS	23	8	8	22	15.6	28	8	28	17.43	830.46
	Mercury		mg/kg DS	6.5	8.75	9.75	15.87	8.09	24.72	6.5	24.72	12.28	689.16
	Nickle		mg/kg DS	22	14	43	11.1	8.45	14.1	8.45	43	18.78	1270.76
	Zinc		mg/kg DS	704	694	680	352	262	483	262	704	529.17	19255.38
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	70.15	144.77	1054.54	94000	840000	3300	70.15	840000	156428.24	33693597.49
	Viable Helminth		Ova/gm DW	16.99	22.04	23.66	0	1	1	0	23.66	10.78	1130.27
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Hillcrest WWTW	
WWTW AREA:	Inland Area	
SLUDGE SOURCE:	Drying Bids	

				OBSERVED VALUES											ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 28/03/2007) (Drying Beds Feed)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Drying Beds-1)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Drying Beds-2)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day															
	Primary Sludge		kg DS/day													
	Secondary Sludge		kg DS/day													
	Tertiary Sludge		kg DS/day													
	Thickened Sludge		kg DS/day													
	Dewatered Sludge		kg DS/day													
	Physical Characteristics															
	Colour		Hazan													
	Odour															
	Specific Gravity															
	Moisture content		% m/m	91.01%	90.52%	90.03%							90.03%	91.01%	90.52%	0.49%
	Drainability		Time to dry													
	Fuel value (thermal content)		Kj/Kg DS													
	Compressibility															
	Viscosity		Kg/m sec													
	Specific Resistance		S^2/g													
	Chemical Characteristics															
COMPU-LSORY	pH			5.5	5.5	6.7	8.6	8.6	8.2	7	7	7.4	5.5	8.6	7.17	1.18
	Total Dry Solids		% m/m	8.99%	9.48%	9.97%							8.99%	9.97%	9.48%	0.49%
	Volatile solids		% m/m	80.18%	73.38%	74.20%							73.38%	80.18%	75.92%	3.71%
	Fixed Solid content		% m/m	19.82%	26.62%	25.80%							19.82%	26.62%	24.08%	3.71%
	Alkalinity ($CaCO_3$)		mg/l													
	COD		mg/l													
	BOD		mg/l													
	SOUR		mg/hr/gm													
	Grease and Fats		% m/m													
	Protein		% m/m													
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	68000	68000	78000	6400	6900	7500	7900	8200	9300	6400	78000	28911.11	31957.57
	Total Nitrogen - N		% m/m	6.80%	6.80%	7.80%	0.64%	0.69%	0.75%	0.79%	0.82%	0.93%	0.64%	7.80%	3%	3.20%
	Phosphorus - P		mg/Kg DS	10250	7650	9750	2852	1943	1426	2068	1930	2450	1426	10250	4479.89	3639.53
	Phosphorus - P		% m/m	1.03%	0.77%	0.98%	0.29%	0.19%	0.14%	0.21%	0.19%	0.25%	0.143%	1.025%	0.45%	0.36%
	Potassium - K		mg/Kg DS	4710	4546	4909	308	234	168	607	576	625	168	4909	1853.67	2159.06
	Potassium - K		% m/m	0.471%	0.455%	0.491%	0.03%	0.02%	0.02%	0.06%	0.058%	0.063%	0.017%	0.491%	0%	0.22%
	Potash (K_2O)		% m/m													
	Cellulose		% m/m													
	Volatile Acids		mg/l	176	126	185							126	185	162.33	3178.57
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS													
	METALS															
COMPULSORY	Arsenic		mg/kg DS	7	12	33	4	4	4	4	4	4	4	33	8.44	959.31
	Cadmium		mg/kg DS	0	0	0	2	3.1	2	2	2	2	0	3.1	1.46	114.79
	Chromium		mg/kg DS	29	34	19	12.8	26	12.5	9.57	9.52	10.1	9.52	34	18.05	938.52
	Copper		mg/kg DS	415	406	372	76	37	22	13.5	13.1	23	13.1	415	153.07	18476.07
	lead		mg/kg DS	16	19	13	3	38	3	3	3	3.14	3	38	11.24	1193.35
	Mercury		mg/kg DS	4.75	6.25	5.5	3.3	2.23	3.12	1.34	1.04	0.782	0.782	6.25	3.15	199.68
	Nickle		mg/kg DS	27	28	22	7	8	6.25	5.44	5.37	5.59	5.37	28	12.74	986.30
	Zinc		mg/kg DS	596	604	554	91	64	36	31	32	42	31	604	227.78	26866.00
RECOMMENDED	Antimony		mg/kg DS													
	Boron		mg/kg DS													
	Barium		mg/kg DS													
	Berylium		mg/kg DS													
	Cobalt		mg/kg DS													
	Manganese		mg/kg DS													
	Molybdenum		mg/kg DS													
	Selenium		mg/kg DS													
	Strontium		mg/kg DS													
	Thallium		mg/kg DS													
	Vanadium		mg/kg DS													
	Iron		mg/kg DS													
	Tin		mg/kg DS													
	Aluminum		mg/kg DS													
	Magnesium		mg/kg DS													
	Sodium		mg/kg DS													
	Sulpher		mg/kg DS													
	Biological Characteristics															
COMPU-LSORY	Fecal coliform		CFU/gm DS	890.21	52.73	50.15	0	0	40	210000	11100	19860	0	210000	26888.12	6902145.45
	Viable Helminth		Ova/gm DW	1.65	2.1	1.22	8	5	2000	10	2	7	1.22	2000	226.33	66513.37
	Total colifom		CFU/gm DS													
	Fecal streptococci		Number/gm DS													
	Salmonella sp.		Number/gm DS													
	Shigella sp.		Number/gm DS													
	Pseudomonas aeruginosa		Number/gm DS													
	Enteric virus		Number/gm DS													
	Parasite ova/cysts		Number/gm DS													

PLANT NAME: KwaNdengezi WWTW
WWTW AREA: Inland Area
SLUDGE SOURCE: Drying Beds

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 02/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	50.41%	76.66%	73.38%	72%	75%	60%	50.41%	76.66%	67.91%	10.41%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.8	6.8	6.8	8	7.8	7.9	6.8	8	7.35	0.61
	Total Dry Solids		% m/m	49.59%	23.34%	26.62%	28.00%	25.00%	40.00%	23.34%	49.59%	32.09%	10.41%
	Volatile solids		% m/m	38.31%	48.03%	44.80%				38.31%	48.03%	43.71%	4.95%
	Fixed Solid content		% m/m	61.69%	51.97%	55.20%				51.97%	61.69%	56.29%	4.95%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	26000	28000	29000	7900	6300	7700	6300	29000	17483.33	11210.61
	Total Nitrogen - N		% m/m	2.60%	2.80%	2.90%	0.79%	0.63%	0.77%	0.63%	2.90%	2%	1.12%
	Phosphorus - P		mg/Kg DS				1942	6082	3737	1942	6082	3920.33	2076.08
	Phosphorus - P		% m/m	0.00%	0.00%	0.00%	0.19%	0.61%	0.37%	0.000%	0.608%	0.20%	0.25%
	Potassium - K		mg/Kg DS	759	956	307	324	1084	580	307	1084	668.33	322.70
	Potassium - K		% m/m	0.076%	0.096%	0.031%	0.03%	0.108%	0.058%	0.031%	0.108%	0%	0.03%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	269	268	270				268	270	269.00	100.00
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	71	0	9	4	4	4	0	71	15.33	2742.02
	Cadmium		mg/kg DS	32	31	47	2	2	2	2	47	19.33	1981.58
	Chromium		mg/kg DS	51	56	47	12.6	23	14.1	12.6	56	33.95	1958.04
	Copper		mg/kg DS	117	136	102	356	69	46	46	356	137.67	11179.39
	lead		mg/kg DS	53	60	47	8.84	22	13.3	8.84	60	34.02	2196.14
	Mercury		mg/kg DS	12.06	13.24	10.06	0.64	0.8	0.88	0.64	13.24	6.28	611.78
	Nickle		mg/kg DS	43	10	14	6.17	9.24	7.39	6.17	43	14.97	1399.32
	Zinc		mg/kg DS	352	440	325	262	281	196	196	440	309.33	8369.87
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	0	0	0	7900	112	6000	0	7900	2335.33	362490.97
	Viable Helminth		Ova/gm DW	4.96	3.65	4.36	2	4	0	0	4.96	3.16	184.16
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Dassenhoek WWTW
WWTW AREA: Inland Area
SLUDGE SOURCE: Drying Beds

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 03/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m				5%	1%	2%	1.00%	5.00%	2.67%	2.08%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6	5.9	5.9	6.9	6.8	6.6	5.9	6.9	6.35	0.47
	Total Dry Solids		% m/m				95.00%	99.00%	98.00%	95.00%	99.00%	97.33%	2.08%
	Volatile solids		% m/m							0.00%	0.00%		
	Fixed Solid content		% m/m							0.00%	0.00%		
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	49000	50000	49000	34000	36000	35000	34000	50000	42166.67	7884.58
	Total Nitrogen - N		% m/m	4.90%	5.00%	4.90%	3.40%	3.60%	3.50%	3.40%	5.00%	4%	0.79%
	Phosphorus - P		mg/Kg DS	6400	6600	8200	17310	15920	5741	5741	17310	10028.50	5184.14
	Phosphorus - P		% m/m	0.64%	0.66%	0.82%	1.73%	1.59%	0.57%	0.574%	1.731%	1.00%	0.52%
	Potassium - K		mg/Kg DS	2008	1602	1418	1145	1151	1364	1145	2008	1448.00	324.13
	Potassium - K		% m/m	0.201%	0.160%	0.142%	0.11%	0.115%	0.136%	0.115%	0.201%	0%	0.03%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	83.5	83.2	75.1				75.1	83.5	80.60	476.55
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	6.72	6.67	4	0	6.72	2.90	332.40
	Cadmium		mg/kg DS	32	30	30	2	4.1	2	2	32	16.68	1535.45
	Chromium		mg/kg DS	56	56	67	38	43	28	28	67	48.00	1424.08
	Copper		mg/kg DS	190	184	145	216	212	264	145	264	201.83	3964.05
	lead		mg/kg DS	88	86	76	50	66	30	30	88	66.00	2252.11
	Mercury		mg/kg DS	42.92	11.8	20.98	1.54	1.01	0.78	0.78	42.92	13.17	1664.07
	Nickle		mg/kg DS	38	35	42	22	23	13	13	42	28.83	1119.67
	Zinc		mg/kg DS	729	672	508	822	712	500	500	822	657.17	12845.92
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	225000	205000	255000	2	2	4	2	255000	114168.00	12607062.04
	Viable Helminth		Ova/gm DW	26.63	36.01	32.89	0	0	0	0	36.01	15.92	1770.10
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Fredville WWTW
WWTW AREA:	Inland Area
SLUDGE SOURCE:	Lagoon

				OBSERVED VALUES								ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 03/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	59.44%	62.32%	64.82%				59.44%	64.82%	62.19%	2.69%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.3	6.3	6.2	8.2	8.5	8.3	6.2	8.5	7.30	1.14
	Total Dry Solids		% m/m	40.56%	37.68%	35.18%				35.18%	40.56%	37.81%	2.69%
	Volatile solids		% m/m	45.80%	46.67%	45.40%				45.40%	46.67%	45.96%	0.65%
	Fixed Solid content		% m/m	54.20%	53.33%	54.60%				53.33%	54.60%	54.04%	0.65%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				599	181	518	181	599	432.67	221.68
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	33000	29000	31000	4300	7600	12000	4300	33000	19483.33	12912.38
	Total Nitrogen - N		% m/m	3.30%	2.90%	3.10%	0.43%	0.76%	1.20%	0.43%	3.30%	2%	1.29%
	Phosphorus - P		mg/Kg DS	4850	3050	4200	2066	1748	3468	1748	4850	3230.33	1200.46
	Phosphorus - P		% m/m	0.49%	0.31%	0.42%	0.21%	0.17%	0.35%	0.175%	0.485%	0.32%	0.12%
	Potassium - K		mg/Kg DS	2435	2990	1418	477	231	485	231	2990	1339.33	1151.81
	Potassium - K		% m/m	0.244%	0.299%	0.142%	0.05%	0.023%	0.049%	0.023%	0.299%	0%	0.12%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	236	209	198				198	236	214.33	1955.33
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	31	32	31	2	2	2	2	32	16.67	1607.07
	Chromium		mg/kg DS	72	74	54	10.3	11.7	14.2	10.3	74	39.37	3073.18
	Copper		mg/kg DS	153	168	191	14.4	88	34	14.4	191	108.07	7368.98
	lead		mg/kg DS	71	83	86	3	4.68	8.28	3	86	42.66	4124.61
	Mercury		mg/kg DS	24.02	13	11.68	0.347	1.12	2.99	0.347	24.02	8.86	918.43
	Nickle		mg/kg DS	44	25	74	6.16	6.86	8.2	6.16	74	27.37	2718.29
	Zinc		mg/kg DS	541	557	656	60	85	138	60	656	339.50	27260.72
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	36.98	358.32	0	50000	2260	1900	0	50000	9092.55	2006390.08
	Viable Helminth		Ova/gm DW	4.71	5.62	4.62	1	3	44	1	44	10.49	1649.64
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Phoenix WWTW
WWTW AREA: Northen Costal Area
SLUDGE SOURCE: Belt Press

		REMARKS	UNIT	OBSERVED VALUES														ESTIMATES	
				File : Result of testing 3 (Sample Date: 10/04/2007) (Belt Press - Digested Sludge)			File : Result of testing 3 (Sample Date: 10/04/2007) (Belt Press - WAS)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Belt Press - Digested Sludge)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Belt Press - WAS)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day																		
	Primary Sludge		kg DS/day																
	Secondary Sludge		kg DS/day																
	Tertiary Sludge		kg DS/day																
	Thickened Sludge		kg DS/day																
	Dewatered Sludge		kg DS/day																
	Physical Characteristics																		
	Colour		Hazan																
	Odour																		
	Specific Gravity																		
	Moisture content		%m/m	80.54%	79.50%	75.54%	90.46%	90.10%	89.90%							75.54%	90.46%	84.34%	6.59%
	Drainability		Time to dry																
	Fuel value (thermal content)		Kj/Kg DS																
	Compressibility																		
	Viscosity		Kg/m sec																
	Specific Resistance		S^2/g																
	Chemical Characteristics																		
COMPU-LSORY	pH			6.7	6.8	6.8	6.3	6.4	6.4	7.5	7.3	7.6	6.4	5.2	5.5	5.2	7.6	6.58	0.72
	Total Dry Solids		%m/m	19.46%	20.50%	24.46%	9.54%	9.90%	10.10%							9.54%	24.46%	15.66%	6.59%
	Volatile solids		%m/m	58.68%	59.02%	60.54%	78.20%	78.38%	76.63%							58.68%	78.38%	68.58%	10.07%
	Fixed Solid content		%m/m	41.32%	40.98%	39.46%	21.80%	21.62%	23.37%							21.62%	41.32%	31.43%	10.07%
	Alkalinity ($CaCO_3$)		mg/l																
	COD		mg/l																
	BOD		mg/l																
	SOUR		mg/hr/gm										58	43	39			46.67	10.02
	Grease and Fats		%m/m																
	Protein		%m/m																
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	45000	42000	46000	92000	86000	84000	8800	1600	1300	1000	1000	1000	1000	92000	34141.67	36826.19
	Total Nitrogen - N		%m/m	4.50%	4.20%	4.60%	9.20%	8.60%	8.40%	0.88%	0.16%	0.13%	0.10%	0.10%	0.10%	0.10%	9.20%	3%	3.68%
	Phosphorus - P		mg/Kg DS	6950	6600	6250	12500	8900	13550	2692	640	797	688	545	720	545	13550	5069.33	4778.65
	Phosphorus - P		%m/m	0.70%	0.66%	0.63%	1.25%	0.89%	1.36%	0.27%	0.06%	0.08%	0.07%	0.05%	0.07%	0.055%	1.355%	0.51%	0.48%
	Potassium - K		mg/Kg DS	3069	0	0	6323	3876	10235	214	86	101	139	116	154	0	10235	2026.08	3303.41
	Potassium - K		%m/m	0.307%	0.000%	0.000%	0.632%	0.388%	1.024%	0.02%	0.01%	0.01%	0.01%	0.012%	0.015%	0.000%	1.024%	0%	0.33%
	Potash (K_2O)		%m/m																
	Cellulose		%m/m																
	Volatile Acids		mg/l	236	209	198	167	167	131							131	236	184.67	3717.35
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS																
	METALS																		
COMPULSORY	Arsenic		mg/kg DS	0	0	0	0	0	0	4	4	4	4	4	4	0	4	2.00	208.89
	Cadmium		mg/kg DS	29	30	31	44	30	30	2	2	2	2	2	2	2	44	17.17	1630.86
	Chromium		mg/kg DS	60	44	44	44	302	51	15.8	8.2	9.12	7.61	6.97	7.72	6.97	302	50.04	8187.41
	Copper		mg/kg DS	229	203	211	160	128	162	94	22	22	49	10.4	17	10.4	229	108.95	8342.66
	lead		mg/kg DS	79	51	80	46	39	47	11.1	3	3	3	3	3	3	80	30.68	3009.79
	Mercury		mg/kg DS	0.467	1.184	0.668	6.81	11.36	0.375	1.01	0.24	0.61	0.2	0.78	0.48	0.2	11.36	2.02	345.39
	Nickle		mg/kg DS	45	10	37	49	166	30	7.5	4.31	4.72	4.09	3.67	4.9	3.67	166	30.52	4605.11
	Zinc		mg/kg DS	620	602	598	267	220	252	196	35	43	24	7.74	11.8	7.74	620	239.71	24127.05
RECOMMENDED	Antimony		mg/kg DS																
	Boron		mg/kg DS																
	Barium		mg/kg DS																
	Berylium		mg/kg DS																
	Cobalt		mg/kg DS																
	Manganese		mg/kg DS																
	Molybdenum		mg/kg DS																
	Selenium		mg/kg DS																
	Strontium		mg/kg DS																
	Thallium		mg/kg DS																
	Vanadium		mg/kg DS																
	Iron		mg/kg DS																
	Tin		mg/kg DS																
	Aluminum		mg/kg DS																
	Magnesium		mg/kg DS																
	Sodium		mg/kg DS																
	Sulpher		mg/kg DS																
	Biological Characteristics																		
COMPU-LSORY	Fecal coliform		CFU/gm DS	3597.12	1951.22	5718.95	4192.87	1313.31	1138.61	8600	810000	49000	4300000	60000000	840000	1138.61	60000000	5502126.01	1720616580.26
	Viable Helminth		Ova/gm DW	5.71	4.78	4.63	1.77	2.33	2.56	0	2	0	13	22	6	0	22	5.40	629.07
	Total colifom		CFU/gm DS																
	Fecal streptococci		Number/gm DS																
	Salmonella sp.		Number/gm DS																
	Shigella sp.		Number/gm DS																
	Pseudomonas aeruginosa		Number/gm DS																
	Enteric virus		Number/gm DS																
	Parasite ova/cysts		Number/gm DS																

PLANT NAME:	Umhlanga WWTW
WWTW AREA:	Northen Costal Area
SLUDGE SOURCE:	WAS / Centrefuge

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 11/04/2007) (Centrefuge)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (WAS)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	90.58%	90.44%	90.50%				90.44%	90.58%	90.51%	0.07%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.1	6.1	6.1	6.7	6.6	6.6	6.1	6.7	6.37	0.29
	Total Dry Solids		% m/m	9.42%	9.56%	9.50%				9.42%	9.56%	9.49%	0.07%
	Volatile solids		% m/m	79.41%	79.71%	79.58%				79.41%	79.71%	79.57%	0.15%
	Fixed Solid content		% m/m	20.59%	20.29%	20.42%				20.29%	20.59%	20.43%	0.15%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				37			37	37	37.00	
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	76000	76000	71000	0.01	0.01	0.01	0.01	76000	37166.67	40754.95
	Total Nitrogen - N		% m/m	7.60%	7.60%	7.10%	0.00%	0.00%	0.00%	0.00%	7.60%	4%	4.08%
	Phosphorus - P		mg/Kg DS	6950	6900	6350	446	307	349	307	6950	3550.33	3493.44
	Phosphorus - P		% m/m	0.70%	0.69%	0.64%	0.04%	0.03%	0.03%	0.031%	0.695%	0.36%	0.35%
	Potassium - K		mg/Kg DS	3370	4365	3173	101	47	55	47	4365	1851.83	1995.88
	Potassium - K		% m/m	0.337%	0.437%	0.317%	0.01%	0.005%	0.006%	0.005%	0.437%	0%	0.20%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	307	361	377				307	377	348.33	3667.88
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS							0	0		
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	31	30	31	2	2	2	2	31	16.33	1570.56
	Chromium		mg/kg DS	44	50	50	10.3	8.44	9.86	8.44	50	28.77	2119.16
	Copper		mg/kg DS	269	247	247	24	4.39	5.91	4.39	269	132.88	13346.26
	lead		mg/kg DS	53	58	43	4.81	3	3	3	58	27.47	2659.35
	Mercury		mg/kg DS	2.113	1.152	34.11	0.2	0.2	0.44	0.2	34.11	6.37	1361.00
	Nickle		mg/kg DS	37	36	61	4.51	4.98	4.9	4.51	61	24.73	2360.18
	Zinc		mg/kg DS	462	414	473	16.2	3.3	4.33	3.3	473	228.81	24279.65
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	18046.71	3138.08	1052.63	2100000	1900000	2900000	1052.63	2900000	1153706.24	129954670.22
	Viable Helminth		Ova/gm DW	10.71	8.96	10.28	0	20	22	0	22	11.99	802.33
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME:	Umdloti WWTW
WWTW AREA:	Northen Costal Area
SLUDGE SOURCE:	Drying Beds/WAS

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 11/04/2007) (WAS)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Drying Beds)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m				72%	66%	79%	66.00%	79.00%	72.33%	6.51%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.1	6.1	6	7.2	7.9	7.8	6	7.9	6.85	0.89
	Total Dry Solids		% m/m				28.00%	34.00%	21.00%	21.00%	34.00%	27.67%	6.51%
	Volatile solids		% m/m										
	Fixed Solid content		% m/m										
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				42	36	37	36	42	38.33	3.21
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	71000	70000	66000	100000	7700	7600	7600	100000	53716.67	37685.99
	Total Nitrogen - N		% m/m	7.10%	7.00%	6.60%	10.00%	0.77%	0.76%	0.76%	10.00%	5%	3.77%
	Phosphorus - P		mg/Kg DS	5350	5600	5600	5944	6590	4036	4036	6590	5520.00	844.82
	Phosphorus - P		% m/m	0.54%	0.56%	0.56%	0.59%	0.66%	0.40%	0.404%	0.659%	0.55%	0.08%
	Potassium - K		mg/Kg DS	2067	2059	1730	834	779	555	555	2067	1337.33	690.58
	Potassium - K		% m/m	0.207%	0.206%	0.173%	0.08%	0.078%	0.056%	0.056%	0.207%	0%	0.07%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	118	94.5	108				94.5	118	106.83	1179.34
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	31	30	30	2	2	2	2	31	16.17	1552.31
	Chromium		mg/kg DS	86	49	50	17.5	20	17.1	17.1	86	39.93	2730.43
	Copper		mg/kg DS	276	229	236	100	138	188	100	276	194.50	6590.83
	lead		mg/kg DS	70	86	69	6.89	7.89	5.67	5.67	86	40.91	3783.63
	Mercury		mg/kg DS	39.49	4.73	4.1	0.65	0.55	0.68	0.55	39.49	8.37	1536.11
	Nickle		mg/kg DS	61	29	25	11	12.8	11	11	61	24.97	1925.01
	Zinc		mg/kg DS	735	623	576	201	270	234	201	735	439.83	23128.63
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	165000	240000	330000	940	6040	620	620	330000	123766.67	14272604.73
	Viable Helminth		Ova/gm DW	5.12	4.66	3.15	2	2	0	0	5.12	2.82	190.17
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Verulam WWTW
WWTW AREA: Northen Costal Area
SLUDGE SOURCE: Screw Press/Drying Beds/Belt press

		REMARKS	UNIT	OBSERVED VALUES														ESTIMATES	
				File : Result of testing 3 (Sample Date: 11/04/2007) (Belt Press)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Screw Press - Digested Sludge)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Screw Press- WAS)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019) (Drying Beds)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day																		
	Primary Sludge		kg DS/day																
	Secondary Sludge		kg DS/day																
	Tertiary Sludge		kg DS/day																
	Thickened Sludge		kg DS/day																
	Dewatered Sludge		kg DS/day																
	Physical Characteristics																		
	Colour		Hazan																
	Odour																		
	Specific Gravity																		
	Moisture content		% m/m	88.46%	89.88%	89.24%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	8%	7%	8%	7.00%	100.00%	74.22%	40.40%
	Drainability		Time to dry																
	Fuel value (thermal content)		Kj/Kg DS																
	Compressibility																		
	Viscosity		Kg/m sec																
	Specific Resistance		S^2/g																
	Chemical Characteristics																		
COMPU-LSORY	pH			7	7	6.8							7.9	7.3	7.4	6.8	7.9	7.23	0.39
	Total Dry Solids		% m/m	11.54%	10.12%	10.76%							92.00%	93.00%	92.00%	10.12%	93.00%	51.57%	44.66%
	Volatile solids		% m/m	63.60%	64.03%	63.94%										63.60%	64.03%	63.86%	0.23%
	Fixed Solid content		% m/m	36.40%	35.97%	36.06%										35.97%	36.40%	36.14%	0.23%
	Alkalinity ($CaCO_3$)		mg/l																
	COD		mg/l																
	BOD		mg/l																
	SOUR		mg/hr/gm										800	1275	1148			1074.33	245.92
	Grease and Fats		% m/m																
	Protein		% m/m																
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	56000	47000	47000							8800	20000	32000	8800	56000	35133.33	18162.23
	Total Nitrogen - N		% m/m	5.60%	4.70%	4.70%							0.88%	2.00%	3.20%	0.88%	5.60%	4%	1.82%
	Phosphorus - P		mg/Kg DS	6950	7050	6750							8233	8169	8044	6750	8233	7532.67	684.38
	Phosphorus - P		% m/m	0.70%	0.71%	0.68%							0.82%	0.82%	0.80%	0.675%	0.823%	0.75%	0.07%
	Potassium - K		mg/Kg DS	45	577	0							992	1305	1361	0	1361	713.33	603.54
	Potassium - K		% m/m	0.005%	0.058%	0.000%							0.10%	0.131%	0.136%	0.000%	0.136%	0%	0.06%
	Potash (K_2O)		% m/m																
	Cellulose		% m/m																
	Volatile Acids		mg/l	209	210	186										186	210	201.67	1357.69
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										1.25	1.25	1.25	1.25	1.25	1.25	0.00
	METALS																		
COMPULSORY	Arsenic		mg/kg DS	0	0	0							4.71	4	4	0	4.71	2.12	233.50
	Cadmium		mg/kg DS	31	31	31							2	2	2	2	31	16.50	1588.40
	Chromium		mg/kg DS	69	69	59							33	33	30	30	69	48.83	1882.99
	Copper		mg/kg DS	268	263	219							160	148	153	148	268	201.83	5558.21
	lead		mg/kg DS	84	81	87							35	36	30	30	87	58.83	2770.86
	Mercury		mg/kg DS	0.028	0.135	0.36							1.09	1.09	0.9	0.028	1.09	0.60	48.40
	Nickle		mg/kg DS	21	15	26							16.4	15.6	15.1	15	26	18.18	443.91
	Zinc		mg/kg DS	667	784	693							351	321	337	321	784	525.50	21104.67
RECOMMENDED	Antimony		mg/kg DS																
	Boron		mg/kg DS																
	Barium		mg/kg DS																
	Berylium		mg/kg DS																
	Cobalt		mg/kg DS																
	Manganese		mg/kg DS																
	Molybdenum		mg/kg DS																
	Selenium		mg/kg DS																
	Strontium		mg/kg DS																
	Thallium		mg/kg DS																
	Vanadium		mg/kg DS																
	Iron		mg/kg DS																
	Tin		mg/kg DS																
	Aluminum		mg/kg DS																
	Magnesium		mg/kg DS																
	Sodium		mg/kg DS																
	Sulpher		mg/kg DS																
	Biological Characteristics																		
COMPU-LSORY	Fecal coliform		CFU/gm DS	1516.46	1136.36	1301.12							310	10	850	10	1516.46	853.99	58767.08
	Viable Helminth		Ova/gm DW	14.92	16.24	13.9							0	0	0	0	16.24	7.51	826.02
	Total colifom		CFU/gm DS																
	Fecal streptococci		Number/gm DS																
	Salmonella sp.		Number/gm DS																
	Shigella sp.		Number/gm DS																
	Pseudomonas aeruginosa		Number/gm DS																
	Enteric virus		Number/gm DS																
	Parasite ova/cysts		Number/gm DS																

PLANT NAME: Tongaat Central WWTW
WWTW AREA: Northen Costal Area
SLUDGE SOURCE: Screw Press

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 12/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	87.50%	87.06%	86.86%				86.86%	87.50%	87.14%	0.33%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.1	6.1	6.1	7.4	7.4	7.6	6.1	7.6	6.78	0.75
	Total Dry Solids		% m/m	12.50%	12.94%	13.14%				12.50%	13.14%	12.86%	0.33%
	Volatile solids		% m/m	50.40%	50.54%	50.53%				50.40%	50.54%	50.49%	0.08%
	Fixed Solid content		% m/m	49.60%	49.46%	49.47%				49.46%	49.60%	49.51%	0.08%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				128	162	811	128	811	367.00	384.89
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	41000	43000	43000	8900	7800	4400	4400	43000	24683.33	19405.20
	Total Nitrogen - N		% m/m	4.10%	4.30%	4.30%	0.89%	0.78%	0.44%	0.44%	4.30%	2%	1.94%
	Phosphorus - P		mg/Kg DS	5750	6050	6000	1204	5788	1340	1204	6050	4355.33	2391.55
	Phosphorus - P		% m/m	0.58%	0.61%	0.60%	0.12%	0.58%	0.13%	0.120%	0.605%	0.44%	0.24%
	Potassium - K		mg/Kg DS	2012	1986	2100	573	1600	690	573	2100	1493.50	690.44
	Potassium - K		% m/m	0.201%	0.199%	0.210%	0.06%	0.160%	0.069%	0.057%	0.210%	0%	0.07%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	99.1	90.4	117				90.4	117	102.17	1356.26
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.06	0.06	0.06	0.06	0.06	0.06	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	30	30	30	2	2	2	2	30	16.00	1533.62
	Chromium		mg/kg DS	38	38	38	10.6	26	10.3	10.3	38	26.82	1350.30
	Copper		mg/kg DS	94	89	90	33	84	34	33	94	70.67	2896.66
	lead		mg/kg DS	42	29	58	5.61	10.8	5.35	5.35	58	25.13	2171.47
	Mercury		mg/kg DS	6.41	4.11	9.49	0.25	1.28	0.41	0.25	9.49	3.66	373.12
	Nickle		mg/kg DS	47	40	43	5.9	8.3	6.1	5.9	47	25.05	2016.88
	Zinc		mg/kg DS	318	344	330	55	130	59	55	344	206.00	13939.15
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	1320	1622.87	1103.5	48800	72000	9300	1103.5	72000	22357.73	3052315.75
	Viable Helminth		Ova/gm DW	11.66	13.55	13.24	3	0	4	0	13.55	7.58	592.57
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Genazzano WWTW
WWTW AREA: Northen Costal Area
SLUDGE SOURCE: Drying Beds

				OBSERVED VALUES								ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 12/04/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	50.34%	57.94%	54.46%	38%	41%	26%	26.00%	57.94%	44.62%	11.92%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			6.2	6.2	6.3	7.1	7	7	6.2	7.1	6.63	0.44
	Total Dry Solids		% m/m	49.66%	42.06%	45.54%	62.00%	59.00%	74.00%	42.06%	74.00%	55.38%	11.92%
	Volatile solids		% m/m	54.33%	48.64%	47.43%				47.43%	54.33%	50.13%	3.68%
	Fixed Solid content		% m/m	45.67%	51.36%	52.57%				45.67%	52.57%	49.87%	3.68%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				194	127	733	127	733	351.33	332.23
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	51000	40000	27000	20000	5300	13000	5300	51000	26050.00	17061.51
	Total Nitrogen - N		% m/m	5.10%	4.00%	2.70%	2.00%	0.53%	1.30%	0.53%	5.10%	3%	1.71%
	Phosphorus - P		mg/Kg DS	4550	4200	5500	5628	7045	7554	4200	7554	5746.17	1330.51
	Phosphorus - P		% m/m	0.46%	0.42%	0.55%	0.56%	0.70%	0.76%	0.420%	0.755%	0.57%	0.13%
	Potassium - K		mg/Kg DS	2899	1361	6603	474	625	648	474	6603	2101.67	2382.83
	Potassium - K		% m/m	0.290%	0.136%	0.660%	0.05%	0.063%	0.065%	0.047%	0.660%	0%	0.24%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	85.4	77.2	77.4				77.2	85.4	80.00	467.76
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS										
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	30	29	30	2	2	2	2	30	15.83	1515.81
	Chromium		mg/kg DS	46	89	85	44	52	54	44	89	61.67	2000.67
	Copper		mg/kg DS	177	185	162	114	175	180	114	185	165.50	2637.23
	lead		mg/kg DS	59	64	55	28	34	36	28	64	46.00	1511.29
	Mercury		mg/kg DS	4.73	3.51	9.49	1.71	2.27	2.11	1.71	9.49	3.97	292.29
	Nickle		mg/kg DS	6	0	5	10.2	11.3	11.5	0	11.5	7.33	452.36
	Zinc		mg/kg DS	506	578	494	54	84	81	54	578	299.50	24999.50
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	9464.36	14978.6	15151.52	0	280	280	0	15151.52	6692.41	741522.15
	Viable Helminth		Ova/gm DW	18.47	12.94	15.42	0	1	0	0	18.47	7.97	855.66
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: Northern WWTW
WWTW AREA: Lower Umgeni Area
SLUDGE SOURCE: Belt Press

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 26/02/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	78.07%	78.98%	79.51%				78.07%	79.51%	78.85%	0.73%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			7.6	7.5	7.7	6.7	6.6	6.7	6.6	7.7	7.13	0.52
	Total Dry Solids		% m/m	21.93%	21.02%	20.49%				20.49%	21.93%	21.15%	0.73%
	Volatile solids		% m/m	57.95%	59.99%	59.84%				57.95%	59.99%	59.26%	1.14%
	Fixed Solid content		% m/m	42.05%	40.01%	40.16%				40.01%	42.05%	40.74%	1.14%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	41000	43000	42000	21000	11000	11000	11000	43000	28166.67	15600.21
	Total Nitrogen - N		% m/m	4.10%	4.30%	4.20%	2.10%	1.10%	1.10%	1.10%	4.30%	3%	1.56%
	Phosphorus - P		mg/Kg DS	5600	4650	4950	3320	2776	2680	2680	5600	3996.00	1231.90
	Phosphorus - P		% m/m	0.56%	0.47%	0.50%	0.33%	0.28%	0.27%	0.268%	0.560%	0.40%	0.12%
	Potassium - K		mg/Kg DS	1214	1412	1457	706	550	493	493	1457	972.00	439.47
	Potassium - K		% m/m	0.121%	0.141%	0.146%	0.07%	0.055%	0.049%	0.049%	0.146%	0%	0.04%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	294	294	259				259	294	282.33	2020.73
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.05	0.05	0.05	0.05	0.05	0.05	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	0	0	0	4	4	4	0	4	2.00	219.09
	Cadmium		mg/kg DS	18	17	17	2	2	2	2	18	9.67	840.63
	Chromium		mg/kg DS	98.3	96	101	11.1	11.6	9.86	9.86	101	54.64	4799.90
	Copper		mg/kg DS	273	342	364	43	36	56	36	364	185.67	15712.25
	lead		mg/kg DS	29	36	36	5.4	5.71	5.2	5.2	36	19.55	1567.29
	Mercury		mg/kg DS	9.9	9.08	3.57	0.23	0.31	0.2	0.2	9.9	3.88	453.84
	Nickle		mg/kg DS	66	46	51	5.77	6.19	5.13	5.13	66	30.02	2744.28
	Zinc		mg/kg DS	2182	2348	2168	213	172	171	171	2348	1209.00	112325.95
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	50.17	66.62	43.92	19100	9860	141400	43.92	141400	28420.12	5587446.60
	Viable Helminth		Ova/gm DW	1.43	1.83	1.72	4	0	0	0	4	1.50	147.73
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: KwaMashus WWTW
WWTW AREA: Lower Umgeni Area
SLUDGE SOURCE: Belt Press

				OBSERVED VALUES								ESTIMATES	
		REMARKS	UNIT	File : Result of testing 3 (Sample Date: 27/02/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	79.97%	78.75%	81.54%				78.75%	81.54%	80.09%	1.40%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			7.7	7.8	7.7	7.1	7	7.1	7	7.8	7.40	0.37
	Total Dry Solids		% m/m	20.03%	21.25%	18.46%				18.46%	21.25%	19.91%	1.40%
	Volatile solids		% m/m	61.23%	59.14%	61.82%				59.14%	61.82%	60.73%	1.41%
	Fixed Solid content		% m/m	38.77%	40.86%	38.18%				38.18%	40.86%	39.27%	1.41%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm										
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	43000	40000	48000	3800	4400	4000	3800	48000	23866.67	21840.76
	Total Nitrogen - N		% m/m	4.30%	4.00%	4.80%	0.38%	0.44%	0.40%	0.38%	4.80%	2%	2.18%
	Phosphorus - P		mg/Kg DS	7800	5900	7200	2301	3099	1566	1566	7800	4644.33	2661.64
	Phosphorus - P		% m/m	0.78%	0.59%	0.72%	0.23%	0.31%	0.16%	0.157%	0.780%	0.46%	0.27%
	Potassium - K		mg/Kg DS	3321	3209	3349	212	268	164	164	3349	1753.83	1687.04
	Potassium - K		% m/m	0.332%	0.321%	0.335%	0.02%	0.027%	0.016%	0.016%	0.335%	0%	0.17%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	334	312	234				234	334	293.33	5254.84
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.09	0.09	0.09	0.09	0.09	0.09	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	16	31	1	4	4	4	1	31	10.00	1154.12
	Cadmium		mg/kg DS	19	19	17	2.75	2	2	2	19	10.29	884.37
	Chromium		mg/kg DS	266	65	169	21	16	11.4	11.4	266	91.40	10415.87
	Copper		mg/kg DS	279	232	226	41	56	25	25	279	143.17	11419.53
	lead		mg/kg DS	100	26	81	23	14.1	6.6	6.6	100	41.78	3881.57
	Mercury		mg/kg DS	5.81	8.25	10	1.01	0.72	0.55	0.55	10	4.39	419.59
	Nickle		mg/kg DS	148	16	43	6.55	5.89	4.51	4.51	148	37.33	5612.13
	Zinc		mg/kg DS	494	16	43	82	108	48	16	494	131.83	18030.69
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	14.98	9.41	27.08	220000	43000	67000	9.41	220000	55008.58	8553635.36
	Viable Helminth		Ova/gm DW	1.64	2.15	3.63	0	0	0	0	3.63	1.24	150.42
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

PLANT NAME: New Germany WWTW
WWTW AREA: Lower Umgeni Area
SLUDGE SOURCE: WAS

		REMARKS	UNIT	OBSERVED VALUES								ESTIMATES	
				File : Result of testing 3 (Sample Date: 28/02/2007)			Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019)			MIN.	MAX.	SUMMARY STATISTICS	
				Morning	Midday	Afternoon	Morning	Midday	Afternoon			Mean	Standard Deviation
	Quantity Kg/day												
	Primary Sludge		kg DS/day										
	Secondary Sludge		kg DS/day										
	Tertiary Sludge		kg DS/day										
	Thickened Sludge		kg DS/day										
	Dewatered Sludge		kg DS/day										
	Physical Characteristics												
	Colour		Hazan										
	Odour												
	Specific Gravity												
	Moisture content		% m/m	95.79%	98.50%	98.81%				95.79%	98.81%	97.70%	1.66%
	Drainability		Time to dry										
	Fuel value (thermal content)		Kj/Kg DS										
	Compressibility												
	Viscosity		Kg/m sec										
	Specific Resistance		S^2/g										
	Chemical Characteristics												
COMPU-LSORY	pH			5	6	6	7.1	7.4	7.2	5	7.4	6.45	0.94
	Total Dry Solids		% m/m	4.21%	1.50%	1.19%				1.19%	4.21%	2.30%	1.66%
	Volatile solids		% m/m	67.42%	71.64%	71.47%				67.42%	71.64%	70.18%	2.39%
	Fixed Solid content		% m/m	32.58%	28.36%	28.53%				28.36%	32.58%	29.82%	2.39%
	Alkalinity ($CaCO_3$)		mg/l										
	COD		mg/l										
	BOD		mg/l										
	SOUR		mg/hr/gm				149	53	104	53	149	102.00	48.03
	Grease and Fats		% m/m										
	Protein		% m/m										
COMPULSORY (NUTRIENTS)	Total Nitrogen - N		mg/Kg DS	37000	63000	63000	1000	1000	1000	1000	63000	27666.67	30715.90
	Total Nitrogen - N		% m/m	3.70%	6.30%	6.30%	0.10%	0.10%	0.10%	0.10%	6.30%	3%	3.07%
	Phosphorus - P		mg/Kg DS	6050	6500	6650	328	332	423	328	6650	3380.50	3313.76
	Phosphorus - P		% m/m	0.61%	0.65%	0.67%	0.03%	0.03%	0.04%	0.033%	0.665%	0.34%	0.33%
	Potassium - K		mg/Kg DS	1243	2094	1262	46	49	59	46	2094	792.17	867.80
	Potassium - K		% m/m	0.124%	0.209%	0.126%	0.00%	0.005%	0.006%	0.005%	0.209%	0%	0.09%
	Potash (K_2O)		% m/m										
	Cellulose		% m/m										
	Volatile Acids		mg/l	1507	453	252				252	1507	737.33	67408.48
	Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.03	0.03	0.03	0.03	0.03	0.03	0.00
	METALS												
COMPULSORY	Arsenic		mg/kg DS	18	0	0	4	4	4	0	18	5.00	666.33
	Cadmium		mg/kg DS	17	16	20	2	2	2	2	20	9.83	868.14
	Chromium		mg/kg DS	320	848	845	12.6	10	12.3	10	848	341.32	40913.49
	Copper		mg/kg DS	178	233	29	106	32	16.6	16.6	233	99.10	8991.63
	lead		mg/kg DS	54	29	24	3.11	3	3	3	54	19.35	2056.09
	Mercury		mg/kg DS	3.32	8.11	7.71	0.61	0.23	0.29	0.23	8.11	3.38	369.51
	Nickle		mg/kg DS	248	764	504	5	5.16	6.1	5	764	255.38	31874.80
	Zinc		mg/kg DS	635	1234	999	51	19.6	16.2	16.2	1234	492.47	54260.28
RECOMMENDED	Antimony		mg/kg DS										
	Boron		mg/kg DS										
	Barium		mg/kg DS										
	Berylium		mg/kg DS										
	Cobalt		mg/kg DS										
	Manganese		mg/kg DS										
	Molybdenum		mg/kg DS										
	Selenium		mg/kg DS										
	Strontium		mg/kg DS										
	Thallium		mg/kg DS										
	Vanadium		mg/kg DS										
	Iron		mg/kg DS										
	Tin		mg/kg DS										
	Aluminum		mg/kg DS										
	Magnesium		mg/kg DS										
	Sodium		mg/kg DS										
	Sulpher		mg/kg DS										
	Biological Characteristics												
COMPU-LSORY	Fecal coliform		CFU/gm DS	4752.84	13339.78	16831.34	75000000	2000000	3400000	4752.84	75000000	13405820.66	3020683471.81
	Viable Helminth		Ova/gm DW	3.91	5.04	6.22	9	0	0	0	9	4.03	355.00
	Total colifom		CFU/gm DS										
	Fecal streptococci		Number/gm DS										
	Salmonella sp.		Number/gm DS										
	Shigella sp.		Number/gm DS										
	Pseudomonas aeruginosa		Number/gm DS										
	Enteric virus		Number/gm DS										
	Parasite ova/cysts		Number/gm DS										

Summary : Southern Coastal Area

	REMARKS	UNIT	Southern Coastal Area				
			KingSburgh WWTW	Umkomaas WWTW	Craigeburn WWTW	Amanzimtoti WWTW	Ispingo WWTW
Physical Characteristics							
Moisture content		% m/m	44.33%	55.63%	57.60%	91.98%	33.65%
Chemical Characteristics							
pH			8.60	7.27	7.00	7.40	6.83
Total Dry Solids		% m/m	55.67%	44.37%	42.41%	8.02%	66.35%
Volatile solids		% m/m		66.75%	66.75%	45.00%	47.84%
Fixed Solid content (Ash)		% m/m		33.41%	33.25%	53.00%	52.16%
SOUR		mg/hr/gm			331.67		
Volatile Acids		mg/l		78.33	69.00	218.00	198.33
Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				0.10	
NUTRIENTS							
Total Nitrogen - N		mg/Kg DS	27,000.00	33,666.67	17,850.00	10,325.00	15,846.67
Total Nitrogen - N		% m/m	2.70%	3.37%	1.79%	1.03%	1.58%
Phosphorus - P		mg/Kg DS	17,283.33	3,557.00	1,912.33	2,015.50	8,547.50
Phosphorus - P		% m/m	1.73%	0.36%	0.19%	0.20%	0.85%
Potassium - K		mg/Kg DS	1,381.67	1,048.67	621.00	963.83	696.50
Potassium - K		% m/m	0.14%	0.10%	0.06%	0.10%	0.07%
METALS							
Arsenic		mg/kg DS	4.00	7.17	10.50	5.50	2.25
Cadmium		mg/kg DS	2.00	9.00	8.51	10.00	8.68
Chromium		mg/kg DS	33.67	84.93	48.32	84.82	68.33
Copper		mg/kg DS	178.33	191.00	110.00	240.67	173.67
lead		mg/kg DS	28.67	43.40	22.09	44.57	56.23
Mercury		mg/kg DS	1.25	2.78	3.96	4.95	4.57
Nickle		mg/kg DS	16.80	20.05	13.62	182.43	14.45
Zinc		mg/kg DS	349.33	753.00	147.50	1,252.00	470.83
Biological Characteristics							
Fecal coliform		CFU/gm DS	3,113.33	90,521.86	815,421.81	2,422,328.19	11,805.00
Viable Helminth		Ova/gm DW	0.33	2.54	10.57	3.23	11.67

Summary : Central Coastal Area

	REMARKS	UNIT	Central Coastal Area			
			Southern WWTW	Central WWTW	Umhlatauzana WWTW	Umbilo WWTW
Physical Characteristics						
Moisture content		% m/m	92.85%	99.29%	99.09%	55.72%
Chemical Characteristics						
pH			4.73	5.12	6.75	6.86
Total Dry Solids		% m/m	7.15%	0.71%	0.91%	44.28%
Volatile solids		% m/m	70.56%	75.64%	67.78%	64.22%
Fixed Solid content (Ash)		% m/m	44.22%	24.36%	32.22%	35.78%
SOUR		mg/hr/gm				
Volatile Acids		mg/l	1,943.33	313.00	159.77	134.33
Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS	0.03	0.03	0.03	0.10
NUTRIENTS						
Total Nitrogen - N		mg/Kg DS	15,550.00	31,166.67	32,166.72	25,477.78
Total Nitrogen - N		% m/m	1.56%	3.12%	3.22%	2.55%
Phosphorus - P		mg/Kg DS	5,509.83	1,229.17	2,704.17	10,239.11
Phosphorus - P		% m/m	0.55%	0.12%	0.27%	1.02%
Potassium - K		mg/Kg DS	663.33	28.15	36.00	257.36
Potassium - K		% m/m	0.07%		0.00%	0.03%
METALS						
Arsenic		mg/kg DS	2.00	2.00	2.00	2.86
Cadmium		mg/kg DS	9.73	1.00	1.00	63.54
Chromium		mg/kg DS	64.05	11.62	34.10	2,367.78
Copper		mg/kg DS	79.69	115.47	244.43	1,503.00
lead		mg/kg DS	56.25	22.07	21.12	1,160.92
Mercury		mg/kg DS	2.46	0.51	15.22	12.90
Nickle		mg/kg DS	23.78	2.32	2.18	1,104.22
Zinc		mg/kg DS	205.46	207.05	439.78	4,033.56
Biological Characteristics						
Fecal coliform		CFU/gm DS	33,774,079.76	3,257,860.18	1,932,165.55	2,857.62
Viable Helminth		Ova/gm DW	1.90	4.92	10.88	0.89

Summary : Inland Area

	REMARKS	UNIT	Inland Area						
			Hammarsdale WWTW	Mpumalanga WWTW	Hillcrest WWTW	KwaNdengezi WWTW	Dassenhoek WWTW	Fredville WWTW	Glenwood WWTW
Physical Characteristics									
Moisture content		% m/m	85.42%	30.06%	90.52%	67.91%	2.67%	62.19%	
Chemical Characteristics									
pH			7.41	6.93	7.17	7.35	6.35	7.30	6.97
Total Dry Solids		% m/m	14.58%	69.94%	9.48%	32.09%	97.33%	37.81%	
Volatile solids		% m/m	81.46%	50.74%	75.92%	43.71%		45.96%	
Fixed Solid content (Ash)		% m/m	18.54%	49.26%	24.08%	56.29%		54.04%	
SOUR		mg/hr/gm	527.33					432.67	310.00
Volatile Acids		mg/l	912.00	159.67	162.33	269.00	80.60	214.33	
Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS	0.05						
NUTRIENTS									
Total Nitrogen - N		mg/Kg DS	33,888.89	29,333.33	28,911.11	17,483.33	42,166.67	19,483.33	1,333.33
Total Nitrogen - N		% m/m	3.39%	2.93%	2.89%	1.75%	4.22%	1.95%	0.13%
Phosphorus - P		mg/Kg DS	6,867.89	14,492.17	4,479.89	3,920.33	10,028.50	3,230.33	465.00
Phosphorus - P		% m/m	0.69%	1.45%	0.45%	0.20%	1.00%	0.32%	0.05%
Potassium - K		mg/Kg DS	2,767.56	1,201.67	1,853.67	668.33	1,448.00	1,339.33	41.67
Potassium - K		% m/m	0.28%	0.12%	0.19%	0.07%	0.14%	0.13%	0.00%
METALS									
Arsenic		mg/kg DS	4.22	15.33	8.44	15.33	2.90	2.00	4.00
Cadmium		mg/kg DS	1.33	1.00	1.46	19.33	16.68	16.67	2.00
Chromium		mg/kg DS	19.44	42.00	18.05	33.95	48.00	39.37	10.62
Copper		mg/kg DS	80.44	139.50	153.07	137.67	201.83	108.07	19.63
lead		mg/kg DS	7.26	17.43	11.24	34.02	66.00	42.66	3.00
Mercury		mg/kg DS	0.48	12.28	3.15	6.28	13.17	8.86	156.17
Nickle		mg/kg DS	11.24	18.78	12.74	14.97	28.83	27.37	5.38
Zinc		mg/kg DS	234.11	529.17	227.78	309.33	657.17	339.50	35.67
Biological Characteristics									
Fecal coliform		CFU/gm DS	22,605.74	156,428.24	26,888.12	2,335.33	114,168.00	9,092.55	18,160.00
Viable Helminth		Ova/gm DW	1.17	10.78	226.33	3.16	15.92	10.49	5.00

Summary : Northern Coastal Area

	REMARKS	UNIT	Northern Coastal Area					
			Phoenix WWTW	Umhlanga WWTW	Umdloti WWTW	Verulam WWTW	Tongaat Central WWTW	Gennazanno WWTW
Physical Characteristics								
Moisture content		% m/m	84.34%	90.51%	72.33%	74.22%	87.14%	44.62%
Chemical Characteristics								
pH			6.58	6.37	6.85	7.23	6.78	6.63
Total Dry Solids		% m/m	15.66%	9.49%	27.67%	51.57%	12.86%	55.38%
Volatile solids		% m/m	68.58%	79.57%		63.86%	50.49%	50.13%
Fixed Solid content (Ash)		% m/m	31.43%	20.43%		36.14%	49.51%	49.87%
SOUR		mg/hr/gm	46.67	37.00	38.33	1,074.33	367.00	351.33
Volatile Acids		mg/l	184.67	348.33	106.83	201.67	102.17	80.00
Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS				1.25	0.06	
NUTRIENTS								
Total Nitrogen - N		mg/Kg DS	34,141.67	37,166.67	53,716.67	35,133.33	24,683.33	26,050.00
Total Nitrogen - N		% m/m	3.41%	3.72%	5.37%	3.51%	2.47%	2.61%
Phosphorus - P		mg/Kg DS	5,069.33	3,550.33	5,520.00	7,532.67	4,355.33	5,746.17
Phosphorus - P		% m/m	0.51%	0.36%	0.55%	0.75%	0.44%	0.57%
Potassium - K		mg/Kg DS	2,026.08	1,851.83	1,337.33	713.33	1,493.50	2,101.67
Potassium - K		% m/m	0.20%	0.19%	0.13%	0.07%	0.15%	0.21%
METALS								
Arsenic		mg/kg DS	2.00	2.00	2.00	2.12	2.00	2.00
Cadmium		mg/kg DS	17.17	16.33	16.17	16.50	16.00	15.83
Chromium		mg/kg DS	50.04	28.77	39.93	48.83	26.82	61.67
Copper		mg/kg DS	108.95	132.88	194.50	201.83	70.67	165.50
lead		mg/kg DS	30.68	27.47	40.91	58.83	25.13	46.00
Mercury		mg/kg DS	2.02	6.37	8.37	0.60	3.66	3.97
Nickle		mg/kg DS	30.52	24.73	24.97	18.18	25.05	7.33
Zinc		mg/kg DS	239.71	228.81	439.83	525.50	206.00	299.50
Biological Characteristics								
Fecal coliform		CFU/gm DS	5,502,126.01	1,153,706.24	123,766.67	853.99	22,357.73	6,692.41
Viable Helminth		Ova/gm DW	5.40	11.99	2.82	7.51	7.58	7.97

Summary : Lower Umgeni Area

	REMARKS	UNIT	Lower Umgeni Area		
			KwaMashus WWTW	Northern WWTW	New Germany WWTW
Physical Characteristics					
Moisture content		% m/m	80.09%	78.85%	97.70%
Chemical Characteristics					
pH			7.40	7.13	6.45
Total Dry Solids		% m/m	19.91%	21.15%	2.30%
Volatile solids		% m/m	60.73%	59.26%	70.18%
Fixed Solid content (Ash)		% m/m	39.27%	40.74%	29.82%
SOUR		mg/hr/gm			102.00
Volatile Acids		mg/l	293.33	282.33	737.33
Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS	0.09	0.05	0.03
NUTRIENTS					
Total Nitrogen - N		mg/Kg DS	23,866.67	28,166.67	27,666.67
Total Nitrogen - N		% m/m	2.39%	2.82%	2.77%
Phosphorus - P		mg/Kg DS	4,644.33	3,996.00	3,380.50
Phosphorus - P		% m/m	0.46%	0.40%	0.34%
Potassium - K		mg/Kg DS	1,753.83	972.00	792.17
Potassium - K		% m/m	0.18%	0.10%	0.08%
METALS					
Arsenic		mg/kg DS	10.00	2.00	5.00
Cadmium		mg/kg DS	10.29	9.67	9.83
Chromium		mg/kg DS	91.40	54.64	341.32
Copper		mg/kg DS	143.17	185.67	99.10
lead		mg/kg DS	41.78	19.55	19.35
Mercury		mg/kg DS	4.39	3.88	3.38
Nickle		mg/kg DS	37.33	30.02	255.38
Zinc		mg/kg DS	131.83	1,209.00	492.47
Biological Characteristics					
Fecal coliform		CFU/gm DS	55,008.58	28,420.12	13,405,820.66
Viable Helminth		Ova/gm DW	1.24	1.50	4.03

Summary : All Areas

	REMARKS	UNIT	Min	Max	Average	Standard Deviation
Physical Characteristics	ALL AREAS					
Moisture content		% m/m	3%	99%	70%	25.23%
Chemical Characteristics						
pH			4.73	8.60	6.86	74.28%
Total Dry Solids		% m/m	1%	97%	31%	25.59%
Volatile solids		% m/m	44%	81%	62%	11.89%
Fixed Solid content (Ash)		% m/m	19%	56%	38%	11.67%
SOUR		mg/hr/gm	37.00	1,074.33	328.94	301.48
Volatile Acids		mg/l	69.00	1,943.33	315.16	408.63
Poly-araomatic Hydrocarbon (PAH)		mg/Kg DS	0.03	1.25	0.17	0.36
NUTRIENTS						
Total Nitrogen - N		mg/Kg DS	1,333.33	53,716.67	26,889.65	10,709.04
Total Nitrogen - N		% m/m	0.13%	5.37%	2.69%	1.07%
Phosphorus - P		mg/Kg DS	465.00	17,283.33	5,611.07	3,975.88
Phosphorus - P		% m/m	0.05%	1.7%	0.6%	0.40%
Potassium - K		mg/Kg DS	28.15	2,767.56	1,122.34	702.12
Potassium - K		% m/m	0.00%	0.28%	0.12%	0.07%
METALS						
Arsenic		mg/kg DS	2.00	15.33	4.79	4.09
Cadmium		mg/kg DS	1.00	63.54	11.99	12.43
Chromium		mg/kg DS	10.62	2,367.78	150.10	466.29
Copper		mg/kg DS	19.63	1,503.00	199.15	277.02
lead		mg/kg DS	3.00	1,160.92	77.86	226.25
Mercury		mg/kg DS	0.48	156.17	11.42	30.44
Nickle		mg/kg DS	2.18	1,104.22	78.11	221.26
Zinc		mg/kg DS	35.67	4,033.56	558.56	782.95
Biological Characteristics						
Fecal coliform		CFU/gm DS	853.99	33,774,079.76	2,518,343.35	7,113,380.28
Viable Helminth		Ova/gm DW	0.33	226.33	14.79	44.28

Appendix 3 - Anaerobic digesters performance (Volatile solids reduction)

	Volatile Solids (Report: Classification of 25 Wastewater Treatment Works Sludges in eThekwini Municipality (Feb 2019))				
	Sample 1	Sample 2	Sample 3	Average Reduction*	Percent Compliance with 38% VS reduction
1 Amanzimtoti Wastewater Treatment Work					
Digester Feed %	54%	61%	61%		
Digested sludge%	45%	38%	46%		
Percentage reduction	30%	61%	46%	46%	67%
2 Isipingo Wastewater Treatment Work					
Digester Feed %	76%	80%	83%		
Digested sludge%	53%	62%	58%		
Percentage reduction	64%	59%	72%	65%	100%
3 Mpumalanga Wastewater Treatment Work					
Digester Feed %	77%	82%	42%		
Digested sludge%	39%	40%	79%		
Percentage reduction	81%	85%	0%	55%	67%
4 KwaNdengezi Wastewater Treatment Work					
Digester Feed %	78%	78%	76%		
Digested sludge%	59%	100%	56%		
Percentage reduction	59%	0%	60%	40%	67%
5 KwaMashu Wastewater Treatment Work					
Digester Feed %	62%	58%	60%		
Digested sludge%	57%	52%	43%		
Percentage reduction	19%	22%	50%	30%	33%
6 Phoenix Wastewater Treatment Work					
Digester Feed %	82%	75%	77%		
Digested sludge%	65%	63%	67%		
Percentage reduction	59%	43%	39%	47%	100%
7 Umbilo Wastewater Treatment Work					
Digester Feed %	62%	100%	82%		
Digested sludge%	63%	56%	57%		
Percentage reduction	0%	100%	71%	57%	67%
8 Northern Wastewater Treatment Work					
Digester Feed %	68%	60%	74%		
Digested sludge%	61%	81%	74%		
Percentage reduction	26%	0%	0%	9%	0%

* Calculated using O'Shaunessy's formula as per DWAF Report TT261/06, titled "Guidelines for the Utilisation and Disposal of Wastewater Sludge", Volume 1, March 2006

Appendix 4 - Sludge fuel value calculations

Fuel value calculations

	Southern Coastal Area				
	KingSburgh WWTW	Umkomaas WWTW	Craigeburn WWTW	Amanzimtoti WWTW	Ispingo WWTW
Proximate Analaysis					
Total Dry Solids	55.67%	44.37%	42.41%	8.02%	66.35%
Fixed Solids	0.00%	33.41%	33.25%	53.00%	52.16%
Volatile Matter	0.00%	66.75%	66.75%	45.00%	47.84%
Inorganic conditioning	0%	0%	0%	0%	0%

1- Fair et al empirical equation:

$$Q = a\left[\frac{P_v\ 100}{100 - P_c} - b\right]\left[\frac{100 - P_c}{100}\right]$$

	Raw/Digested	Raw
a	131.00	107.00
b	10	5

Q fuel value, Btu/lb DS

P_v Percent volatile solid in sludge

P_c Percent of inorganic conditioning chemical in sludge (assumed 0.7% for mechanical dewatered sludge)

	KingSburgh WWTW	Umkomaas WWTW	Craigeburn WWTW	Amanzimtoti WWTW	Ispingo WWTW
Fuel Value Btu/lb DS		6,607.61	6,607.61	4,585.00	4,957.04
Fuel Value Kj/Kg DS		15,369.29	15,369.29	10,664.71	11,530.08

2- P. Aarne Vesilind emprical equation

$$Q = 122\ P_v - 660$$

	KingSburgh WWTW	Umkomaas WWTW	Craigeburn WWTW	Amanzimtoti WWTW	Ispingo WWTW
Fuel Value Btu/lb DS		7,483.91	7,483.91	4,830.00	5,176.48
Fuel Value Kj/Kg DS		17,407.57	17,407.57	11,234.58	12,040.49

Fuel value calculations

	Central Coastal Area			
	Southern WWTW	Central WWTW	Umhlatauzana WWTW	Umbilo WWTW
Proximate Analaysis				
Total Dry Solids	7.15%	0.71%	0.91%	44.28%
Fixed Solids	44.22%	24.36%	32.22%	35.78%
Volatile Matter	70.56%	75.64%	67.78%	64.22%
Inorganic conditioning	0%	0%	0%	0.3%

1- Fair et al empirical equation:

$$Q = a\left[\frac{P_v\,100}{100 - P_c} - b\right]\left[\frac{100 - P_c}{100}\right]$$

	Raw/Digested	Raw
a	131.00	107.00
b	10	5

	Southern WWTW	Central WWTW	Umhlatauzana WWTW	Umbilo WWTW
Fuel Value Btu/lb DS	7,014.56	7,558.48	6,717.46	7,081.07
Fuel Value Kj/Kg DS	16,315.87	17,581.02	15,624.81	16,470.56

Q fuel value, Btu/lb DS

P_v Percent volatile solid in sludge

P_c Percent of inorganic conditioning chemical in sludge (assumed 0.7% for mechanical dewatered sludge)

2- P. Aarne Vesilind emprical equation

$$Q = 122\,P_v - 660$$

	Southern WWTW	Central WWTW	Umhlatauzana WWTW	Umbilo WWTW
Fuel Value Btu/lb DS	7,947.91	8,568.08	7,609.16	7,174.84
Fuel Value Kj/Kg DS	18,486.85	19,929.35	17,698.91	16,688.68

Fuel value calculations

	Inland Area						
	Hammarsdale WWTW	Mpumalanga WWTW	Hillcrest WWTW	KwaNdengezi WWTW	Dassenhoek WWTW	Fredville WWTW	Glenwood WWTW
Proximate Analaysis							
Total Dry Solids	14.58%	69.94%	9.48%	32.09%	97.33%	37.81%	0.00%
Fixed Solids	18.54%	49.26%	24.08%	56.29%	0.00%	54.04%	0.00%
Volatile Matter	81.46%	50.74%	75.92%	43.71%	0.00%	45.96%	0.00%
Inorganic conditioning	0.1%	0.5%	0.1%	0%	0%	0%	0%

1- Fair et al empirical equation:

$$Q = a\left[\frac{P_v\,100}{100 - P_c} - b\right]\left[\frac{100 - P_c}{100}\right]$$

	Raw/Digested	Raw
a	131.00	107.00
b	10	5

	Hammarsdale WWTW	Mpumalanga WWTW	Hillcrest WWTW	KwaNdengezi WWTW	Dassenhoek WWTW	Fredville WWTW	Glenwood WWTW
Fuel Value Btu/lb DS	8,172.60	5,311.14	7,583.46	4,416.45		4,382.36	
Fuel Value Kj/Kg DS	19,009.48	12,353.70	17,639.12	10,272.65		10,193.38	

Q	fuel value, Btu/lb DS
P_v	Percent volatile solid in sludge
P_c	Percent of inorganic conditioning chemical in sludge (assumed 0.7% for mechanical dewatered sludge)

2- P. Aarne Vesilind emprical equation

$$Q = 122\,P_v - 660$$

	Hammarsdale WWTW	Mpumalanga WWTW	Hillcrest WWTW	KwaNdengezi WWTW	Dassenhoek WWTW	Fredville WWTW	Glenwood WWTW
Fuel Value Btu/lb DS	9,277.71	5,530.28	8,602.24	4,673.03		4,946.71	
Fuel Value Kj/Kg DS	21,579.96	12,863.43	20,008.81	10,869.46		11,506.06	

Fuel value calculations

	Northern Coastal Area					
	Phoenix WWTW	Umhlanga WWTW	Umdloti WWTW	Verulam WWTW	Tongaat Central WWTW	Gennazanno WWTW
Proximate Analaysis						
Total Dry Solids	15.66%	9.49%	27.67%	51.57%	12.86%	55.38%
Fixed Solids	31.43%	20.43%	0.00%	36.14%	49.51%	49.87%
Volatile Matter	68.58%	79.57%	0.00%	63.86%	50.49%	50.13%
Inorganic conditioning	0.1%	0.1%	0%	0.4%	0.1%	0%

1- Fair et al empirical equation:

$$Q = a\left[\frac{P_v\,100}{100 - P_c} - b\right]\left[\frac{100 - P_c}{100}\right]$$

	Raw/Digested	Raw
a	131.00	107.00
b	10	5

	Phoenix WWTW	Umhlanga WWTW	Umdloti WWTW	Verulam WWTW	Tongaat Central WWTW	Gennazanno WWTW
Fuel Value Btu/lb DS	7,665.01	7,973.39		6,275.18	4,863.10	4,829.27
Fuel Value Kj/Kg DS	17,828.82	18,546.10		14,596.06	11,311.56	11,232.87

Q	fuel value, Btu/lb DS
P_v	Percent volatile solid in sludge
P_c	Percent of inorganic conditioning chemical in sludge (assumed 0.7% for mechanical dewatered sludge)

2- P. Aarne Vesilind emprical equation

$$Q = 122\,P_v - 660$$

	Phoenix WWTW	Umhlanga WWTW	Umdloti WWTW	Verulam WWTW	Tongaat Central WWTW	Gennazanno WWTW
Fuel Value Btu/lb DS	7,706.15	9,047.13		7,130.51	5,499.78	5,456.27
Fuel Value Kj/Kg DS	17,924.50	21,043.63		16,585.57	12,792.49	12,691.28

Fuel value calculations

	Lower Umgeni Area		
	KwaMashus WWTW	Northern WWTW	New Germany WWTW
Proximate Analaysis			
Total Dry Solids	19.91%	21.15%	2.30%
Fixed Solids	39.27%	40.74%	29.82%
Volatile Matter	60.73%	59.26%	70.18%
Inorganic conditioning	0.1%	0.1%	0%

1- Fair et al empirical equation:

$$Q = a\left[\frac{P_v\,100}{100 - P_c} - b\right]\left[\frac{100 - P_c}{100}\right]$$

	Raw/Digested	Raw
a	131.00	107.00
b	10	5

	KwaMashus WWTW	Northern WWTW	New Germany WWTW
Fuel Value Btu/lb DS	6,636.48	6,443.62	6,973.90
Fuel Value Kj/Kg DS	15,436.45	14,987.87	16,221.30

Q	fuel value, Btu/lb DS
P_v	Percent volatile solid in sludge
P_c	Percent of inorganic conditioning chemical in sludge (assumed 0.7% for mechanical dewatered sludge)

2- P. Aarne Vesilind emprical equation

$$Q = 122\,P_v - 660$$

	KwaMashus WWTW	Northern WWTW	New Germany WWTW
Fuel Value Btu/lb DS	6,749.06	6,569.72	7,901.55
Fuel Value Kj/Kg DS	15,698.31	15,281.17	18,379.01

Fuel value calculations

	All Areas		
	Min	Max.	Average
Proximate Analaysis			
Total Dry Solids	0.0%	97%	29%
Fixed Solids	0.0%	56%	34%
Volatile Matter	0.0%	81%	54%
Inorganic conditioning			

1- **Fair et al empirical equation:**

$$Q = a\left[\frac{P_v\,100}{100 - P_c} - b\right]\left[\frac{100 - P_c}{100}\right]$$

	Raw/Digested	Raw
a	131.00	107.00
b	10	5

Q fuel value, Btu/lb DS

P_v Percent volatile solid in sludge

P_c Percent of inorganic conditioning chemical in sludge (assumed 0.7% for mechanical dewatered sludge)

	Min	Max.	Average
Fuel Value Btu/lb DS	4,382.36	8,172.60	6,316.89
Fuel Value Kj/Kg DS	10,193.38	19,009.48	14,693.10

2- **P. Aarne Vesilind emprical equation**

$$Q = 122\,P_v - 660$$

	Min	Max.	Average
Fuel Value Btu/lb DS	4,673.03	9,277.71	6,922.12
Fuel Value Kj/Kg DS	10,869.46	21,579.96	16,100.84

Appendix 5 – Sludge thickening

1. Gravity thickener (Wang et al., 2007 and Qasim et al., 2018)

Gravity thickening is the simplest and most widely used sludge thickening method in wastewater treatment plants. It is accomplished in circular concrete or steel tanks similar to those used for primary and secondary sedimentation. However; concrete circular tanks are the most common configuration for gravity thickeners, rectangular and square concrete tanks have also been used. Typically the circular tank has a 2:12 to 2:13 slopping floor toward the centre. It is also equipped with a central drive unit, rotating bottom scrapper, vertical pickets, rotating scum arms, scum box, scum baffles, overflow weir and central feed well.

Gravity thickening is the most economic thickening method; however, it’s not the most efficient in terms of the thickened sludge concentration. Primary, secondary or combined sludge can be thickened and concentrated in a gravity thickener. The degree of thickening may vary from two to five times the incoming sludge's concentration; however, the maximum solid concentration achieved by Gravity thickening is less than 10 percent, Chlorine is also used; but this time to prevent sludge septicity and gasification, which affect the optimum solids concentration of organic materials. To prevent this issue a free chlorine residual of 0.5 to 1.0 ppm is to be maintained in the gravity thicker supernatant. Chlorine overdosing should be avoided as it may disperse sludge flocs.

Table 1-1 present typical gravity thickener loading rates and performance. The sludge volume ratio (SVR), which is the sludge blanket volume in the thickener divided by the volume of the thickened sludge removed per day, should be between 0.5 to 2 days from a good operation practice. Another essential operation practice is the Sludge Index Volume (SVI) of the feed sludge. It is not a function of the thickener operation; however, it affects the thickening process by reducing the underflow solids concentration and increase the solids washout (low capture rate). Feed sludge with SVI of less than 100 indicates an older, denser, faster settling sludge. SVI of higher than 150 indicates a young, lower density, slower settling sludge. Typically, a sludge with an SVI greater than 200 is considered a bulking sludge, a very difficult sludge to thicken. Threefold benefits are achieved using gravity thickening; (a) Concentration, (b)Flow and quality equalisation, (b) and storage. However, Storage and retention time must be carefully considered to avoid septicity and gasification. The septic conditions that may devlope during thickening results in floating solids that pass over into the thickener supernatant (overflow), foul odours, and reduced underflow solids concentration. The gravity thickener performance and the concentration of the underflow solids depends on many factors such as,

- The sludge type being thickened and its volatile solids content. It has been found that the underflow solids from secondary sludge will not reach the same concentration level as the underflow solids from raw primary sludge. This is since the volatile solids settle slowly, resist compaction and tend to stratify. The ratio of primary to secondary sludge and the degree of biological treatment will affect the final solids concentration achieved by gravity thickening.

- Initial solid concentration and temperature: Rudolfs and Logan investigated the importance of initial solids concentration and temperature on sludge thickening. They found that the solids concentration achieved is much greater with low initial feed solids concentrations than a high initial feed solids concentration. A pilot-plant and full-scale investigation have concluded that the maximum solids concentration by gravity thickening is achieved when the feed solid concentration is between 0.5 and 1%. The effect of temperature is also found to be of utmost significance, particularly with "aged" sludge. It was found that the maximum degree of compaction is achieved at a temperature of 37°C, regardless of initial feed solids concentration; it also has been noticed that higher and lower temperatures resulted in less compaction.
- Sludge blanket depth and retention time. It has been found that the sludge blanket depth up 1 m will increase compaction, leading to a higher underflow solids concentration. However, a sludge blanket deeper than 1 m will significantly increase the water flow resistance through the sludge blanket layer, leading to septic conditions, gasification and bulky sludge which doesn’t compact or dewatered well. Increasing the sludge blanket depth increases the sludge's retention time within the thickener, increasing the solids' detention in the sludge blanket results in increased solids concentration, up to a point. For maximum compaction and maximum underflow solid concentration, a maximum of 24 hours retention time is suggested, especially in hot climate countries.
- Gentle agitation increases compaction by creating ways for the water through the sludge blanket.
- Chemicals addition influences the degree of thickening. A combination of many different additives to many different sewage sludges has been used; for example, alum and ferric salts didn’t increase sludge concentrations after 24 hours of compaction. However; sulfuric acid increased solids concentration by improving compaction, but the high dose required (600 - 1000 ppm) compared to the achieved concentration made the process uneconomical and impractical. Dosages of lime between 250 to 500 ppm increased sludge compaction significantly. Iron oxides, diatomaceous earth, and fly ash were also added to the sludge to promote compaction and increase concentration, but they have insignificant effect at reasonable dosages. The use of organic polyelectrolytes (Anionic, cationic, and nonionic polymers) has been found beneficial in gravity thickening by aiding compaction and increasing underflow solids concentration. It has also been found that the return of centrate from the dewatering stage containing organic polymer or inorganic coagulant to the thickener feed may improve the compaction and underflow solids concentration. Chlorine is also used; but this time to prevent sludge septicity and gasification, which affect the optimum solids concentration of organic materials. Keeping a free chlorine residual between 0.5 to 1.0 mg/l in the gravity thicker supernatant prevents this problem. Overdosing must be avoided because excessive chlorine may disperse biosolids.

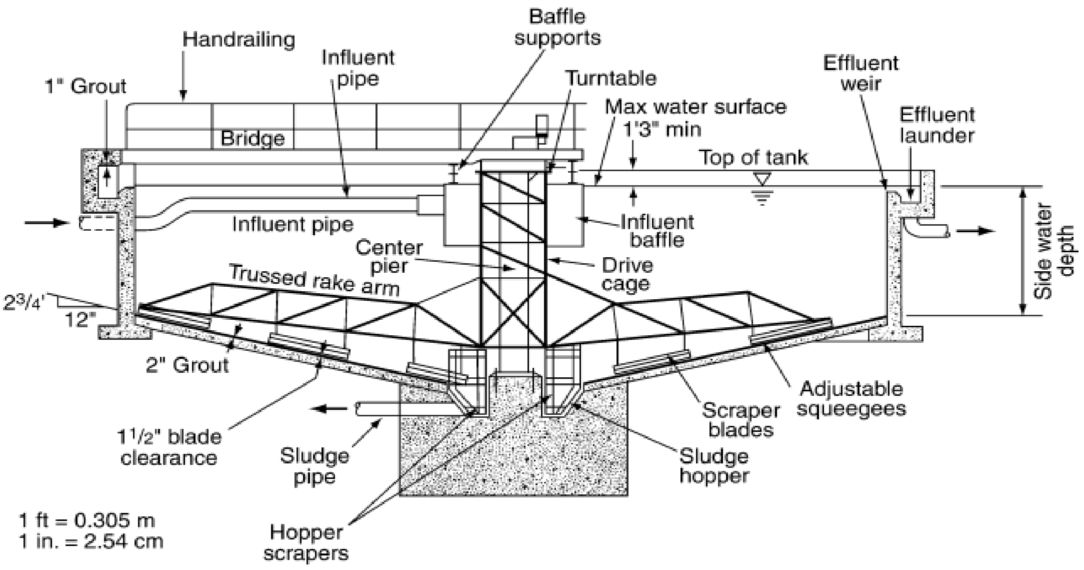


Figure 1-1 Cross-sectional view of a circular gravity thickener (reprinted with permission from Springer Nature)

Table 1-1 Typical Loading Rates and Performance Parameter Ranges of Gravity Thickener

Type of sludge	Feed Solids Content %	Solids Loading $Kg/m^2.d$	Hydraulic Loading $m^3/m^2.d$	Solids Capture %	Thickened Sludge (Underflow) Solid Content %
PS	1 -6	100 – 150	15 - 30	85 – 98	4 – 10
TFS	1 - 4	40 - 50	4 - 8	80 - 92	3 - 6
WAS	0.2 – 1.2	20 - 40	4 - 8	60 - 85	2 – 4
PS + WAS	1 - 4	25 - 75	6 - 12	80 - 92	3 - 6

2. Flotation thickening (Qasim et al., 2018)

Flotation thickening is a solid-liquid separation process where the separation is induced by introducing air. The air bubbles become attached to the solid particulates in an air-bubble formation. The bulk density of the air-solid formation is less than the liquid's density and rise to the water's surface. Once the solid particles rise to the surface, they can be skimmed and collected by a surface skimming mechanism. This thickening process is becoming increasingly popular at sewage treatment plants, especially for the waste-activated sludges. Its ability to thicken particles of small size and density close to water is a considerable advantage over gravity thickener. This advantage resulted in better overall performance and higher thickened solids concentrations. Another advantage flotation thickening has over gravity thickening is the lower initial capital cost for the equipment.

There are four processes of flotation thickening, where air or gas bubbles are used to aid the flotation of solids particles; these processes are:

(1) Dispersed air flotation: in this process, the air bubbles are generated by introducing air through a revolving impeller or porous media.

(2) Dissolved air flotation (DAF): in this process, the air is dissolved into the solution under elevated pressures and later released at atmospheric pressure to create the microbubbles,
(3) Dissolved air-vacuum flotation: in this process, a vacuum is applied to wastewater aerated at atmospheric pressure
(4) Biological flotation: in this process; the bubbles are generated from the gases produced during the natural biological activity
(5) Electroflotation: in this process, the microbubbles are generated at two electrically charged electrodes by water dissociation into hydrogen and oxygen.

Only dissolved air-pressure flotation will be discussed in details as a process for thickening sludge. The dispersed air flotation and dissolved air-vacuum flotation are more applicable as wastewater sedimentation processes; as it is challenging to increase the sludge concentrations to the typical thickened sludge concentration level. Biological flotation occurs under either anaerobic or denitrification conditions, and both are susceptible biological processes to operation and change in the feed quality, in addition to the required start-up time that may be required due to any upset to the biological activities. For these reasons, the biological flotation was not considered. Electroflotation is also not considered due to the following disadvantages; (a) low throughput, (b) emission of hydrogen and oxygen (creating potential hydrogen explosion), (c) the high cost of the electrodes, (d) the cost of maintenance (ex. Power consumption), (e) the high level of safety requirements (f) and it doesn't provide any additional advantages to thickened sludge concentration if compared to the DAF.

Dissolved air flotation (DAF) thickener; as mentioned above the air is introduced at a pressure way above atmospheric pressure (275 to 415 KPa). Since air solubility increase with pressure, a large quantity of air can be dissolved at this pressure. When the solution is depressurised, the excess air is released, forming fine bubbles 50 to 100 µm in diameter. These bubbles attach to the solids resulting in solid-air formation with less density than water (0.6 to 0.7); accordingly, they rise to the surface.. The floating is then collected from the surface using skimmers.

The DAF tank can be either circular or rectangular and made of steel or concrete. Typically small tanks are made of steel and delivered pre-assembled. For large installations, either multiple steel tanks or one large tank made of concrete is more economical. Rectangular tanks possess more advantages than circular tanks. In rectangular tanks; skimming is more efficient as the skimmer flights skim the entire surface of the tank and the flights can be closely spaced. In the rectangular tanks, surface and bottom skimmers can be driven by a separate drive unit allowing better operation control. On the other hand, the circular unit main advantage is the lower cost in terms of structural concrete and equipment. It should also be mentioned that for the steel pre-assembled tanks, the circular-shaped tanks are limited to 90 m^2 or less and rectangular tanks are limited to 40.5 m^2 due to shipping problems.

The DAF process has three different configurations of the pressurisation (saturation) system; (1) Pressurising the entire feed sludge flow, (2) Pressurising a portion of the feed sludge flow, (3) and pressuring the recycle flow from the DAF. Configuration one and two are called direct pressurisation; however, configuration three is called indirect pressurisation. Figure 2-1 shows schematics of the different pressurised system configurations. The indirect pressurisation configuration has two significant advantages over the direct pressurisation configuration. It minimises the applied shear to the feed sludge flocs and eliminates clogging of the pressurisation system equipment.

The main design and operation variables for DAF thickening are:

(1) pressure; It determines the degree of air saturation, air bubbles size and floating solids concentration. Typically increase pressure increase the thickened solids concentration and decrease the solid concentration in the supernatant.

(2) recycle ratio and (3) feed solids concentration are interrelated, Increase the recycling of clarified supernatant, enabling more air to dissolve and dilute the feed sludge. Increase the air aid the saturation and the formation of microbubbles, and dilution reduces particles' interference on the water/solid separation rate (solid rise rate). The effluent recycling can range from 30% to 150% of influent flow, typically 40 to 50% are used.

(4) The detention time; it was found that an increase in detention time increases the thickened solids concentration and decreases the supernatant's solid concentration. A detention time up to three hours is found to be optimum for thickening, beyond three hours no additional thickening was noticed.

(5) air-to-solids ratio (A/S); theoretically, the amount of air required to achieve good flotation is directly proportional to the amount of solids entering the DAF tank. It has been reported that for sewage sludges, air-to-solid ratio range from 0.01 to 0.4 is adequate, with most systems operating at a value under 0.1. The A/S ratio for a particular application is a function of the feed sludge characteristics; mainly the sludge volume index (SVI), the air saturation (pressurisation) system efficiency, and the amount of turbulence present at the point of pressure reduction (low turbulence will affect the rate of formation of the microbubble; however excessive turbulence affects the sludge floc shear).

(6) type and quality of feed sludge, Different types of sludges can be thickened effectively using DAF thickener. These include conventional WAS, extended aeration sludge, attached growth sludge, and aerobically digested sludge. Detailed information is needed about the feed sludge expected solids concentration range. It is essential if WAS is to be thickened, the sludge volume index (SVI) of the sludge in the aeration tank to be determined because SVI can significantly affect the DAF thickening performance. If thickened sludge with a concentration of 4% is required, the SVI should be less than 200.

(7) solids and hydraulic loading rates, The solids loading rate is expressed as the weight of solids per unit time per unit effective floatation area (Kg/m^2.d). However; the hydraulic loading rate is expressed as combined flow rates of feed sludge and recycles per unit time per unit effective floatation area (m^3/m^2·d). Typical solids loading rate and hydraulic loading rate are given in Table 2-1

(8) use of chemical conditioning, chemical conditioning with polymer has a great effect on DAF thickener performance. Small size particles in some sludge types may not be amenable to the flotation

process due to air not attaching to its surface because of its small size. The surface of sludge particles may also be charged, causing an electrically charged layer to form. This electrically charged layer will oppose particles' aggregation. The polymer can neutralise the charge, causing the particles to coagulate and grow in size so that air bubbles can attach easily to them for adequate flotation.

To determine the optimum dosing rate of polymer and the dosing location for a specific type of solids, Bench- or pilot-scale testing are recommended. Typical polymer dosages are presented in Table 2-1.

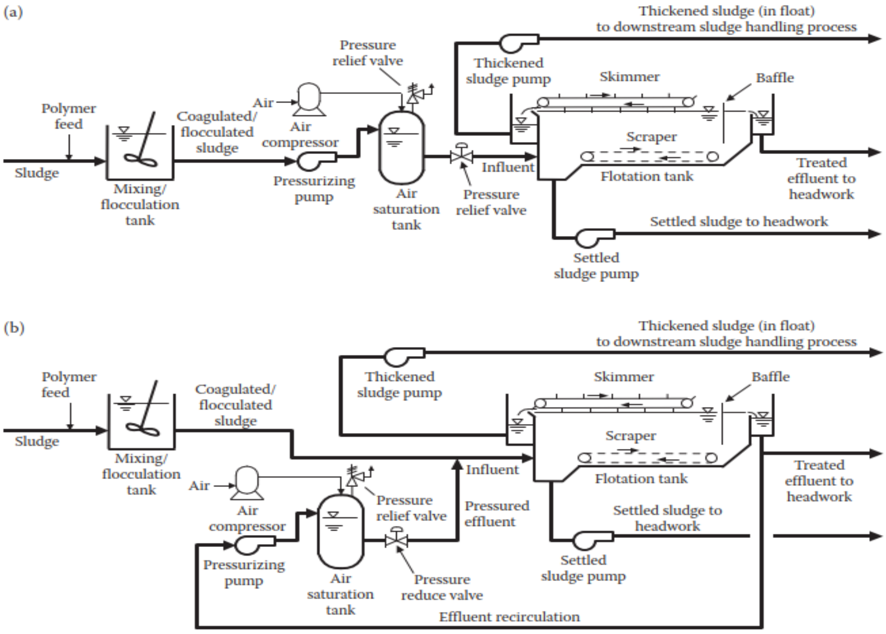


Figure 2-1 Schematics of DAF systems: (a) direct pressurisation and (b) indirect pressurisation. (Reprinted with a permission from Taylor & Francis Group LLC-Books)

The main components of the DAF thickening are ; (1) pressurising pump, (2) air saturation tank (3) air-compressor, (4) flotation tank (SWD = 2 - 4.5 m), (5) surface skimmer and bottom scraper, (6) Floculator (mixing/flocculation), mixing velocity Grediant G = 50–100 s−1 and retention time 1 - 2.5 min, (5) polymer preparation, storage and feed system with metering pumps,(6) thickened sludge pump, (7) settled sludge pump, (8) flow meters, and (9) pressure relief valves, pressure reducing valves, pressure switches, and pressure indicators, (10) and control system.

Table 2-1 Typical Design and Performance Parameter Ranges of Dissolved Air Flotation Thickener

Type of Sludge	Air/Solid Ration	Solids Loading $Kg/m^2.d$		Hydraulic Loading Rate $m^3/m^2.d$	Polymer Dose g/Kg DS (Polymer/Feed Sludge)	Solid Capture %
		Without Polymer	With Polymer			
PS	0.04 - 0.07	100 - 150	Up to 300	90 - 250	2 - 5	80 - 95
TFS	0.02 - 0.06	70 - 100	240 - 270	90 - 250	1 - 3	90 - 98
WAS	0.02 - 0.05	30 - 70	220 - 240	60 - 180	1 - 3	80 -95
PS + WAS	0.03 - 0.06	70 - 150	240 - 270	90 - 250	2 - 4	90 - 95

3. Centrifugal thickening

Centrifugation is a process by which sludge is thickened or dewatered under the influence of centrifugal force (McFarland 2001). Centrifuges operate in G units, which is the "ratio of centrifugal acceleration to the acceleration of gravity" (Wang et al., 2007). The centrifugal forces applied within the centrifuge is 500 to 3000 times the gravity forces (Turovskiy and Mathai, 2006). Centrifuges are commonly applied to waste activated sludge (WAS) (Turovskiy and Mathai, 2006). Primary sludge should undergo de-gritting before being processed by centrifuges because the grit is abrasive and can be detrimental to some types of centrifuges (Turovskiy and Mathai, 2006). The centrifuge's main advantages compared to gravity and flotation thickening are; the small footprint, the least odour potential and minimum housekeeping requirements (Qasim et al., 2018). On the other hand, capital and operational cost (maintenance & power) are higher. For these reasons the uses of centrifuges are usually limited to large treatment plants (Turovskiy and Mathai, 2006). The main types of centrifuges used for thickening are, (1) disk nozzle, (2) imperforate basket, (3) and solid bowl (Qasim et al., 2018). The first type is more common for sludge thickening, while the other two types are more common for sludge dewatering (Gurjar et al., 2017). Figure 3-1 shows the schematics of all three types of centrifuges.

Disk nozzle centrifuges (McFarland, 2001); The feed sludge can be introduced to the machine either from the top or the bottom. For top-fed machines; the feed sludge passes down to the centre where a rotor distribute it to fill the outer chamber. However; heavier sludge moves toward the wall of the rotor due to the centrifugal force. The collected liquid (centrate) with lighter solids flow inside the disc stack. The centrate passes through the stack into an overflow chamber and is discharged into an effluent line. The disc centrifuge is suitable for the thickening of sludge that does not contain coarse solids. It can handle high sludge feed rates. It is very efficient for sludge containing very fine particles at low concentrations. It is more suitable for contentious extended operation. However, after stopping the unit must be cleaned, and the bowl must be cleared of solids before restarting it. Small units require minimal maintenance mainly because the bearing is grease-packed, while larger units have circulating oil or spray-mist systems requiring high maintenance. The disk nozzle centrifuge is not recommended for sludge containing abrasive material unless some internal parts and surfaces are hardened. If the feed sludge passes through a screen, the unit can operate contentiously for as long as eight weeks. Because the feed sludge flow and quality may vary, automatic control is recommended to maintain thickened sludge consistency. This control utilises a viscosity-sensing loop to indicate the sludge discharge consistency and moderate the recycling rate. The main operation problem that is repeatedly reported using this type of centrifuge is clogging of the lines. Therefore, it is recommended to have some pre-treatment (i.e. screening) to remove fibrous material and large particles from the feed sludge. A typical performance data of a disc centrifuge is given in Table 3-1. It should be noted that the solids level increased from 1% solids to 5 or 6% solids without the addition of polymer. This is generally considered acceptable because 80% of the liquid is removed as a centrate even without polymer addition. The main advantages and disadvantages of disc centrifuge are;

Advantages;

- Can handle large throughputs
- High clarity centrate can be produced
- Applicable to sludges having finer particles
- Can produce high thickened sludge without polymer addition

Disadvantages;

- Large particles, fibres cause clogging
- Typically requires intensive pre-screening
- Large units require moderate to high maintenance
- Skilled operators required Skilled operators required

Imperforate basket centrifuge (Wang et al., 2007); This type of centrifuge can be used in thickening and dewatering of sewage sludge and industrial wastewater sludge. It is more suitable for plants with wastewater flow in the range of 7500 to 15000 m^3/day. The basket centrifuge consists of mainly a rotating vertical chamber that has a weir at the top. The sludge is fed from the top at semicontinuous bases. The solids move toward the chamber wall, and the centrate is discharged out of the chamber by flowing over the weir. The centrifugal force applied in commercial scale is up to 1500 G. Dewatered sludge (cake) is removed intermittently from the bottom. The basket deceleration and acceleration is controlled by the feed and removal of the sludge.

A basket centrifuge's typical operating characteristics are; (1) cycle time 6–8 min, (2) solids in dewatered sludge is 10–25% wt, (c) and sludge feed rate 11 - 17 m^3/h. The basket centrifuge is more suitable for soft or small solids and fluctuates in concentration and solids characteristics. The fact that the basket centrifuge operates at a slower speed than other centrifuges minimised the maintenance requirements. It also extended the bearing life to a maximum of three years. The unit lubrication is simple, and power consumption is lower compared to other centrifuges.

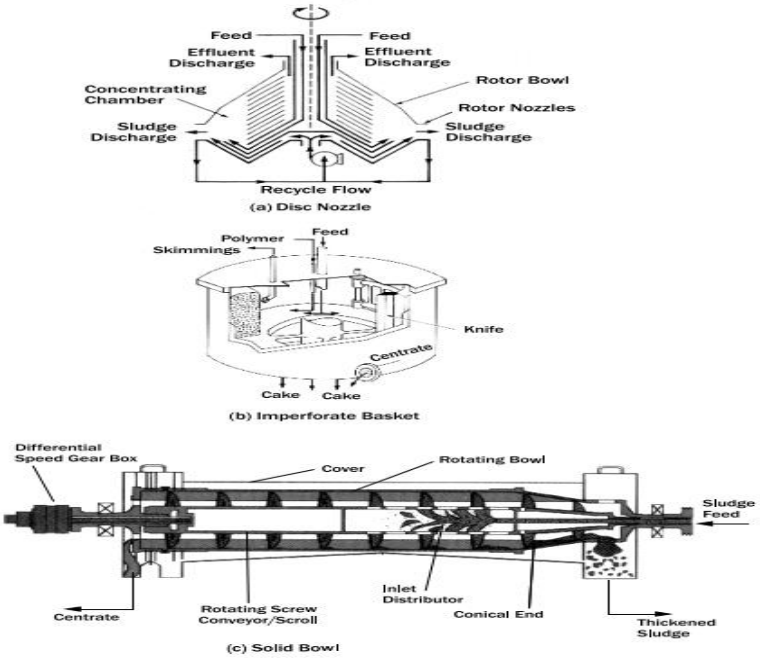


Figure 3-1 Schematics of centrifuges for thickening- (a) Disk Nozzle, (b) Imperforated Basket, (c) Solid Bowl (Reprinted with a permission from Johan Wiley & Sons-Books)

Table 3-1 Typical Performance Data for a Disc Nozzle Centrifuge from Different Installations

Feed Capacity m^3/h	Feed Solid % DS	Thickened Solids % DS	Solids Recovery %	Dry Polymer g/Kg DS (Polymer/Feed Sludge)
34	0.75 - 1	5 - 5.5	90	None
91	-	4	80	None
11 - 18	0.7	5 - 7	93 - 87	None
14 - 61	0.7	6.1	97 - 80	None
15	1.5	6.5 - 7.5	87 - 97	None
45	0.75	5	90	None

The main advantages and disadvantages of basket centrifuge are;

Advantages;

- Can handle small throughputs
- Can handle difficult to dewater sludge
- Grit in the feed does not pose a problem
- Low sensitivity to feed sludge fluctuation

Disadvantages;

- Semicontinuous
- Low solids concentration in thickened sludge (for dewatering only)
- Poor solids capture

- Low capacity
- G limitations

Typical performance data of a basket centrifuge are listed in Table 3-2. The data shows that a concentration up to 25–30% can be achieved with raw primary sludge. However, with only raw waste activated sludge, the performance drops drastically; however, it is still satisfactory if the unit's intended use is thickening.

Solid-Bowl Centrifuge (Wang et al., 2007); often referred to as scroll or decanter centrifuge and operates in two different configurations; (1) counter current, (2) and concurrent. The main differences between the two are the configuration of the conveyor (scroll) toward the machine's liquid discharge end and the location and configuration of the solids discharge port.

Table 3-2 Typical Performance Data for a Basket Centrifuge

Sludge Type	Feed Solids Concentration % DS	Average Thickened/Dewatered Sludge Concentration % DS	Dry Polymer g/Kg DS (Polymer/Feed Sludge)	Recovery Based on Centrate %
PS	4 - 5	25 - 30	1 – 1.5	95 - 97
TFS	2 - 3	9 - 10 10 - 12	0 0.8 – 1.5	90 - 95 95 - 97
WAS	0.5 – 1.5	8 - 10 12 -14	0 0.5 - 15	85 - 90 90 - 95
PS + TFS (30:70)	2 - 3	9 - 11 7 - 9	0 0.8 – 1.5	95 - 97 94 - 97
PS + WAS (50:50)	2 - 3	12 - 14	0.5 – 1.5	93 - 95
PS + RBC (60:40)	2 - 3	20 - 24 17 - 20	0 2 - 3	85 - 90 98+
ANDS+WAS (50:50)	1 - 2	12 - 14 10 - 12 8 - 10	0 0.8 – 1.5 2 - 3	75 - 80 85 - 90 93 - 95
ANDS	1 - 3	8 - 11 12 - 14	0 0.5 - 1.5	80 - 95 90 - 95

The solid-bowl centrifuge consists of a long bowl typically mounted horizontally with one conically elongated end. The sludge is fed continuously to the bowl through a concentric tube at one end. The centrifugation force causes the solids to accumulate and concentrate on the periphery. The water (centrate) pools above the solids layer and flows toward the centrate outlet ports located at the larger end of the machine. The accumulated sludge is then moved toward the conical end using an internal spiral scroll spinning slightly different from the bowel. An additional solid concentration occurs due to the conical shape, and the thickened sludge is discharged at that end. The bowl is equipped with a height-adjustable weir that controls the centrate level and accordingly influences the centrifuge performance. The main difference between thickening and a dewatering centrifuge is that the conical part's slope is less in a thickening centrifuge. Typically, the cake's solids concentration is higher in a solid-bowl centrifuge than in a basket centrifuge for the same amounts of polymer addition. The typical performance data presented in Table 3-3 show that primary sludge can be dewatered up to 25–36% DS while with waste-activated sludge only 8–12% DS. Polymer addition amounts in the case of anaerobically digested sludges is rather significant. The main advantages and disadvantages of the solid-bowl centrifuge are;

Advantages; (1) Minimum supervision is required, (2) Ability to handle a variety of sludge types, (3) Larger throughputs compared to other centrifuges types, (4) Lower polymer dosages required, (5) Easy start-up and shutdown, (6) Can separate fine solids, (7) Can handle dilute sludges ,and 8)Odour emission is very low compared to other centrifuges.

Disadvantages; (1) Generate noise and vibration, (2) Poor supernatant quality, (3) High wear, (4) High maintenance costs, and (5) Greater sensitivity to feed fluctuation

Centrifuges are typically used for thickening air or oxygen waste activated sludge. Aerobically and anaerobically digested sludge have also been thickened successfully by centrifuges. The thickening performance is highly affected by the particle size and particle distribution within the feed sludge.

Polymer addition is an essential factor in the centrifuge performance as the naturally flocculated sludge (Sludge Floc) is often not strong enough to stay together under the high shearing forces encountered within a centrifuge. Polymer addition improve solids capture efficiency to a range of 90 to more than 95%. Operational variables that affect thickening include, (1) Feed sludge flow rate, (2) Feed sludge characteristics such as particle size and shape, density, concentration, temperature, volatility of solids, and sludge volume index, (3) Rotational speed of the bowl, (4) The difference in rotational speed between the conveyor and the bowl, (5) Water pool height in the bowl, (6) required cake dryness, and (7) Polymer conditioning.

Centrifuges thickener operate at a wide range of speed depending on the size and purposes (thickening or dewatering). It has been proven that the higher the speed, the smaller bowl diameter, the higher the solids capture and the drier the cake produced. However, high-speed machines are subject to vibration, noise, abrasion and frequent maintenance. High-speed machines consume more power. It also consumes more polymer as the high-speed may brake the sludge floc creating smaller floc size. On the other hand, machines operate at low-speed consume less power, generate less vibration and noise, and result in lower solids capture and less concentrated cakes. The manufacturers of low-speed machines typically use the approach of introducing the feed sludge deep inside the machine as far as possible from the cake discharge end to allow for longer solids residence times, thus producing a cake with higher sludge concentration at lower-speed.

Maintenance and power cost of centrifuge thickeners can be substantial; therefore, the process is attractive for installations with a capacity larger than 0.2 m^3/sec. Different manufacturers have different design features included in their centrifuges. Therefore, these variables' interrelationships will differ in each location, and specific design recommendations are difficult to achieve. The best approach to predict centrifugal thickening performance is bench-scale testing and field pilot tests. In general, there are a few points to consider for centrifuge thickening facilities include the following (WEF, 1998):

- In the event the wastewater treatment plant screening, degritting and grinding are inadequate. In that case, sludge should undergo degritting and grinding before feeding the centrifuge to avoid plugging and abrasion, except in case of basket centrifuge.
- A blending step before the centrifuge is a must if different sludge types are fed to the centrifuge simultaneously to ensure that the feed sludge is relatively consistent.
- Feed sludge flow should be constant
- The quality and quantity of the centrate must be determined, and accordingly, the discharge rout to be selected, either to primary or secondary treatment process; centrate handling may require a foam suppression system.
- Consider an overhead hoist for equipment maintenance.
- Provide clean water for centrifuge flushing during a shutdown, and for polymer preparation units.
- Consider the need for a heated water supply to flush grease build-up periodically.
- Provide proper centrifuge venting and consider the need for odour control.
- Consider struvite formation potential in anaerobic digesters when thickening anaerobically digested sludge.
- Capital, operating, and maintenance cost of equipment.

Table 3-3 Typical Performance Data for a Solid-Bowl Centrifuge

Sludge Type	Feed Solids Concentration % DS	Average Thickened/Dewatered Sludge Concentration % DS	Dry Polymer g/Kg DS (Polymer/Feed Sludge)	Recovery Based on Centrate %
PS	5 - 8 28 - 36	25 - 36 0	0.5 - 2.5 35 - 45	95 - 97
ANDS (PS)	2 - 5 9 - 12	28 - 35 30 - 35 25 - 30	3 - 5 0 0.5 – 1.5	98+ 65 – 80 82 - 92
WAS	0.5 - 3	8 - 12	5 - 8	85 - 90
ANDS (WAS)	1 - 3	8 - 10	1.5 - 3	90 - 95
PS + WAS (Thermally conditioned)	9 - 14 13 - 15	35 - 40 29 - 35	0 0.5 - 2	75 - 85 90 - 95
PS + TFS	7 - 10	35 - 40 30 - 35	0 1 - 2	60 - 70 98+
High Lime	10 - 12	30 - 50	0	90 - 95
PS + WAS	4 - 5	18 - 25	1.5 – 3.5	90 - 95
ANDS (PS + WAS)	2 - 4 4 - 7	15 - 18 17 - 21	3.5 - 5 2 - 4	90 - 95 90 - 95

Sludge Type	Feed Solids Concentration % DS	Average Thickened/Dewatered Sludge Concentration % DS	Dry Polymer g/Kg DS (Polymer/Feed Sludge)	Recovery Based on Centrate %
ANDS (PS + WAS + TFS)	1.5 – 2.5	18 - 23	1 – 2.5	85 - 90
		14 - 16	6 - 8	85 -90

4. Gravity Belt Thickening (GBT) (Qasim et al., 2018)

The Gravity Belt Thickening utilises the gravity solid-liquid separation principal to concentrate the solids by draining the free water through a porous horizontal belt. In principle, it is similar to the upper gravity drainage zone of the belt filter press used for sludge dewatering. The schematic process diagram of the GBT is shown in Figure 4-1. The feed sludge typically requires conditioning using a polymer as an essential step for forming large and heavy flocs to achieve successful thickening. The amount of polymer used depends on the feed sludge type and characteristics. The polymer is injected and mixed with the feed sludge before entering the flocculation tank. The degree of mixing is critical as it affects the formation of the floc. The chemically conditioned sludge is fed evenly over the moving belt width. The belt is typically driven using a variable speed drive to control the thickening time to cater for different sludge feed qualities and the required thickened sludge concentration.

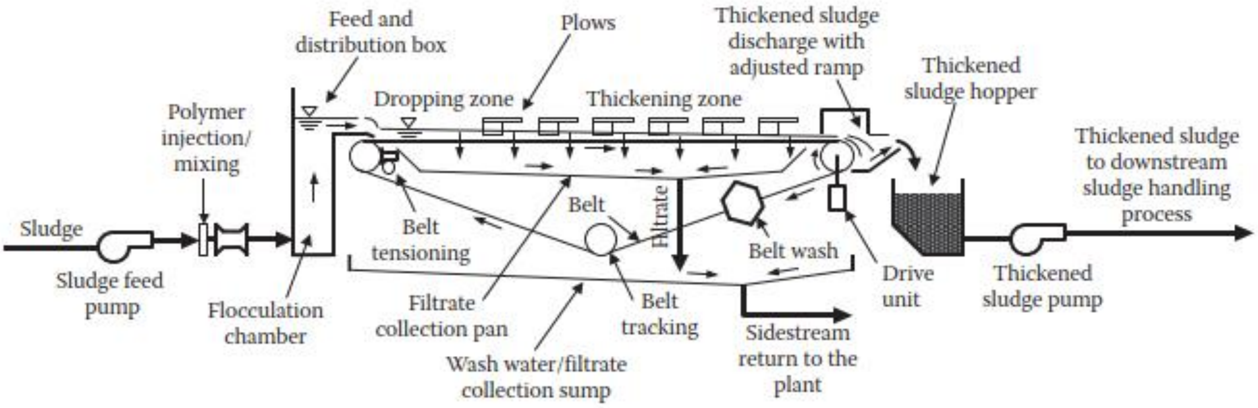


Figure 4-1 Schematic of Gravity Belt Thickener (Reprinted with permesion from Taylor & Francis Group LLC-Books)

The free water starts to separate and drain down through the moving belt to drain pans and is routed to a sump. The moving sludge is turned over by rows of ploughs or vans placed on top of the belt. The ploughs and vans help to release more water by turning the concentrated sludge and clearing spacing for water to drain. The sides of the GBT is equipped with restrainers and rubber seals to prevent sludge from running off the sides. At the discharge end of the GBT, the sludge travels over an adjustable ramp. The adjustable ramp increases residence time and provides a shearing action to the solid material enhancing the thickening. After that the thickened sludge is scraped off the belt by a scraper blade and fall into the sludge hopper. The belt continues moving toward a washing jet mechanism, Where the belt is washed, and the solids that penetrate the porous weave are removed. A sludge with solid concentration as low as 0.4% can be thickened using GBT. A typical solids capture efficiency of 95% can be achieved. However, capture efficiency as high as 99% has been reported. Relatively moderate capital cost and relatively low power consumption are other advantages of the GBT. The GBT performance is polymer dependent; a typical polymer dosing rate is 1 to 7 g/kg DS. Other disadvantages include odour potential and semicontinuous supervision to optimise polymer feed and belt speeds. Indoor installation is preferable for the GBT to protect the thickening operation from inclement weather. The GBT is used for thickening of waste activated sludge, aerobically and anaerobically digested sludge. The main design and operation parameters to consider are (1) feed sludge characteristics, (2) polymer type and dose, flocculation device, degree of mixing and application point, (3) solids loading rate, (4) hydraulic loading rate, (5) solids capture rate, (6) thickened sludge concentration, (7) belt width, (8) belt speed, (9) quantity of filtrate, and (10) wash water requirement. Design and performance criteria of the GBT are presented in Table 4-1. Typical hydraulic loading rates for GBT are 400 to 1000 L/min per meter of belt width. The commercially available belt width is between 0.4 and 4 m with an increment of 0.5 - 1 m. The belt size ranges from 2.5 to 20 m^2 per unit. Major components of a GBT system include; (1) polymer feed, (2) polymer mixing device, (3) belt thickener assembly with ploughs or vans, (4) flocculation zone, (5) thickening zone, (6) thickened sludge hopper, (7) belt scraper, and (8) wash station. It is recommended to perform testing to verify if the sludge can be thickened using GBT and determine the optimal design and performance parameters.

Table 4-1 Gravity Belt Thickener Design Criteria and Performance

Sludge Type	Dry Solids %	Solids Loading Kg DS/m.h	Polymer Dosage g/Kg DS	Thickened Sludge % DS
PS	2 - 5	900 - 1400	1.5 - 3	8 - 12
WAS	0.4 – 1.5	300 - 540	3 - 5	4 - 6
PS + WAS (50:50)	1 – 2.5	700 - 1100	2- 4	6 - 8
ANDS (50 PS: 50 WAS)	2 - 5	600 - 790	3 - 5	5 - 7
ANDS (100% WAS)	1.5 – 3.5	500 - 700	4 - 6	5 - 7
ADS (100% WAS)	1 – 2.5	500 - 700	3 - 5	5 - 6

5. Rotary Drum Thickening (RDT) (Turovskiy and Mathai, 2006)

In the rotary drum thickener (RDT) the sludge thickening is achieved by draining the free water through a porous media, which is similar to the gravity belt thickener. The RDT also requires a pre-chemical conditioning step using polymer to produce satisfactory results. The porous media is a drum with wedge wires, perforations, stainless steel fabric, polyester fabric, or a combination of stainless steel and polyester fabric. The chemically conditioned sludge is fed along the drum length. The drum rotates on trunnion wheels and is driven by a variable-speed drive at a speed of 5 - 20 rpm. The speed variation caters for feed sludge quality fluctuation and required degree of thickening. Inside the drum, the free water drains through the drum perforation while an internal screw transports flocculated thickened solids to exit at the opposite end through a discharge chute. The drained water is collected in a trough and discharged to a sump. The RDT is typically equipped with a rotary brush, and a water spray bar extends the entire drum length to clean the drum to prevent blinding of the perforations. The machine is usually covered for housekeeping and odour control. Figure 5-1 present a typical rotary drum thickener schematic. A feed sludge with a concentration as low as 0.5% can be thickened using RDT with high solid capture rate. Advantages of RDT include small footprint and relatively low capital cost and power consumption. However, its main disadvantage is being polymer dependent; it is sensitive to polymer type because of the shear potential of flocs in the rotating drum. The typical range of polymer dosage for RDT is 2.5 - 5 g/kg dry solids. It is also more suited for indoor installation. RDT can be used for thickening waste activated sludge, anaerobically and aerobically digested sludge. The typical design and operation parameters for RDT are: (1) Feed sludge characteristics, (2) polymer type and dosage, flocculation device, degree of mixing, and application point, (3) solids and hydraulic loading rates , (4) drum rotational speed, (5) solids capture rate, (6) thickened sludge concentration, (7) drum dimensions, (8) filtrate quality, and (9) wash water requirement. Typical performance criteria of the GBT are presented in Table 5-1.

RDT is usually utilised in small to medium-sized wastewater treatment plants. Units are available up to 24 L/sec and 500 kg DS/h. Table 3.12 presents typical performance data for rotary drum thickeners.

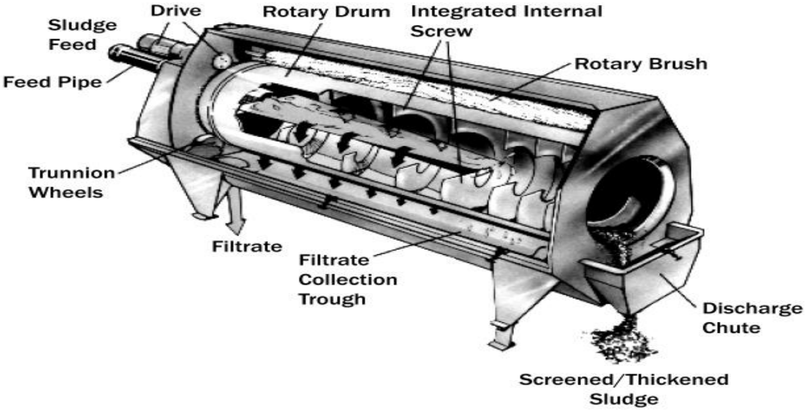


Figure 5-1 Schematic Diagram of the Rotary Drum Thickener (Reprinted with permission from Johan Wiley & Sons-Books)

Table 5-1 Typical Performance Data for Rotary Drum Thickeners

Sludge Type	Feed Solid % DS	Water Removed %	Thickened Sludge % DS	Solids Recovery % DS
PS	3 - 6	40 - 75	7 – 9	93 - 98
WAS	0.5 - 1	70 – 90	4 - 9	93 - 99

Sludge Type	**Feed Solid % DS**	**Water Removed %**	**Thickened Sludge % DS**	**Solids Recovery % DS**
PS + WAS	2 - 4	50	5 - 9	93 - 98
ADS	0.8 - 2	70 – 80	4 - 6	90 - 98
ANDS	2.5 - 5	50	5 - 9	87 - 99

Appendix 6 – Sludge stabilisation

1. Aerobic Digestion

Aerobic digestion is a suspended growth biological process similar to the activated sludge process where the biodegradable organic part of the sludge is oxidised to carbon dioxide, water and ammonia (Wang et al., 2007). As the digestion process proceeds, the ammonia is further oxidised to nitrate (Wang et al., 2007). The difference is that it operates at almost zero food-to-microorganism (F/M) ratio where biodegradable organic matter oxidation occurs within the microorganisms cell tissue as the microorganisms begin to consume their own protoplasm to obtain energy for cell maintenance reactions (Turovskiy and Mathai, 2006). This phenomenon of obtaining energy from the oxidation of cell tissue, known as endogenous respiration (Turovskiy and Mathai, 2006). The aerobic stabilisation occurs over a long sludge retention time (SRT) period, varying between 40 to 60 days until the sludge is fully stabilised, odourless, and only biologically stable solids remain (Qasim et al., 2008). During the stabilisation process, 75 to 80% of the microorganisms cell tissues are oxidised (Qasim et al., 2008). The remaining 20 to 25% contains fixed suspended solids (FSS), nonbiodegradable VSS, cell debris, and a small amount of biodegradable VSS (Qasim et al., 2008). Aerobic digestion is the most commonly used sludge stabilisation process in wastewater treatment plants that treat less than 20,000 m^3/d (Turovskiy and Mathai, 2006, Qasim et al., 2008). The major advantages of the aerobic digestion are; (1) Simple process operation that doesn't require special skills, (2) low capital cost, (3) the supernatant is low in BOD_5, (4) the digested sludge is odourless, humuslike, biologically stable (5) the process has a high tolerance to feed sludge quality fluctuation and toxicity (5) suitable for digesting nutrient-rich sludge, (6) Safe process, no emission of explosive gasses, (7) easy to construct, (8) allows recovery of fertilizer value in biosolids, and (9) the digested sludge is dewatered readily on sand drying beds (Turovskiy and Mathai, 2006, Qasim et al., 2008).

The major disadvantages are: (1) the produces sludge exhibits poor dewaterability by mechanical equipment; (2) high operation cost due to high air supply rate, increase further if oxygen is used; (3) performance is affected by temperature, solids concentration, location and aeration and mixing equipment; (4) the process consumes alkalinity, and (5) the methane gas is not produced, therefore no energy recovery (Turovskiy and Mathai, 2006, Qasim et al., 2008).The aerobic digestion processes used in sludge stabilisation are (Qasim et al., 2008):

- Conventional aerobic digestion (mesophilic);
- Aerobic digestion with pure oxygen;
- Thermophilic aerobic digestion.

Conventional Aerobic Digester (Qasim et al., 2008)**;** The conventional aerobic digester is the mst commonly used. This process can be used for waste activated sludge or a combined waste activated sludge and primary sludge. It involves the aeration and mixing of the sludge in an unheated tank (mesophilic temperature range). The aeration is the source of oxygen, and can be accomplished by diffused air system or surface aeration; mixers can also be used if needed. The solids concentrations within the aerobic stabilisation tank shouldn't be more than 3% DS. Higher solids concentration dramatically decreases the system's oxygen transfer efficiency, hindering the oxygen assimilation by microorganisms and promoting anaerobic conditions in the core of the bacterial floc.

The conventional aerobic digestors have two modes of operation; batch and continuous-flow. Batch-operated aerobic digesters are commonly used in small size plants (less than 2000 m^3/d). The operation sequence of a batch-operated aerobic digester is fill, settle and decant. It may also require a pre-storage for the sludge; a pre-gravity thickener can also be utilised. The continuous-flow aerobic digester may utilise a pre or post gravity thickener. The different operation modes and arrangements of conventional aerobic sludge digester are presented in Figure 2-1. Post storage is required for both modes of operation before dewatering.

Process Parameters of concern for performance and design of the conventional aerobic digester are: (1) sludge retention time (SRT) or aeration period or Hydraulic retention time, (2) organic solids loading, (3) air or oxygen requirements, (4) volatile solids reduction, (5) feed sludge concentration and volatile solids fraction in the digester, (6) energy requirement for mixing, (7) Dissolved oxygen level, (8) temperature, (9) the ratio of aeration to mixing periods, (10) Ultimate disposal requirement, and (11) supernatant quality (if decanting).

The conventional aerobic digester can achieve volatile solids reduction (VSR) ranging from 20 to 50%. The VSR is a function of the sludge temperature-time factor (°C-d). A typical VSR of 40% at 20 °C can be achieved within 10 to 15 days of SRT. Values of VSR with respect to the sludge temperature-time factor are presented in Table 2-1. Another critical item to assess the conventional aerobic digester performance is the supernatant quality. For a well operated conventional aerobic digester, the supernatant quality is close to the raw wastewater influent quality; therefore, recycling the supernatant to the treatment plant mainstream is trouble-free. The typical supernatant quality of a conventional aerobic digester is presented in Table 2-2. Alkalinity consumption will occur during aeration as the nitrification process occurs. The nitrification process will consume two moles of alkalinity for each mole of ammonia oxidised. Alkalinity consumption will drop the pH if enough alkalinity is not present. On the other hand, if the complete nitrification/denitrification step occurs, approximately 50% of the consumed alkalinity can be recovered. To overcome the alkalinity consumption and maintain pH control, maintain dissolved oxygen level to less than one mg/l. At such low oxygen concentration, nitrification will not occur. The basic design and performance parameters of the conventional aerobic digest are presented in Table 2-3.

2. Anaerobic Digestion

Anaerobic digestion is one of the oldest sludge stabilisation processes (Turovskiy and Mathai, 2006). The process involves transforming organic matter in the sludge into methane, carbon dioxide and inoffensive matter, in the absence of oxygen (Metcalf & Eddy/AECOM, 2014). The produced sludge is stable, has no offensive odour and is low in pathogens (Qasim et al., 2008). A reduction in the sludge quantity is also achieved in the anaerobic digestion process (Metcalf & Eddy/AECOM, 2014). The associated advantages and disadvantages of anaerobic digestion in comparison to other stabilisation methods are;

Principal advantages (Turovskiy and Mathai, 2006) ;

- It offers the possibility of energy recovery by using the biogas (65% methane) produced. In most cases, the amount of biogas produced exceeds the amount required to maintain the digestion process temperature. Excess biogas can be used to generate electricity to run some of the treatment work equipment.
- It achieves a typical sludge mass reduction between 30% to 50%. This reduction is mainly in the volatile solid content. Such reduction can significantly reduce the cost of sludge disposal.
- The digested solids are typically free of offensive odours.
- The digested biosolids have relatively good fertilizer value as they contain nutrients such as nitrogen, phosphorus, and organic matter that can improve the fertility and texture of soils.
- It improves sludge dewaterability.
- The digested sludge has a low pathogen count, especially with the thermophilic digestion process.

Principal disadvantages (Turovskiy and Mathai, 2006);

- High capital cost due to process requirements, such as closed tanks fitted with heating system, feed, mixing and gas storage.
- Large reactors are required to provide the necessary sludge retention time (hydraulic retention time) for effective sludge stabilization.
- The anaerobic digestion process is sensitive to small changes in operating conditions. Therefore, the process is susceptible to upsets. The digestion process is also slow, limiting the system's speed to adjust to changes in operation conditions, such as loads, temperature, pH, etc.
- The process produces poor-quality supernatants with a high concentration of COD suspended solids, nitrogen, and phosphorus. The supernatant may require additional treatment to remove contaminants mentioned above, before recycling to the plant head-of-works or disposal.

Anaerobic digestion involves several successive stages of chemical and biochemical reactions by several groups of facultative and anaerobic microorganisms (McFarland, 2001).

Table 2-1 Typical Volatile Solids Reduction for Different Temperature–Time Factor in Conventional Aerobic Digestion (Qasim, 2018)

*Digester Liquid Temperature-Time Factor, °C-d	Volatile Solids Reduction (VSR), %
135	20
235	30
325	35
500	40
854	45
1400	50

*Digester liquid temperature-time factor = Temperature (in °C) x SRT (in days).

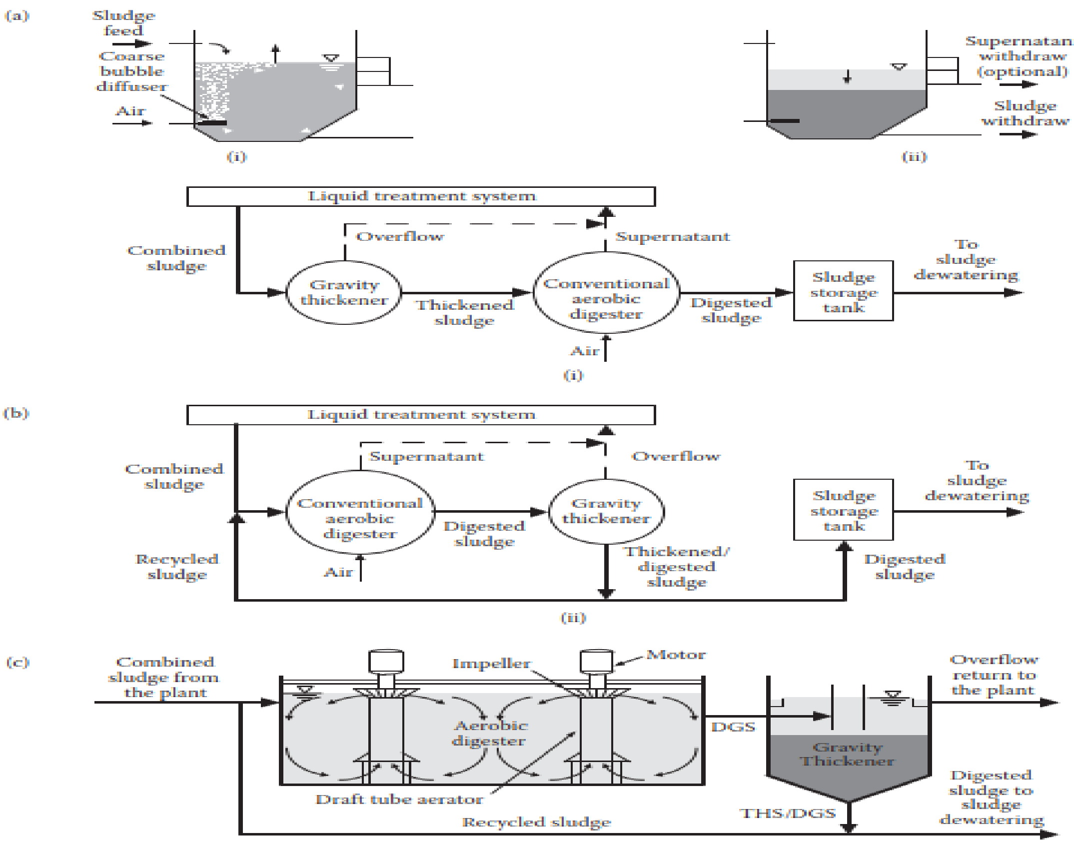


Figure 2-1 Conventional aerobic sludge digester: (a) batch-operated aerobic digester: (i) aeration cycle with sludge feed and (ii) settling cycle with supernatant and digested sludge withdrawal; (b) continuous-flow aerobic digester: (i) pre-thickening and (ii) post-thickening; and (c) schematic of a continuous-flow rectangular aerobic digester with post-thickening and aeration draft tubes. (Reprented with permission from Taylor & Francis Group LLC – Books)

Table 2-2 Characteristics of Supernatant from Conventional Aerobic Digestion (Qasim, 2018)

Parameter mg/l	Range (Typical value)
pH	6 - 7.5 (7)
BOD_5	200 - 1500 (500)

Parameter mg/l	Range (Typical value)
Soluble BOD_5	5 - 200 (50)
COD	200 - 8000 (2500)
TSS	500 - 10 000 (3500)
Total Kjeldahl N (TKN), as N	10 - 400 (150)
Total P (TP), as P	20 - 250 (100)
Soluble P, as P	2 - 60 (25)

Table 2-3 Performance and design Parameters of Conventional Aerobic Digester (Qasim, 2018)

Parameter	Value or Range	Remarks
SRT, d	10 - 15 @ 20 °C	For VSS reduction only
Volumetric solids loading (VSL), kg VSS/m^3·d	1.6 - 4.8	
Per capita capacity requirement (PCCR), m^3/capita	0.06 - 0.2	
Oxygen requirement, kg O_2/kg VSS reduced		
- Stabilisation of cell tissues in waste activated sludge (WAS)	2.3	
- Oxidation of BOD_5 in primary sludge	1.6 - 1.9	
Volatile solids reduction (VSR), %	20 - 50	
Minimum energy requirement for mixing;		
- Diffused aeration, sm^3/m^3·min		
- WAS	0.02 - 0.04	
- PS + WAS	0.06	
- Mechanical aeration, KW/m3	0.02 - 0.04	
Power requirement per 10,000 population equivalent, kW	6 - 7.5	
Solids content, % DS		Feed solids content of 3 - 4% may require careful selection of mixing and aeration equipment.
- Feed Sludge	1 - 4	
- Digested Sludge	1 - 3	
Minimum DO in the liquid, mg/l	1 - 2	The alternation between aeration and mixing is recommended to optimise nitrification and denitrification for alkalinity recovery and energy saving.
Minimum sustained low temperature, °C	15	For cold climate; the use of high-purity oxygen is recommended.
Minimum pH	>5.5	Addition of alkalinity is recommended as needed to maintain the pH above 5.5

The process comprises of three phases as follows; (1) hydrolysis phase, (2) acidogenesis phase, and (3) methanogenesis phase (Qasim et al., 2008). Figure 2-2 is a simplified representation of the reactions involved in anaerobic digestion. In the hydrolysis phase, complex organic matters such as carbohydrates, proteins, lipids and other complex organics in the sludge are solubilised and converted to their simple monomers (Qasim et al., 2008). In the acidogenesis phase (also known as fermentation or acidogenic phase), acid-forming microorganisms convert the soluble organic products formed in the first phase to short-chain organic acids: mainly, acetic, propionic, butyric and lactic acids, and hydrogen and carbon dioxide (Qasim et al., 2008). The degree and rate of Hydrolysis are the limiting factors for the acidogenesis phase (Taricska et al., 2007).

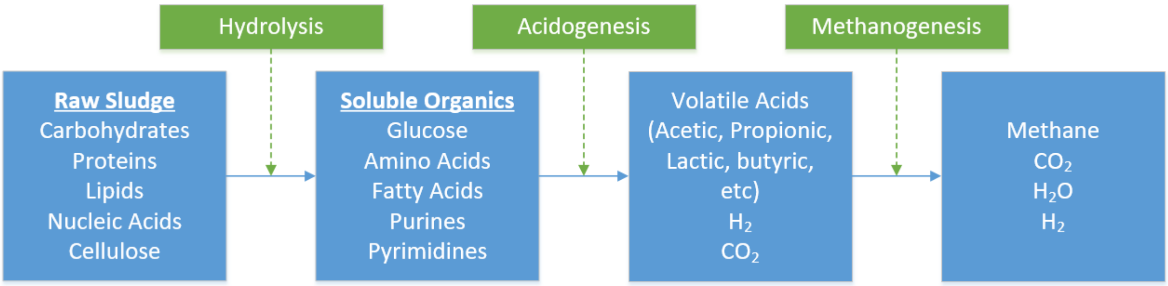


Figure 2-2 General Anaerobic Biological Reactions

The acid-forming microorganisms are primarily facultative bacteria (Turovskiy and Mathai, 2006). They are relatively tolerant to changes in pH and temperature (Turovskiy and Mathai, 2006). Facultative bacteria also consume dissolved oxygen during metabolism (Turovskiy and Mathai, 2006). Hence; it protects the methanogens bacteria, which are strict anaerobes, from the dissolved oxygen in the feed sludge (Turovskiy and Mathai, 2006).In the methanogenesis phase (also known as methanogenic phase), the methane forming bacteria convert the volatile acids into methane, carbon dioxide, water and hydrogen (Taricska, 2007).

The acidogenesis and methanogenesis phases are in dynamic equilibrium, where methane and carbon dioxide are formed at the same rate as volatile acids and Hydrogen (Turovskiy and Mathai, 2006). As a result, a properly working digester should have low levels of volatile acid and hydrogen (Turovskiy and Mathai, 2006). However, the methane forming bacteria are naturally very slow-growing and susceptible to even small change in pH, temperature, substrate composition, and toxic compounds (Wang, 2007). On the contrary, acid-forming bacteria, are fast-growing and can function over a wide range of environmental conditions (Wang, 2007). Therefore, when the anaerobic digester is under shock loads or temperature stress, the sensitive methanogenic bacteria don't adjust to such changes fast enough. As a result, the volatile acids and hydrogen are not converted to methane and carbon dioxide at the same rate they are formed(Turovskiy and Mathai, 2006). Once the dynamic balance between the acidogenesis and methanogenesis phases is interrupted, volatile acids and hydrogen accumulate and the pH drops. Therefore, further inhibition of the methanogenic bacteria occur (typically at pH below six methane formation ceases), and the digestion process eventually fails(Turovskiy and Mathai, 2006).

The typical environmental and performance factors that influence the anaerobic process are (Qasim, 2018), (1) Solids retention time (SRT) and Hydraulic retention time (HRT), (2) Temperature, (3) pH and Alkalinity, (4) Toxic substances (5) Feed Sludge composition, (6) Volatile solids reduction, (7) Per Capita basis, (8) mixing, (9) Pathogens reduction, (10) Biogas production and (11) Heating. The sensitivity of the anaerobic organisms to environmental factors is presented in Table 2-4 (Turovskiy and Mathai, 2006).

Table 2-4 Sensitivity of the Anaerobic Organisms to Environmental Factors

Parameters	Acidogenic bacteria	Methanogenic bacteria
Growth Rate	High	Slow
pH	Low sensitivity	High sensitivity
Temperature	Moderate sensitivity	High sensitivity
Toxic materials	Moderate sensitivity	High sensitivity
Volatile caids	Low sensitivity	High sensitivity
Redox potential	Low sensitivity	High sensitivity

1. Solids Retention Time (SRT) and Hydraulic Retention Time (HRT) (Turovskiy and Mathai, 2006 , Qasim 2018);

The SRT can be defined as the average time the solids are kept in the digester, and the HRT can be defined as the average time the liquid sludge is kept in the digester. From operation prospective SRT and HRT can be defined as;

- SRT (days) is the mass of solids in the digester (kg) divided by the mass of solids withdrawn daily (kg/d).
- HRT (days) is the volume of sludge in the digester (m^3) divided by the volume of digested sludge withdrawn daily (m^3/d).

The SRT of the anaerobic process should cater to the slow-growing methanogenic microorganisms that control the reaction time required for the process to be completed. There is a minimum SRT to complete the hydrolysis, fermentation, and methanogenesis phases. If SRT is less than the minimum, the overall process efficiency will decrease dramatically and may cease. It's also worth noting that the anaerobic process efficiency doesn’t increase indefinitely as SRT and HRT increase. After the optimum SRT and SRT are reached, the rise in process efficiency is minimal. However, in practice, the anaerobic digester is designed with SRT and HRT higher than the optimum to make up for common operational issues such as (1) fluctuation of feed sludge rate, (2) inefficiency of the sludge mixing system, (3) variation of ambient temperature and (4) accumulation of inert material inside the digester. Typically, the SRT for the mesophilic temperature range is 15 – 20 days and 8 – 12 days for the thermophilic temperature range. SRT lower than seven days is insufficient for stable digestion and results in very low volatile solids destruction and accumulation of volatile fatty acids in the digester. The SRT is also a function of the digester type.

2. Temperature (Turovskiy and Mathai, 2006 , Qasim 2018);

The temperature greatly impacts the anaerobic digestion process as it affects the microorganisms' growth rate and kinetics. Therefore, the temperature influences the SRT and HRT selection and the overall process efficiency. The anaerobic digesters can operate in the mesophilic 30–38°C, and the thermophilic 50–57°C temperature ranges. However, most of the anaerobic digesters are operated in the mesophilic range. Thermophilic digestion has several advantages: (1) improve volatile solids reduction and gas production; (2) higher overall performance efficiency; and (3) improve dewatering properties of digested sludge. However, the energy required to maintain thermophilic range is high, and it may require supplementary fuel to maintain temperature range, especially in cold climates. It is essential to maintain a constant temperature range within the digester and avoid sharp temperature changes or continuous fluctuation.

3. pH and Alkalinity (Turovskiy and Mathai, 2006 , Qasim 2018);

The microorganisms involved in the anaerobic digestion process in different phases has a different range of optimum pH. Hydrolytic and acidogenic bacteria are active above pH 5.0. Methane-producing bacteria are susceptible to pH. The optimum pH for methanogenic bacteria ranges between 6.7 and 7.5. Therefore, single-stage anaerobic digesters generally function in a pH range of 6.8–7.2.

The volatile acids produced during the acidogenesis phase is usually counteracted by the alkalinity produced during the methanogenesis phase. Alkalinity is essential to provide buffering capacity, especially during sudden increases in the volatile acid concentration. In a well-operated digester, the total alkalinity should range from 2000 to 5000 mg/L with a volatile acid to alkalinity ratio of 0.05–0.25 (typical ratio < 0.1 is preferred). If pH drops below 6.0, methane formation will cease, volatile acids will accumulate, and the digestion process will reach a standstill. In the event alkalinity is needed to correct operational problems; bicarbonates of calcium, magnesium, and ammonium can be used as alkalinity sources.

4. Toxic Substances (Turovskiy and Mathai, 2006 , Qasim 2018);

Several substances are toxic to the anaerobic process; however, heavy metals, ammonia, sulfides, and some inorganic materials are of primary concern. Toxic conditions typically occur due to overloading, excessive addition of chemicals, or from the addition of industrial wastewater containing toxic substances to the plant influent. Table 2-5 and Table 2-6 present typical toxic and inhibitory substances of concern. However, heavy metal toxicity is the primary cause of the anaerobic digester failure; they are required in trace amount for cell synthesis. Sewage sludge typically contains a low concentration of heavy metals unless industrial wastewater is introduced to the wastewater treatment works feed.

Ammonia is a product of the urea and protein anaerobic digestion, and it is considered toxic if present at a concentration of 1000 mg/L or higher. Sulphide is considered toxic to the methanogenic bacteria if present at a concentration higher than 200 mg/l. Sulphide precipitation as iron sulphide by adding the iron salts to the digester is the typical method to control its toxicity.

Table 2-5 Selected Toxic and Inhibitory Inorganic Materials in Anaerobic Digester

Substance	Moderately Inhibitory Concentration – mg/l	Strongly Inhibitory Concentration – mg/l
Sodium -Na^+	3500 - 5500	8000
Potassium - K^+	2500 - 4500	12000
Calcium - Ca^{2+}	2500 - 4500	8000
Magnesium - Mg^{2+}	1000 - 1500	3000
Ammonium - NH_4^+	1500 – 3500	3000
Sulphur - S^{2-}	200	200
Cupper - Cu^{2+}		0.5 (soluble) 50 - 70 (total)
Chromium 6 - Cr^{6+}		3 (soluble) 200 – 250 (total)
Chromium 3 - Cr^{3+}		2 (soluble) 180 – 420 (total)
Nickel - Ni^{2+}		30 (total)
Zink - Zn^{2+}		1 (soluble)

Table 2-6 Selected Toxic and Inhibitory Organic Materials in Anaerobic Digester

Substance	Concentration Resulting in 50% Reduction in Activity - (mM)
1-chloropropene	0.1
Nitrobenzene	0.1
Acrolein	0.2
1-Chloropane	1.9
Formaldehyde	2.4
Lauric acid	2.6
Ethylbenzene	3.2
Acrylonitrile	4
3-Chlorol-1,2-propanediol	6
Crotonaldehyde	6.5
2-Chloropropionic acid	8
Vinyl acetate	8
Acetaldehyde	10
Ethyl acetate	11
Acrylic acid	12
Catechol	24
Phenol	26
Aniline	26
Resorcinol	29
Propanol	90

5. Feeding and Sludge composition (Gurjar et al., 2017);

Typically, the feed sludge to the digester is a mixture of primary and secondary sludge. The primary sludge is discrete and rich in lipids, whereas the secondary sludge is more flocculated and protein-rich. As a result, the hydrolysis of primary sludge is faster than that of secondary sludge and is readily biodegradable. Typically, primary sludge and secondary sludge are digested together after being blended and thickened to improve volatile solids and COD reduction. Increasing the primary sludge fraction in the feed sludge and the SRT generally increases the overall volatile solids reduction.

Feeding the sludge into a high-rate digester continuously or at regular intervals maintains

Sludge is fed continuously or at equal intervals into a high-rate digester to maintain steady process conditions in the digester and avoid shock loads. Shock loading the digester may affect its temperature and dilutes the alkalinity, affecting the digester buffering capacity against pH.

6. Volatile solids reduction (Metcalf & Eddy/AECOM, 2014);

Volatile solids reduction in high-rate anaerobic digesters usually ranges from 50 to 65%. The volatile solids reduction achieved in any digesters type depends on the feed sludge's characteristics and the operating parameters of the digestion system. The performance of the digester is measured by the degree of volatile solids reduction. For high-rate digesters, the following empirical equation calculates the percentage of volatile solids reduction.

$$V_d = 13.7\ \ln(SRT) + 18.9$$

Where V_d is the volatile solids reduction (%), and SRT is the design Sludge retention time (days).

7. Per Capita basis (Turovskiy and Mathai, 2006);

Per Capita is the oldest and simplest criteria used to size the digester volume initially. It provides an estimate to the digester volume based on the population served by the treatment work. However; it shouldn't be the only criteria to size the digester.

8. Mixing (Qasim, 2018);

The mixing is a critical parameter for the digester performance. Mixing the digester content provides the following benefits; (1) It reduces thermal stratifications, (2) allow for better contact between the raw sludge and active bacteria, (3) almost eliminate scum buildup, (4) provide a homogeneous environment and reduce the adverse effect of feed sludge quality fluctuation, (5) maintain the useful volume of the reactor, (6) allow gas to separate easily, and (7) prevent inorganic material from settling. Natural mixing may occur as a result of the rising of gas bubbles and the thermal convection currents formed by the feed of heated sludge, however, it is inadequate, particularly for high-rate digesters.

The methods used for mixing include external mixing pumps, mechanical mixers, and gas mixing. Each of these methods has advantages and disadvantages; therefore it must be selected carefully, considering the local experience and availability. Mechanical mixing requires about 0.007 kW/m3 of digester volume to provide efficient mixing. On the other hand, the mixing power required for external mixing pumps is 0.005 to 0.008 kW/m^3 of digester volume, with 20 to 30 minutes of turnover time. However; unit gas flow requirement for gas mixing is 0.005 to 0.007 $m^3 \cdot min$

9. Pathogens reduction (Metcalf & Eddy/AECOM, 2014);

Raw sludge contains a great variety of pathogenic organisms. Pathogens reduction is essential to minimise health risks to the population and the workers who handle the sludge and reduce negative environmental impacts when used for land application. The anaerobic digestion process significantly reduces these organisms, mainly in the thermophilic range due to the higher temperature.

10. Biogas production (Wang et al. 2007 , Qasim et al. 2018);

Anaerobic digestion processes produce biogas as a by-product of the digestion process. The Biogas produced from a healthy digestion process is a mixture of methane (CH_4 – 65 to 70%), carbon dioxide (CO_2 – 30 to 35%), small concentrations of nitrogen, oxygen, hydrogen , hydrogen sulphide and traces of volatile hydrocarbons. The biogas production is approximately 0.8 to 1.1 m^3/kg volatile solids reduced, equivalent to approximately 25 to 35 L/capita·day. The composition of the Biogas influences its density and heating value; hence higher the methane concentration in the biogas, the higher its heating value and the lower its density. Biogas with 70% methane content has a heating value of approximately 23,380 kJ/m3 (6.5 kW/m3), while natural gas has a heating value of 37,300 kJ/m3 (10.4 kW/m3).

11. Heating (Andreoli et al., 2007 , Qasim, 2018);

Heating the digester content and maintaining the operating range's temperature with minimal fluctuation is very critical. The produced Biogas can be utilised as a fuel source to generate the necessary heat. In most cases, the digestion process is self-sufficient and doesn’t require an external fuel source. The external fuel source will only be required during system start-up.

The amount of heat required to raise and maintain the digester temperature can be calculated using the following equations;

$$\mathrm{H_R} = [\mathrm{Q}\,\mathrm{C_P}\,(\mathrm{T_2} - \mathrm{T_1})] + \mathrm{H_L}$$

Where

H_R = heat required, J/d

Q = feed sludge weight, kg/d

C_p = specific heat of sludge, J/kg · °C

T_2 = design operating temperature of the digester, °C

T_1 = temperature of feed sludge, °C

H_L = heat loss, J/d

The heat loss of the digester wall, cover and floor can be calculated using the following equation;

$$\mathrm{H_L} = \mathrm{U}\,\mathrm{A}\,(\mathrm{T_2} - \mathrm{T_3})\ 86{,}400$$

Where

H_L = heat loss, J/d

U = heat transfer coefficient, J/s.m^2.°C

A = surface area of digester through which heat losses occur, m^2

T_2 = temperature of sludge in the digester, °C (°F)

T_3 = temperature outside the digester, °C (°F)

The most common equipment used for heating is the external heat exchangers. Other heating methods are less common or discontinued due to its complexity and low efficiency, such as steam injection directly into the tank, direct flame heating by passing hot combustion gases through the sludge, and heat exchanger coils placed inside the tank. The external heat exchanger also allows the raw sludge's blending with recycled hot sludge before feeding to prevent possible thermal shock to the anaerobic bacteria. The external heat exchanger has three commonly used types: water bath, jacketed pipe, and spiral. Each type has its advantages and disadvantages that must be considered during the selection process along with local experience and availability.

Type of Anaerobic Digesters (Qasm, 2018) (Turovskiy & Mathai, 2006, Qasim, 2018);

The anaerobic digesters can be categorised as single-stage or multiple-stage. The single-stage digesters may operate at a standard- or high-rate. The multiple-stage digesters are further categorized as staged or phased digestion. The multi-stage digesters and the single-stage-high-rate digesters operate in the either mesophilic or thermophilic temperature range. However, The single-stage digester operates at a lower temperature than the mesophilic range. The required heat value to maintain operating temperature can be reduced by insulation the digester cover, wall and floor. The primary design and performance parameters are presented in Table 2-7.

a) Single-stage anaerobic digesters – Standard Rate;

The single-stage anaerobic digester is the oldest and most straightforward type of the anaerobic sludge digestion process. It is mainly a single cylindrical tank with a sloped floor and a flat or domed roof. The process is unheated and unmixed. The raw sludge is fed to the digester intermittently; however, the digested sludge and supernatant are withdrawn periodically. The feed sludge is typically unthickened. The produced gas rise to the top and provide some degree of mixing; however, the digester contents are stratified into four layers. These layers from top to bottom are, (1) scum, (2) supernatant, (3) actively digesting solids, and (4) digested sludge. A lengthy detention time between 30 to 60 days is one of the main characteristics of this process. Reduction in the active digester volume and sometimes pH drop in some layers are additional disadvantages. Oil and grease digestion is low, because they tends to float to the top of the digester. The accumulated scum on the surface requires an additional mechanism for its destruction. Methanogenic bacteria are removed with the digested sludge and not recycled to the top layers below the scum, where volatile acids accumulate, resulting in poor operation. This process is typically considered for small plants of less than 3800 m^3/d; however, they are seldom used today.

b) Single-stage anaerobic digesters – High Rate;

The standard-rate digesters were developed further by adding a few improvements, resulting in a high-rate anaerobic digestion system. These additional improvements include heating, auxiliary mixing, pre-thickening of raw sludge, and uniform feeding. As a result, the tank volume is reduced, and the stability and efficiency of the process are improved. The high-rate digester can handle a higher solids load if compared to the standard-rate digester. The sludge feed and withdrawal are made on continuous bases with an option to decant. Typically the high-rate digester operates in the mesophilic temperature range. Heating is critical as it determines the rate of microbial growth and the rate of digestion and gas production. Maintaining a constant process temperature is critical as temperature fluctuation affects performance where a minor temperature change quickly inhibits the methanogenesis bacteria. Mixing the digester content provides several benefits, as mentioned above under mixing. Thickening sludge before feeding it to the high-rate digester was found beneficial. Thickened sludge has less moisture and hence requires less digestor volume. Thickened sludge will also reduce the amount of supernatant if decanting occurs or when used in the two-stage arrangement. Maximum feed sludge concentration should not exceed 6% DS; otherwise, the fluidity of the sludge will be intricate, hence hampering its movement in pipes and mixing in the digester. The high-rate digesters may operate in the thermophilic temperature range; however, it’s uncommon. The high-rate thermophilic digesters are claimed to have the following advantages and disadvantages;

Advantages; (1) Higher temperature increase reaction rate, thus permitting higher volatile solids reduction, and (2) higher pathogens destruction.

Disadvantages; (1) Higher energy consumption for heating, (2) produces supernatant with low quality that contains large quantities of dissolved matters, (3) higher potential to release odour, (4) Thermophilic bacteria are more sensitive to temperature fluctuation, (5) digested sludge has poor dewaterability if compared to the mesophilic digested sludge, (6) Higher ammonia concentration in the supernatant if used with decanting or two-staged digester, (7) complex system if head recovery is utilised, and (8) More susceptible to foaming.

c) Multi-Stage digester - Staged mesophilic anaerobic digester

The staged anaerobic digester is also called two stages digester. It consists of primary and secondary digesters. The primary digester is a high-rate digester, while the secondary digester is a standard-rate digester. The two-staged digester typically operates in the mesophilic temperature range. The secondary digester provides additional digestion and storage. It also allows for decanting of the digested sludge before the withdrawal. The decanting increases the digested sludge concentration and reduces the volume of the liquid withdrawn with the solids. The secondary digester can be fitted with a floating or fixed cover to provide additional storage and recovery for the digester gas. In many cases the secondary digester is equipped with heating and mixing capabilities like the primary digester, to provide standby digester capacity. It has been noticed that the secondary digester may not perform as expected in decanting and thickening, and it may produce diluted digested sludge and low-quality supernatant. The evolving gas is a major contributor to the low supernatant quality as the bubbles attach to the sludge particles and provide a buoyant force that hinders settling. Another contributor to low supernatant quality is mechanical mixing, as it produces fine solids that don't settle well. The two-stage digestion process is currently not in use as common as before.

d) Multi-Stage digester - Staged thermophilic anaerobic digester

Two or more high-rate thermophilic anaerobic digesters are typically used in series. The first digester is the largest in size to achieve efficient volatile solids reduction. It is followed by one or two smaller digesters that operate in batch mode to prevent short-circuiting of pathogens.

c) Phased digesters - Acid/gas phased anaerobic digesters

In this process, the anaerobic digestion phases occur in two separate digesters; in particular, the hydrolysis and acidogenesis phase occurs in a separate digester followed by a second digester where the methanogenesis phase occurs. The digesters can be either high-rate mesophilic or high-rate thermophilic, or combination of high-rate mesophilic and high-rate thermophilic. The first reactor, known as acid-phase digester, is designed for 1 to 3 days detention time. The reactor pH is between 5.5 and 6.5 with a volatile acid concentration that may exceed 6000 mg/l, and almost no methane gas production occur. The second digester, known as gas-phase digester, is designed for maximum ten days detention time. In the 2nd digester, the volatile acids are converted into Methane and Carbon dioxide. The phase separation was found to have some advantages including; (1) Higher volatile solids reduction, (2) Higher gas production with higher Methane content, (3) Higher pathogen reduction, (4) less foaming problems and (5) better overall process stability.

Table 2-7 Primary Design and Performance Parameters of Various Anaerobic Digestion Processes

	Single-stage digester		**Multi-stage digester**		**Phased digester**
Process **Parameter**	**Standard Rate anaerobic digester**	**High Rate anaerobic digester**	**Staged mesophilic anaerobic digester**	**Staged thermophilic anaerobic digester**	**Acid/gas phased anaerobic digester**
Temperature, °C **-** **Mesophilic** **Thermophilic**	20 - 30 - -	- 30 - 38 -	- 30 - 38 -	- - 50 - 57	- 30 -38 50 - 57
pH **1^{st} reactor** **2^{nd} reactor** **3^{rd} reactor**	6.8 - 7.2 - -	6.8 - 7.2 - -	6.8 - 7.2 6.8 - 7.2 -	6.8 - 7.2 6.8 - 7.2 -	< 6 6.8 - 7.2 -
SRT, day **1^{st} reactor** **2^{nd} reactor** **3^{rd} reactor**	30 – 60 - -	15 – 20 - -	7 - 10 Variable -	17 - 22 1.5 – 2 1.5 - 2	1 - 3 >10 -
VSL, **Kg VSS/m^3.d**	0.6 - 1.6	1.6 - 4.8	0.5 - 1.6	4.8 - 6.4	4.8 - 6.4
PCCR, m^3/capita **PS** **WAS** **PS + WAS**	0.06 - 0.09 0.12 - 0.18 0.12 - 0.15	0.03 - 0.06 - 0.09 - 0.12	-	-	-
Solids Content, % **Feed Sludge** **Digested Sludge**	2 - 4 4 - 6	4 - 6 3 - 5	4 - 6 3 - 5	5 - 6 3 - 5	5 - 6 3 - 5
VSR, %	30 - 40	40 - 60	40 - 60	50 - 65	50 - 60

3. Lime Stabilisation (McFarland, 2001, Turovskiy and Mathai, 2006)

In addition to the aerobic and anaerobic stabilisation, sludge can be stabilised by the addition of chemicals. The original objective of lime addition was for sludge conditioning to improve its dewaterability, but it was observed that odours and pathogen levels were also reduced in time. Subsequently, lime addition became a major sludge stabilization alternative. In this process, the stabilisation is achieved by adding lime and lime containing materials to the sludge. Three different lime stabilization processes are available (1) liquid lime stabilization (also known as pre-lime stabilisation), (2) dry lime stabilization (also known as post lime stabilisation), and (3) advanced alkaline stabilization. In the first two processes, the principal chemicals used are hydrated lime and quicklime (calcium oxide). In the lats process, other materials than lime are used. These materials are; cement kiln dust, lime kiln dust, carbide lime, certain types of fly ash from burning wood and fossil fuels, by-products of stack gas desulfurization and drinking water treatment sludge.

The lime stabilisation primary objectives are to inhibit bacterial decomposition and inactivate pathogenic organisms. To accomplish the primary process objectives; (1) the sludge is typically treated in the liquid state (i.e. thickened), (2) pH is raised to 12.5 and maintained for 30 min (which keeps the pH > 12 for at least two hours), and (3) added lime should provide residual alkalinity so that the pH does not drop less than 11.0 for several days. This process typically allows sufficient time for disposal or use before the sludge starts to petrify again.

The required lime dose determination depends on sludge type (i.e. Primary, secondary), chemical composition, and moisture content. Generally, primary sludge requires less lime dose than secondary sludge, except when iron salts or alum are used for sludge precipitation. Iron salts or alum reacts with a significant amount of the added lime forming iron and/or aluminium hydroxide species. These type of side reactions leads to higher lime consumption to achieve and maintain the required pH for adequate stabilization. In general, lime stabilization involves several side reactions that reduce the concentrations of soluble phosphate, ammonia, nitrogen, and total Kjeldahl nitrogen (TKN) compared with anaerobically digested sludge. Therefore, the lower nutrient concentrations in lime-stabilized sludge may reduce its value for agricultural and land application use.

Liquid lime stabilisation (Pre-lime Stabilisation);

Quicklime (CaO) and hydrated lime [$Ca(OH)_2$] are both used for liquid lime stabilisation. However, quicklime does not mix easily with liquid sludge and needs to be slaked before application. This process is typically a batch treatment. The contact tank where the liquid sludge (i.e. Thickened sludge)is mixed with the lime is designed for a minimum of two hours of contact time. The mixing process involves the release of gases, predominantly ammonia. The released gases may need to be treated before releasing it into the atmosphere. The stabilised sludge using this process can be used directly for land application; however, transporting large quantities of stabilised sludge limits this process to small wastewater treatment plants. This process is predominantly used as a sludge conditioning step before dewatering. Addition of lime alone for conditioning before dewatering without other conditioners (iron salts or alum), may result in ineffective dewatering. Vacuum filters or pressure filter presses typically accomplish dewatering of lime-stabilized sludge. Centrifuge and belt filter press are hardly used for dewatering of lime-conditioned sludge because of its abrasive nature and scaling problems. Typically the amount of lime dosage required for sludge conditioning is much less than that required for sludge stabilisation. Typical lime dosage for pre-lime stabilisation is given in Table 3-1.

Dry lime stabilisation (Post-lime Stabilisation);

In this process, the dry lime is mixed with the dewatered sludge cake to raise the pH. Quicklime (CaO) is the primary chemical for dry lime stabilisation since it reacts with the moisture and releases heat. Dry hydrated lime may also be used but limited to small installations. Quicklime is less expensive than hydrated lime and is easier to handle in large-scale facilities using lime over 2 to 4 tons/day.

Table 3-1 Lime Dosage for Sludge Pre-lime Stabilization

	Dry Solids Ccentration %		Lime Dosage % Ca(OH)2/ Dry Weight	
Sludge Type	**Range**	**Typical**	**Range**	**Typical**
PS	3 - 6	4.3	6 -17	12
WAS	1- 3	1.3	21 - 43	30
ADS	6 - 7	5.5	14 - 25	19

Additionally, the heat generated from the exothermic reaction of quicklime and the moisture in sludge cake (approximately 64 KJ/g.mole); and the additional heat generated from the reaction between the quick lime and the carbon reaction dioxide (approximately 180 KJ/g.mole) will enhance pathogen destruction. The process requires adequate mixing between the dry lime and sludge cake to avoid pockets of putrescible material and to produce a homogeneous mixture.

Several studies have shown that the addition of 30–50% of CaO on a dry weight basis (0.3 to 0.5 kg CaO per kg TS) to dewatered sludge produces stabilised sludge with non detected pathogenic organisms. If Hydrated lime is used, it will not result in a significant temperature increase, requiring longer contact time. The primary advantages of dry lime stabilization are (1) no moisture is added to the sludge in the form of a lime slurry, (2) no lime-related abrasion and scaling problems to handling or other processing equipment.

Advanced alkaline stabilisation;

Advanced alkaline stabilisation utilises chemical materials other than lime to achieve the required degree of stabilisation. It is a modification of the dry lime stabilisation process. However, materials such as cement kiln dust, lime kiln dust, carbide lime, certain types of fly ash from burning wood and fossil fuels, by-products of stack gas desulfurization and drinking water treatment sludge are used. The primary advantages of this process include; (1) the produced sludge is well-stabilised and is easy to handle; (2) Stabilised sludge has low odour potential and has value as a liming agent; (3) Low capital cost; and (4) easy to operate, start-up, and shut down. The disadvantages include ; (1) high operating costs due to the extensive odour control system required to treat ammonia and other off-gases, (2) the increase in total solids/chemical mass to transport, and the established sludge is not suitable for all soils type, and (3) Proprietary technologies.

Liquid lime and dry lime stabilization processes have several advantages as follows;

- Low capital cost.
- Reliable processes.
- Simple operation

- Quick and easy startup and shutdown.
- Higher reported pathogen reduction in comparison to digestion processes.
- Low product sludge odour, if homogeneous lime feed and mixing occur.
- Stabilized sludge demonstrates improved dewaterability, especially with other conditioners (i.e. Iron salts or alum) added.
- Stabilised sludge may be used as a liming agent on acid soils.
- The elevated pH fix or immobilize specific heavy metals in sludge and soil and, therefore, restrict their possible uptake by plants.

On the other hand, there are several advantages of these processes include;

- Lime stabilisation doesn't reduce the sludge mass.
- Lime stabilisation increase the sludge mass., resulting in higher transportation and ultimate disposal costs.
- Moderate operator attention and housekeeping are required due to the inherent dust in lime.
- Stabilised sludge has lower concentrations of nitrogen and phosphorus than anaerobically digested biosolids.
- Ammonia gas and other off-gases produced by the processes may require treatment before being vented to the atmosphere.
- Dewatered sludge treated with lime can harden during storage.

4. Thermal stabilisation (McFarland, 2001, Wang et al. 2007)

Thermal stabilisation of sludge, also known as thermal conditioning or Heat treatment, is a continuous flow process typically used for sludge stabilisation and conditioning. The process doesn't involve the addition of chemicals. Typically thickened sludge is heated to a temperature of 140 - 250°C for 30 - 60 minutes in a closed vessel under a pressure of 1720 –2760 kN/m^2. The high heat and pressure applied to the sludge break the gel structure and release the bound water, resulting in solids' coagulation. The process also reduces the water affinity of sludge solids. The heat-treated sludge is sterilised, practically deodorised, and dewatered readily without chemicals. There are two leading operations of heat treatment used in sludge in sludge treatment; (1) Low-pressure oxidation (LPO) and (2) Heat Treatment. The main difference between both operations is that the Low-pressure oxidation process involves the introduction of air. Figure 4-1 presents a schematic of both operations.

The thermal stabilisation process is most applicable to biological sludges that may be difficult to stabilise or condition by other means. The high capital costs of equipment generally limit its use to large treatment works (more than 720 m3/h) where space may be limited. Several proprietary systems are available for the heat treatment of sludge. These systems' typical process flow starts with grinding thickened sludge before treatment to obtain particle sizes no greater than 4 to 5 mm. The ground sludge then passes through a heat exchanger into a reactor vessel where steam is injected into the sludge to increase the temperature and pressure to the required operation level. LOP operation introduces high-pressure air into the sludge flow upstream of the heat exchanger. The air improves heat transfer and converts sulphur products in the biosolids to sulphate, slightly reducing odour from off-gases. After the thermal treatment is completed inside the reactor, the sludge passes back through the heat exchanger for heat recovery sludge is discharged to a decanting tank. The dry solids content of dewatered thermally treated sludge may reach up to 30 to 50%. The fuel and electrical energy requirements that form a large portion of the operation cost is presented in Table 4-1.

The thermal stabilisation process causes a portion of the volatile suspended solids to solubilise due to the sludge structure's breakdown. However, the solubilisation process does not change the sludge's total organic carbon content; it affects the liquid side stream (decanting tank supernatant and filtrate, centrate, or decantate generated from the mechanical dewatering) composition. The liquid side stream represents about 50% of feed sludge flow (by volume). Its composition is a function of sludge type, feed volatile solids concentration, reaction time, and temperature; therefore, it varies greatly. The reported concentrations of liquid side stream composition are (1) biochemical oxygen demand – BOD (5000–15,000 mg/L), (2) chemical oxygen demand – COD (10,000–30,000 mg/L), (3) ammonia-nitrogen NH3–N (30–800 mg/L), (4) total phosphorus-P (140–250 mg/L), (5) total suspended solids (9000–12,000 mg/L), (6) volatile suspended solids (8000–10,000 mg/L), and (7) pH 4.0–6.0. The side stream will add loads to the treatment works if recycled to the secondary treatment. If the plant

has not been designed for this additional load, a separate treatment before return may be necessary. It also should be noted that the process generates some non-condensable gases that may require treatment. The rule of thumbs to calculate the VSS and BOD_5 in the HT operation side stream are;

$$\mathrm{VSS} = 0.1\ \mathrm{PS} + 0.4\ \mathrm{WAS}$$

$$\mathrm{BOD}_5 = 0.07\ \mathrm{PS} + 0.3\ \mathrm{WAS}$$

In LPO operation, VSS and BOD_5 production are approximately the same. The advantages of the heat-treatment process are;

- Improves sludge dewatering characteristics except for straight WAS.
- The process produces sludge that doesn’t require chemical conditioning before dewatering.
- Produces sterilised and deodorised sludge that is suitable for ultimate disposal after dewatering.
- The process produces sludge with a heating value of 26,000–30,000 kJ/kg of volatile solids, suitable for incineration or anaerobic digestion with energy recovery.
- The process is less sensitive to feed sludge composition; hence it is suitable for many types of sludges that can't undergo biological stabilisation because of the presence of toxic materials.
- Reduce the size of the subsequent dewatering unit.
- Reduce the requirements of subsequent incineration energy, if incineration is used.

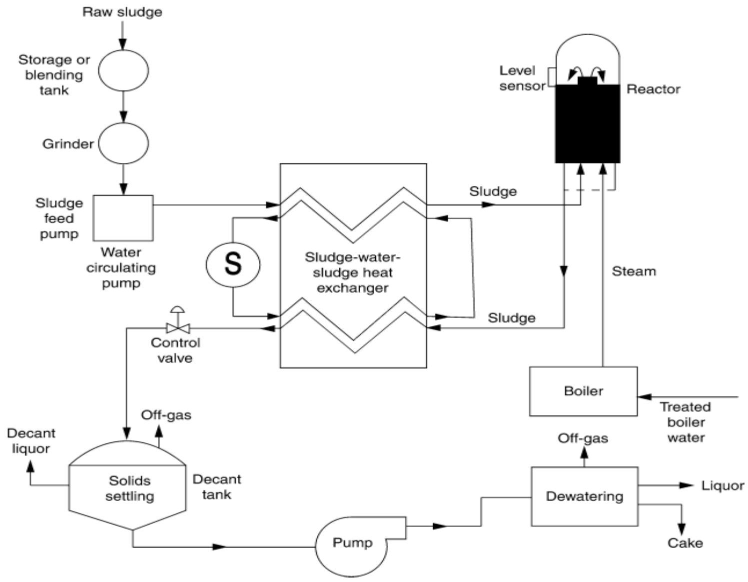
The disadvantages o the heat-treatment process are;

- High capital and operation cost.

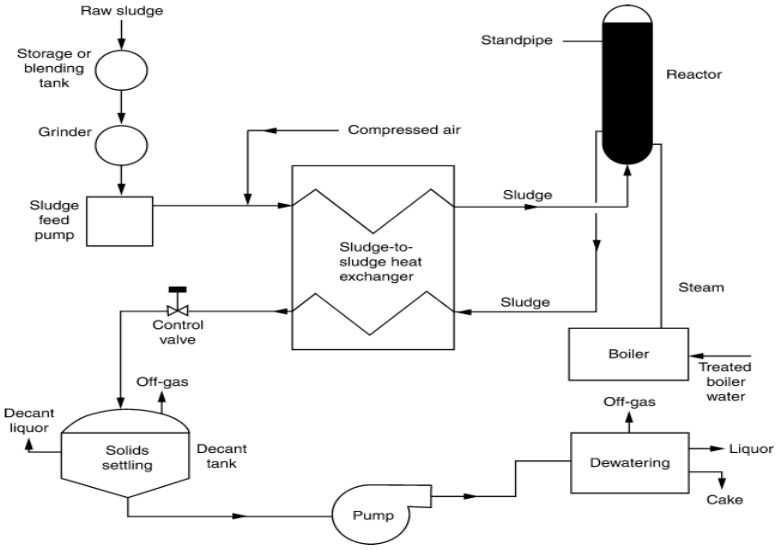
- Highly skilled and specialised operators are required.
- High corrosion resistance material is required resulting in additional expenditure.
- The process produces off-gas that requires treatment before release.
- The process produces a liquid side stream that requires treatment before return to head-of-works or disposal.
- Heavy metals concentrate in the liquid side stream, and further treatment may be required.
- Scale formation in heat exchangers, pipes, and reactor require acid washing.

Table 4-1 Fuel and Electrical Energy Requirements for thermal Treatment Processes (Wang et al. 2007)

Treatment Capacity m^3/day	Air Supply Conditions	Fuel KWh/year	Electrical energy KWh/year
5.5	No air supply	82 000	30 000
54.5	No air supply	805 945	70 000
545	No air supply	7 619 847	425 000
5.5	air supply	123 000	36 000
54.5	air supply	1 216 245	130 000
545	air supply	12 015 914	600 000



(a) low-pressure oxidation



(b) heat treatment

Figure 4-1 Schematic diagrams of thermal stabilisation/conditioning processes: (a) low-pressure oxidation; (b) heat treatment (Reprinted with permission from Springer Nature)

Appendix 7 – Sludge conditioning

1. Chemical conditioning

Chemical conditioning is the most widely spread method for sludge conditioning (Qasim et al., 2018). The process utilises organic and inorganic chemicals to condition sludge, primarily before dewatering (Qasim et al., 2018). The commonly used inorganic chemicals are Ferric chloride and lime. Less commonly used inorganic chemicals are ferrous sulphate, ferrous chloride and alum (Qasim et al., 2018). However, the commonly used organic chemicals are polymers (Qasim et al., 2018). The primary objective of chemical conditioning is to join the small sludge particles and form a large floc(Qasim et al., 2018). Chemical conditioning is a two-step process; coagulation and flocculation (McFarland, 2001). Coagulation involves the neutralisation of the sludge particles surface charge (Qasim et al., 2018). Neutralising particles' surface charge reduces or eliminates the static repulsion force between particles, allowing them to join together(Qasim et al., 2018). Flocculation is the aggregation of the coagulated flocs by gentle mixing resulting in a floc size increase (McFarland, 2001). The main characteristics that influence the sludge thickening and dewatering and subsequently chemical conditioning process are; (1) source, (2) particle size and distribution, (3) concentration, (4) surface charge and degree of hydration, (5) compressibility, (6) pH and Alkalinity and (7) Other factors (i.e. biopolymer production, degree of filamentous growth, pumping and mixing) (Turovskiy et al., 2006).

Sludge source (Turovskiy et al., 2006); the sewage sludge source is typically screenings, grit, scum, primary sludge, secondary sludge, and/or chemical sludge. This combination includes various organic and inorganic particles of mixed sizes. The sludge's origin also determines the internal water contents, degrees of hydration, and surface chemistry. The sludge source is a good indicator of the chemical conditioner to use and it's dose, all based on published data. However, it should be noted that published data is only a guideline as the conditioning requirements for the same source of sludge may vary from plant to plant.

Particle Size and Distribution(Turovskiy et al., 2006); Particle size is the main factor influencing sludge dewaterability. Sewage sludge consists of a considerable amount of small particles in the range of 1–10 µm in size. As the number of small particles increases, the surface area to the volume ratio increases exponentially. Increased surface area means greater hydration and higher resistance to dewatering. The higher resistance to dewatering occurs due to Greater electrical repulsion between particles due to larger negatively charged area and higher frictional resistance to water movement. The sludge particles size depend on the sludge source and prior treatment processes. For example, since the primary clarifiers don't capture fine and colloidal particles but secondary clarifiers do; the primary sludge has a larger particles size than secondary sludge; therefore, it is easier to dewater. Another example is the aerobic and anaerobic digested sludge; the digestion (stabilisation) process decreases the average particles size; therefore the digested sludge is more difficult to dewater than undigested sludge.

Mixing, storage and pumping of sludge are operations that also influence the sludge particle sizes if not designed and managed correctly.

Sludge concentration(Turovskiy et al., 2006); the concentration of solids in the sludge is also an important factor. At low concentration, the particles in the sludge behave in a discrete manner with very little interaction opposing conditioning's primary objective to increase the particle sizes.

Particle surface charge and degree of hydration(Turovskiy et al., 2006); The sludge particles typically carry a negative surface charge and therefore repel one another. Forcing the particles closer to each other increase the repulsion force exponentially. Hydration by capillary action or adsorption occurs on the surface of the particles. It prevents particles from interacting as the water layer binds to the particles' surface and prevents particles from approaching one another.

Compressibility(Turovskiy et al., 2006); since the sludge particles are compressible to a degree, mechanical dewatering will results in particles deformation and reduce the voids between them. The reduction in voids traps the water and restrict its movement leading to a reduced rate of dewaterability. The pre-conditioning forms a matrix of sludge flocs in relatively clear water before dewatering. Once the matrix is introduced to a filter media, the sludge maintains a high degree of porosity, and a large portion of the water will be released. However, too high pressure will cause the conditioned sludge flocs to collapse, decreasing the filtration rate. Therefore the net effect of conditioning is during the quick removal of water at the start of the dewatering process.

pH and Alkalinity (Turovskiy et al., 2006, Christensen et al., 2015); sludge pH and Alkalinity determine the predominant species formed during the coagulation process. Each of these species has a different surface charge nature, consequently affecting the chemical conditioner's selection and dose. It’s important to monitor pH as high pH reduce dewaterability as flocs disintegrate.

Other factors(Turovskiy et al., 2006); factors that decrease the particles size or increase the hydration. Typically these factors are associated with either the wastewater treatment processes (example: biopolymer production and degree of filamentous growth) and sludge handling (example: Pumping and mixing). The main factors to be considered in the selection of the conditioning chemical in addition to performance and cost are (1) the additional volume and weight each chemical conditioning add to the original sludge weight, (2) storage and handling, (3) availability,(4) Operation and maintenance of the conditioning chemical preparation and feeding unit, and (5) available disposal options for the dewatered sludge (inorganic chemical increase metal concentration, i.e. Iron) (Wang et al., 2007). The most common conditioning chemicals as a function of the dewatering equipment are listed in Table 1-1 (McFarland, 2001).

Table 1-1 Chemicals Typically Used for Sludge Conditioning (McFarland, 2001)

Dewatering Process	Lime	Ferric Chloride	Organic polymer
Centrifuge			Commonly Used
Belt filter press			Commonly Used
Vacuum Filter	Commonly Used	Commonly Used	Commonly Used

Dewatering Process	Lime	Ferric Chloride	Organic polymer
Filter Press	Commonly Used	Commonly Used	possibly used but not common
Drying Bed		possibly used but not common	

Ferric chloride (McFarland, 2001 and Wang et al., 2007,); is typically available in liquid form with a 20-45% ferric chloride concentration and 12 to 17% iron by weight. It is generally used at the same concentration received as dilution can lead to hydrolysis reaction and precipitation of ferric hydroxide. The ability to store the ferric chloride for long periods without deterioration in the concentration is a huge advantage. However, it mustn't be stored at low temperature to avoid crystallisation. The crystallisation occurs at a lower temperature as the concentration of the ferric chloride decrease. For this reason, in cold climates, ferric chloride may be shipped at lower concentrations to avoid crystallization.

The Ferric chloride mechanism is to destabilise the negatively charged sludge particles by forming positively charged iron complexes. It also reacts with alkalinity to form ferric hydroxide that flocculates the destabilised sludge particles. The reported optimum pH for ferric chloride is above 6; therefore, lime is usually added to counteract the pH reduction during the ferric chloride reaction and maintain the optimum pH level. The commercially available ferric chloride is an orange-brown corrosive and acidic solution. Special consideration must be taken to select the material used to handle ferric chloride due to its corrosive nature. Materials such as epoxy, rubber, PVC, FRP, vinyl, etc., are suitable for handling the ferric chloride solution. Personal protecting equipment (PPE) must be used when handling the ferric chloride solution as it can results in severe burns to the eyes and skin, and fumes can cause internal burns if inhaled.

Lime (McFarland, 2001 and Wang et al., 2007); is typically used in conjunction with ferric chloride in the chemical conditioning process. The main reason for using lime with ferric chloride is to control the pH. However, lime offers a few more advantages, such as odour reduction, stabilisation and disinfection. Additionally, the reaction between lime and alkalinity produce calcium carbonate that provides a better porosity to the sludge structure and reduces comparability, leading to better dewaterability.

Lime is typically available in two dry forms as quicklime (CaO) and hydrated lime ($Ca(OH)_2$). Quicklime is usually sold in pebble or granular form, and hydrated lime is usually sold in powder form. However, quick lime requires to be slaked to form hydrated lime before use. The slaking process produces a significant amount of heat, and thus special equipment is required. Quicklime is typically available in three grades: high (88–96%) CaO; medium (75–88%) CaO; and low (50–75%) CaO. In general, highly reactive and quick slaking quicklime is to be used for conditioning. Quicklime must be stored in a dry area, as it reacts with moisture in the air and can become unusable. Hydrated lime is preferred as it doesn't require slaking; it mixes easily with water and produces a little heat. However, quick lime is much cheaper and more available. Thus, quick lime is used for large wastewater treatment facilities with a lime demand of more than two tonnes per day, even though slaking is required. Hydrated lime and quick lime can be purchased in bulk or bags. If purchased in bags, the storage building must be waterproof, or the bags are to be waterproof; in both cases, no more than 60 days storage capacity is recommended. However, if purchased in bulk, storage hoppers should be both watertight and airtight. Storage and handling material can be steel and/or concrete since lime is not corrosive.

Inorganic chemical conditioners dosage (McFarland, 2001 and Wang et al., 2007); the typical dosing rate for ferric chloride is 2 – 80 kg/tonne of sludge dry solids, regardless if lime is used or not. Lime typical dosage rate is 75 – 300 kg/tonne of sludge dry solids. Table 2-1 lists typical ferric chloride and lime dosages for various sludge types. It should be noted that the addition of inorganic chemicals for conditioning increases sludge quantity by 20 to 30% on a dry weight basis and lowers the fuel value for incineration.

Other inorganic chemicals and additives (Wang et al., 2007 , Qasim et al., 2018); Other types of inorganic materials such as ferrous sulphate ($FeSO_4$), ferrous chloride ($FeCl_2$), power plant fly ash, pulverised coal, cement kiln dust, incinerator ash, and diatomaceous earth have been used in sludge conditioning.

Ferrous sulphate ($FeSO_4$) and ferrous chloride ($FeCl_2$) (waste pickle liquor - a by-product of the steel industry) may be used instead of ferric chloride. The decision to use such an alternative is based on performance, cost, and availability. Additionally, the composition of the waste pickle liquor may affect the sludge quality and its suitability for reuse, and it may also cause problems to final disposal methods. Power plant fly ash, pulverised coal, cement kiln dust, incinerator ash, and diatomaceous earth have also been used as conditioning chemicals in centrifuge and vacuum filters and before and after stabilization. These conditioning chemicals have limited use due to mainly material handling problems, cost and availability, and the fact that Ferric chloride, lime, and polymer are typically dosed along with these conditioning agents.

Organic Polymer (Turovskiy, 2006 , Wang et al., 2007) ; Polymers (or polyelectrolytes) are organic, water-soluble, long-chain chemicals. Polymers are categorised by charge, molecular weight and form. By Charge; polymers are categorized as anionic (negative), cationic (positive), or non-ionic (neutral). Cationic polymers are the most commonly used type for sludge conditioning. However, anionic and non-ionic polymers are also used in sludge conditioning either independently or in conjunction with cationic polymers or inorganic conditioning agents. For example, very old sludge that lost its charge may require cationic and anionic polymers for effective conditioning. Cationic and anionic polymers may also be used to aid the flocculation of destabilised particles by inorganic chemical conditioning chemical. By molecular weight; polymers are categorised to either low molecular weight or high molecular weight. Low molecular weight polymers are more often used for coagulation; however, high molecular weight polymers are used for flocculation. By form, polymers are categorised as dry polymer, emulsions, mannich and liquid. Dry polymers are supplied as powder, granules, beads, or flakes with 90 to 95% active content. The primary disadvantage of dry polymer is handling equipment compared to liquid and emulsion polymers. Emulsions are high molecular weight polymers dispersed in hydrocarbon oil, with active polymer content of 25 to 50%. Manniche polymers have a very high viscosity and high molecular weight, with active polymer content of 2 to 10%. The pH of the mannich polymer can be as high as 12. It has a short shelf life, and it contains formaldehyde which poses a health and safety risk. The liquid polymer has low to high molecular weight, with 10 to 60% active polymer content. The pH of the liquid polymer is typically neutral to acidic. Depending on the manufacturer, the shelf life of liquid polymer can be anything between two months to one year. It is essential to highlight that the commercially available polymers vary significantly in chemical composition, function and cost. Therefore, the suitable polymer selection requires proper initial investigation and testing; however, continuous evaluation of the polymer performance is a must. The primary advantages for the use of polymers over metal coagulants are: (1) do not appreciably increase sludge quantity, (2) do not lower the cake's fuel value, and (3) safer and easier to handle than the inorganic chemicals.

Depending on the type and dewaterability of sludge, polymer dosages can vary from 1 to 10 Kg/tonne of dry solids. Polymers are prepared or diluted by water to a dosing concentration of 0.1 to 0.2%. It is important to note that increasing the dosages beyond the optimum values worsens the dewaterability of sludge. Potassium permanganate (often used for colour removal and odour control) has been proven to reduce polymer doses on mechanical dewatering units. It has been reported that the use of potassium permanganate in conjunction with polymer has reduced polymer consumption by 5 to 15%.

Laboratory tests are generally required to determine the dosages of all conditioning chemicals, filter yield, and suitability of various filtering media. The standard laboratory tests include (1) Büchner funnel, (2) leaf filter, (3) capillary suction time test (CST), and (4) standard jar test. The chemical dosages for pre-dewatering conditioning based on dry sludge weight for different chemicals are presented in Table 2-1.

2. Thermal conditioning

The thermal conditioning of the sludge has been discussed under item 2.2.2.4, “Thermal Stabilisation.”

Table 2-1Typical Chemical Dosages Used for Sludge Conditioning (McFarland, 2001)

Dewatering Process	**PS Kg/tonne**	**PS + WAS Kg/tonne**	**AND Kg/tonne**
Centrifuge (Polymer)	0 – 2.5	1 - 5	1 - 5
Belt filter press (Polymer)	2 - 4	2 - 5	4 – 7.5
Vacuum Filter			
- Polymer	2 - 5	3 - 6	-
- Lime	80 - 100	90 - 160	150 - 210
- Ferric chloride	2 - 40	25 - 60	30 - 60
Filter Press			
- Polymer	-	2 - 7	-
- Lime	110 - 140	110 - 160	110 - 300
- Ferric chloride	40 – 60	40 - 70	40 - 100

3. Elutriation (Wang et al., 2007)

Elutriation is the process of washing the sludge with treated effluent or other freshwater sources. The process is used mainly to reduce the sludge alkalinity and fine particles, thus reducing the inorganic conditioning chemical demand by 50%. This process is usually associated with the washing of anaerobically digested sludge before vacuum filtration. A secondary application of elutriation is washing out toxic materials that inhibit sludge digestion or other biological processes and treat dirty digester supernatant liquor. The wash water to sludge ratio is commonly within the range of 2:1 to 12:1, with a typical ratio of 3:1. The factors impacting the selection of wash water to sludge ratio are (1) sludge alkalinity, (2) required sludge alkalinity after washing, (3) wash water alkalinity, (4) subsequent process to elutriation, and (5) elutriation basins capacity.

The elutriation process may be operated in continuous, intermittent or batch modes. This can be achieved in either (1) single-tank, multiple elutriation stages or (b) multiple-tank counter current elutriation. The tanks used for the elutriation process are typically constructed as gravity thickeners with a solids loading of 40 – 50 $kg/m^2 \cdot d$ and hydraulic loading of 8 – 16 $m^3/m^2.d$, with detention time between 12 to 24h. Elutriation may not be used extensively as the cost of the process equipment and tanks may not justify the savings in chemicals' cost. Additionally, the generated wash water is approximately two to six times the volume of sludge. This wash water contains high solids concentrations, approximately 10 to 45% of the solids from the incoming sludge; recycling it back to the plant increases organic and solids loadings leading to an overall degradation of the plant performance.

Appendix 8 – Sludge disinfection

1. Pasteurisation

Pasteurisation involves the heating of raw or digested sludge to eliminate pathogenic organisms. Pasteurisation can be performed solely or in conjunction with sludge thermal stabilisation and thermal conditioning. The optimal temperature and exposure period to activate different pathogenic organisms as well as eggs and cysts of parasites is 70 ^{o}C for a period of 4 to 25 minutes. However, 60 minutes was also observed to reach complete inactivation. Typically, pasteurization at 70°C for 30 minutes inactivates parasite ova and cysts; and reduces the viruses and bacteria below detectable levels. It was found that faecal streptococci bacteria were most heat-resistant, followed by coliforms and then Salmonella. Additionally, it was found that a higher temperature (90°C) for a shorter period (10 minutes) also destroys all pathogens.

The primary two methods used for pasteurising liquid sludge involve (1) the direct injection of steam and (2) indirect heat exchange. The direct injection of steam seems to be the most effective heating method because heat exchangers tend to scale up or become fouled with organic matter. Besides, the heat transfer through the sludge slurry is slow and undependable. Another factor that significantly affects the performance of the pasteurisation process is mixing. Incomplete mixing will either increase the minimum required heating time, reduce process effectiveness or both. However, overheating or a very long detention time may increase trace metal mobilization, aggravate odour problem and waste energy. The principal equipment of a pasteurisation system include (1) a steam boiler, (2) a preheater, (3) a sludge heater, (4) a high-temperature sludge holding tank, (5) blow-off tanks, and (6) storage basins for the untreated and treated sludge. Typically, batch processing is preferable to avoid reinoculations if short-circuiting occurs. In the typical batch process with a one-stage heat recuperation system, thickened sludge enters the preheater stage to raise its temperature to approximately 38°C by hot vapours discharged from the blow-off tanks. Heat recovery provides at least 30 to 40% of the total required heat. After the preheating stage, the sludge is pumped to the pasteurisation tank, where steam is directly injected to raise sludge temperature to at least 70°C. The sludge remains in the pasteurisation tank for 30 minutes to ensure effective pathogen destruction. Finally, the sludge is transferred to the blow-off tanks, where two stages of sludge cooling take place using fans or blowers, first 45°C at 10 kpa pressure and then 35°C at 5 Kpa pressure. The number of stages of a cost-effective heat recuperation system depends on the sludge flow. If the sludge flow rates between 2 to 3 l/s, a single-stage heat recuperation system is the most economical. For a sludge flow rate of 4.8 to 5.7 l/s, a two-stage system is the most economical. For higher sludge flows, a three-stage heat recuperation system would be the most economical. However, for plants with a sludge flow capacity of 200 l/s or more, the pasteurisation process may not be a cost-effective solution due to its high capital costs. Other heat disinfection methods (thermal conditioning, thermal stabilisation, heat drying and composting) are described under different sections of this review.

2. Chemical disinfection

Chlorine and lime are the most common chemicals used for sludge disinfection. Chemicals are typically added to liquid sludge before dewatering. Ozon is also proven suitable for sludge disinfection in both pilot plant and full scale. However, its high capital cost, high operation and maintenance cost, operation complexity, and safety make it less used.

(1) Lime; The addition of lime in the treatment of wastewater and sludge is a common practice. Lime stabilisation is discussed in details in this review under section 2.2.2.3. It has been found that pathogenic bacteria is reduced to almost non-detectable at pH between 11.5 and 12.5 after 24h for chemical (alum and one with ferric chloride) treated secondary sludge. Qualitative checks for higher life forms such as Ascaris ova indicated that they survived 24 h at a pH greater than 11.0. Other studies on virus inactivation in limed sludges have shown that pH above 11.5 should inactivate known viruses.

(2) Chlorine; it is very effective chemical for inactivation of bacteria and virus. Cysts and ova of parasites are very resistant to chlorine. Chlorine is less effective if applied to a solution with a high suspended solid concentration such as sludge. However, if applied in sufficient quantity to develop free chlorine residual, a considerable reduction in pathogenic organisms can be achieved. For example; Chlorine doses of 1000 mg/L applied to WAS with a 0.5% solids concentration reduced total bacteria counts by 4–7 logs and coliform bacteria and coliphage to less than detection limits. Primary sludge with a 0.5–0.85% solids concentration was treated with 1000 mg/L chlorine, and total and faecal coliform counts were reduced to less than the detectable limits. Using chlorine in sludge disinfection has several disadvantages: (1) reducing the sludge pH between 2-3, raising the need for sludge neutralisation before use or further processing, (2) high chlorine dose resulting in higher operating cost and (3) produce CO_2 when treating high alkalinity digested sludge or digester supernatants, resulting in possible cavitation in pumps.

3. Long-Term Storage

considerable pathogenic organisms reduction has been achieved through long-term sludge storage in lagoons. Hinesley et al.. have reported a 99.9% reduction in faecal coliform density after 30 d storage. For an anaerobically digested sludge stored in anaerobic conditions for 24 weeks at 4°C, Stern and Farrell reported significant reductions in faecal coliform, total coliform, and Salmonella bacteria. The same bacteria could not be measured in similar tests at 20°C, after 24 weeks, in the same period, virus reduction of 67% at 4°C was accomplished, and further reduction to less than the detectable limits at 20°C was achieved. Faecal coliform reductions of one to three orders of magnitude during long-term storage of anaerobically digested mixture (primary and waste activated sludge) in facultative lagoons were demonstrated by Storm et al.. The primary disadvantages of long-term storage is the availability of space, the cost of land and development of odours.

4. Irradiation

Irradiation is a process where high-energy radiation, particularly Beta and Gamma rays, are used to disinfect the sludge. Beta rays are high-energy electrons generated by an electron-accelerator device, while gamma rays are high-energy photons emitted from atomic nuclei of radioactive isotopes. The inactivation of pathogens occurs by inducing a secondary ionization in the sludge during penetration. The secondary ionization also produces oxidising and reducing compounds that in turn inactivate pathogens.

(1) Beta ray (electron beams); The pathogen-reducing power of Beta rays depends on the electrons' number and energy impacting the sludge. The energy of all radiation is measured in units called rads. One rad is equal to the absorption of 100 ergs of energy per gram of material. Since beta radiation distributes energy throughout the volume of material regardless of the nature of the material, the disinfection efficiency depends only on the rays' penetration depth to the material.

The penetration depth of electrons is limited to 0.5 cm in water and sludge when a potential of 1 Million Volts has accelerated the electrons. Maintaining the thickness of the sludge layer below this depth ensure adequate disinfection with Beta rays. Another method used to ensure very effective disinfection is to limit the sludge layer thickness so that the intensity of the exiting rays is about 50% of its initial intensity. It should be noted that Beta rays can induce radioactivity in the material they impact. However, the electrons energy level at which sludge irradiation occurs (about 2 Million Volts) is well below the electron energy required (about 10 Million Volts) to induce significant radioactivity.

The primary system components of an electron-beam sludge radiation unit, in order, are (1) sludge screens, (2) sludge grinder, (3) sludge feed pumps, (4) a sludge spreader, (5) an electron-beam power supply, (6) an electron accelerator, (7) an electron-beam scanner, and (8) a sludge removal pumps. The Beta ray system must be housed in a concrete building. Concrete is sufficient to shield the radiation from the outside environment. Progressive cavity pumps are preferable to ensure smooth sludge feed to the Beta ray system. Screening and grinding before radiation are essential to ensure the sludge is homogenous and the required sludge thickness passes under the electron beam. The primary disadvantages are (1) generating Ozone around the accelerator during the cooling process of the electron beam scanner, (2) workers safety and (3) high power consumption. A facility with a 50 kW electron beam would require about 100 kW of total electrical power, including 25 W for screening, grinding, and pumping, 10 kW for cooling, and 12 kW for electrical conversion losses. Energy requirements for 450 m^3/day are 6.6 kWh/tonne of wet sludge at 5% solids or 132 kWh per dry tonne. However, the energy consumption is high, but it is less than that used for pasteurisation.

(b) Gamma-ray, the disinfection efficiency of gamma radiation, is similar to that of Beta radiation.

There is two primary difference between gamma rays and beta rays. First, gamma radiation can penetrate to much greater depths than beta rays. Second, gamma rays emission is continuous and uncontrollable since it is generated due to radioactive isotope decay. Additionally, gamma-ray energy level is constant, and the only mean to change the applied energy to the sludge is only through changing the exposure time. The two commonly isotopes used in sludge radiation systems are caesium-160 (^{160}Cs) and cobalt-60 (^{60}Co). ^{137}Cs has a half-life of 30 years and emits a 0.66 million volts gamma-ray, whereas ^{60}Co has a half-life of 5 years and emits two gamma rays with an average energy of 1.2 million volts. There are two systems available for sludge disinfection. The first system is for liquid sludge. It operates as a batch process, where the sludge fed and circulated in a closed vessel surrounding the gamma-ray source. The dosage of radiation is regulated through retention time. The second system is for dewatered or composted sludge. The sludge is loaded on a special hopper conveyor that brings the sludge to the gamma source inside of a concrete volute. A variable speed conveyor is used to control the radiation dose. The volute that house the gamma radiation source should be shielded with steel-lined concrete and designed to be flooded with water during loading and unloading of the gamma radiation source. Air cooling is also required even during downtimes.

The irradiation systems are very effective in sludge disinfection; however, it’s not popular as it poses a hazard to workers and the environment.

Appendix 9 – Sludge dewatering

1. Mechanical dewatering systems

The mechanical dewatering systems are used for large wastewater treatment facilities (Qasim et al., 2018). These systems are typically installed inside a building along with a chemical conditioning feed system (Qasim et al., 2018). The conditions that favour the use of mechanical dewatering systems include (1) aesthetics, (2) climate, (3) costs, and (4) site limitations (McFarland, 2001). All mechanical dewatering systems use filtration as a mechanism for water removal (McFarland, 2001). The pressure drop required for filtration is significant (McFarland, 2001). The mechanical dewatering systems archive the required pressure drop through (McFarland, 2001); (1) creating a centrifugal force, (2) placing a vacuum on one side of a porous medium and (3) Raising the pressure on one side of a porous medium. At present, belt filter presses and solid-bowl centrifuges are the mechanical dewatering systems most frequently used(McFarland, 2001, Qasim et al., 2018).

1.1 Centrifugal dewatering (Qasim et al., 2018)

Besides sludge thickening, centrifuges are also used for sludge dewatering. The main advantages of using centrifugal dewatering are; (1) continuous operation, (2) the produced cake has a high solid concentration,(3) enclosed system, clean with no spills and minimal odours, (4) wash water requirement is very low, and in some designs not required, (5) suitable for thin sludge dewatering like WAS (< 0.5% solids), (6) easy to install, (7) small footprint, (8) low initial capital costs, and (9) easy startup and shutdown. On the other hand, the centrifuges major disadvantages are; (1) high power consumption, (2) the centrate has a relatively high TSS concentration, (3) high operation and maintenance costs, and (4) prone to produce noise and vibration. Chemical conditioning before the centrifuge is required to aid its performance. The organic polymer is the typical chemical used for conditioning. The organic polymer dosage is in the range of 1 to 25 g/kg of dry solids. The dry solid concentration of the sludge cake produced by the centrifuges is 20–30% solids with an 85–95% solids capture rate. The available unit capacity is between 5–280 m3/h. The principal operating parameters controlling the centrifuge performance are; the sludge feed rate, rotational speed, type of polymer used, and feed sludge characteristics (concentration, particle size, shape, density, temperature and liquid viscosity). For more details, please see section **Error! Reference source not found.Error! Reference source not found.**

1.2 Belt filter press (BFP) (Turovskiy and Mathai, 2006, Qasim et al., 2018)

The belt filter press is a continuous-feed sludge dewatering machine where the dewatering occurs by compressing the sludge between two tensioned porous moving belts. It is presently the most widely used dewatering equipment in the world. The BFP operation involves four basic processes (1) chemical conditioning, (2) gravity drainage, (b) low-pressure compression, and (c) high-pressure compression. The chemical conditioning occurs in a vertical column, a chemical conditioning tank, or a long pipe with a static mixer. The mixing time between the polymer and sludge should be between 15 to 45 sec for efficient mixing. The conditioned sludge is then fed into the gravity zone of the moving porous belts. The gravity zone allows a significant amount of the free water to drain through the belt and collected in a pan and routed to a sump. The gravity zone is equipped with plows. The plows significantly increase the gravity drainage process by clearing spaces for water to drain and by turning the solid mass on the belt. The liquid sludge is stopped from running off the sides of the belt by restrainers and rubber seals. At the end of this zone, the sludge is typically a loosely structured cake. From the gravity drainage zone, the sludge falls into the low-pressure zone (also called wedge zone) where the sludge is introduced between the two belts then passes to the high-pressure zone where a series of rollers apply pressure to expel nearly all the free water from the sludge. A schematic of a belt filter press is shown in Figure 1-1.

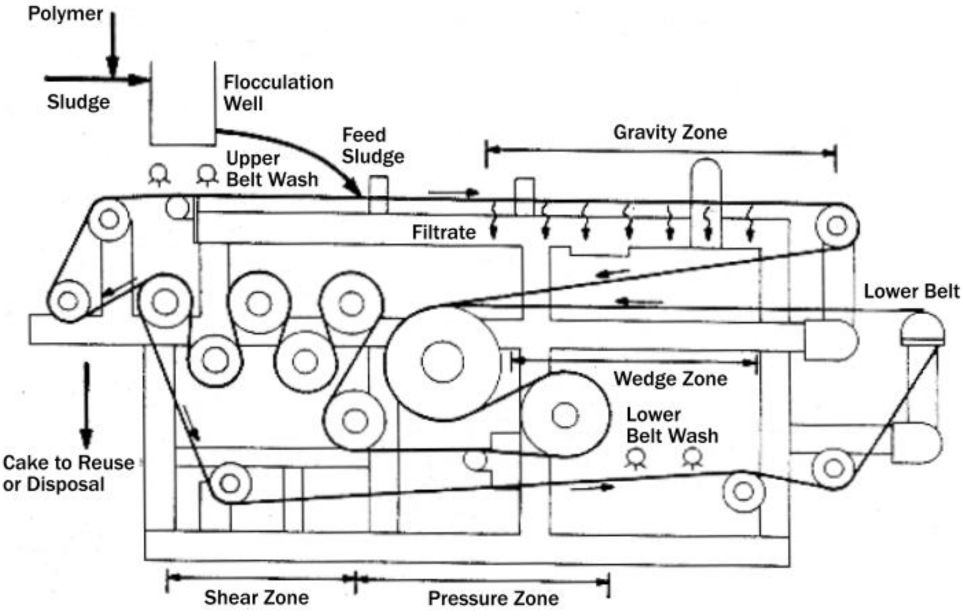


Figure 1-1 Belt Filter Press Schematic (Reprinted with permission from Johan Wiley & Sons-Books)

The principal advantages of the belt filter press are (1) simple operation and maintenance; (2) easy startup and shutdown; (3) continuous operation, (4) low power requirement, (5) Produced cake with high solids content; and (6) low noise level. On the other hand, the major disadvantages are (1) uses a large volume of wash water, (2) screening, grinding, or degritting of sludge is required to protect the belt from damages, and (3) high operation cost, and (4) requires enclosure for odour control. BFP typically produces sludge cake with dry solids concentration between 15% and 30% at a solids capture rate of 95–98%. The wash water supply is continuous and typically in the range of 150 to 300 L/m.min at 12 to 17 KPa. The typical performance data of the belt filter press is presented in Table 1-1.

Critical auxiliary systems required for the operation of the BFP are; (1) belt wash water supply and (2) compressed air for pneumatic or hydraulic belt tensioning systems. The major component of the BFP are; (1)dewatering belts, (2) rollers, (3) drive unit with control, (4) belt tracking (or steering) system, (5) belt tensioning system, (6) belt washing system, and (7) automatic shutdown system for belt misalignment, insufficient belt tension, belt drive failure; sludge conditioning tank failure; loss of pneumatic or hydraulic system pressure; low belt wash water pressure; and emergency stop.

The most common size of the belt width is 2m. However, BFP is available with a belt width between 0.5 to 3.5 m. BFP units with 2-belts and 3-belts are currently available for dewatering of thickened and unthickened sludges with solids contents of 2–6% and 1.5% or less, respectively. The typical number of rollers is 6 to 24 arranged in series. The arrangements of the these rollers categorise the BFP to a horizontal and vertical belt.

Table 1-1 Typical Design and Performance Parameters of Belt-Filter Presses (Qasim et al., 2018)

Sludge Type	Feed Solids Concentration % DS	Solids Loading[a] Kg/m.h	Hydraulic loading[a] L/m.min	Polymer Dose g/Kg DS (Polymer/Feed Sludge)	Cake Solids Content %DS
Raw or TFS:					
PS	4 - 8	1000 - 1500	250 - 600	1.5 - 2.5	25 - 35
WAS	1 - 4	200 - 350	200 - 350	3 - 7.5	15 - 20
PS + WAS	3 - 6	350 - 800	350 - 800	5 - 10	15 - 25
SBR/MBR sludge	1 - 2	250 – 400	250 - 350	5 - 10	10 – 20
ANDS:					
PS	2 - 5	700 - 900	250 - 600	2 - 5	25 - 35
WAS	2 - 3	250 - 400	100 - 350	4 - 10	15 - 20
PS + WAS	2 - 4	300 – 550	150 - 450	4 - 8	15 - 25
ADS:					
WAS	1 – 3	250 - 400	150 - 350	6 - 10	10 - 20
TFS	2 - 5	350 - 600	100 - 500	2 – 12.5	10 - 20

a. Based on belt width in meter

1.3 Filter Press (Turovskiy and Mathai, 2006 , Qasim et al., 2018)

Filter press is also called plate and frame filter press or recessed plate filter press. It operates in batches in which dewatering is achieved by applying high pressure to force the water out from the sludge. The cake produced using filter press is the drier if compared with other dewatering alternatives. The filter press generally consists of a series of plates, each equipped with a recessed section. When the plates come together, it forms a chamber into which the sludge is pumped for dewatering. The chamber walls are covered by filter media (cloth) that permit the filtrate to pass through. There are two common types of filter press (1) fixed-volume recessed plate, and (2) Variable volume recessed plate. The typical filtration area for either type ranges from 0.3 to 6 m^2 per chamber with a plate size of 0.5–2 m. A filter unit may consist of 20 – 200 chambers. Chemical conditioning of the feed sludge is required for both types of filter-presses. The typical chemicals used for conditioning are ferric chloride and quick lime with a typical dosage of 50 g/kg for ferric chloride and 100 g/Kg for quick lime on a dry solids basis. The typical solids loading rate is 5 $Kg/m^2 h$. The operation sequence of both types of filter press are; (1) Feed; conditioned sludge is pumped to the chamber, (2) apply and maintain the desired pressure for the required period, (3) the filtrate passes through the filter cloth and plate to outlet ports, (4) separate the plates and remove the cake, and (5) wash the cloth and close the press for the following operating cycle. In the fixed-volume recessed-plate filter press, the sludge is pumped into the chamber between the plates at relatively high pressure between 700 to 1550 KPa and maintained for 1 to 3 hours. The plates are then moved away mechanically from each other, and the cake is dropped from the chambers onto a truck or conveyor belt for disposal of further processing. The cake thickness varies from 25 to 38 mm, with a dry solids concentration between 35 and 42%. Following cake removal, the filter press is washed and ready for the next cycle. The overall cycle time varies from 1.5 to 5 hours. In the variable-volume recessed-plate filter press, a diaphragm is added behind the filter media. The sequence starts with feeding the conditioned sludge to the chamber at a lower pressure between 690 and 860 KPa. Once the chamber is filled, the sludge feed pump is stopped. Water or air are pumped between the diaphragm and the media, squeezing the already formed cake and releasing more water from the cake. Typically the water or air pressure applied is between 1380 to 2070 KPa for a period of 15 to 30 minutes. The diaphragm is then deflated, and the press opens, and the cake is dropped from the chambers onto a truck or conveyor belt for disposal of further processing. The cake thickness varies from 25 to 38 mm, with a dry solids concentration between 38 and 50%. Following cake removal, the filter press is washed and ready for the next cycle. The overall cycle time varies from 1 to 3 hours. The variable-volume filter press offers several advantages over the fixed-volume filter press such as, (1) It produces a dryer sludge cake, (2) shorter operation cycle, therefore a higher daily production, (3) lower O & M for the feed pumps, and (4) the ability to dewatered marginally conditioned sludge. On the other hand, the principal disadvantage of the variable-volume filter press is the higher initial capital cost, which can be as much as two to three times compared to a fixed-volume filter press with the same daily capacity. Performance data for both types of filter presses is presented in Table 1-2 and Table 1-3.

The advantages of plate and frame filter press compared to other dewatering systems are: (1) high cake dryness, (2) high solids capture rate, (3) low TSS concentration in filtrate, and (4) simple operation. The major disadvantages are (1) batch operation only, (2) Higher capital and O&M costs, (3) labour-intensive, (4) large footprint, (5)requires high-pressure washing system, (6) an acid wash system is required to remove lime scales, (7) cake shredder is required mainly if the dewatered sludge to be incinerated, and (8) Increase sludge quantity considerably due to the high inorganic chemical for conditioning. The filter presses may be more suitable for dewatering water treatment sludge where metal salt and/or lime are already added as coagulants in the treatment processes. The performance of both types of filter presses is affected by several operational parameters, including (1) feed sludge dry solids concentration, (2) chemical conditioning dosage, (3) required cake solids content, (4) total cycle time, (5) solids capture, and (6) sludge load kg/m^2 .h).

1.4 Vacuum filter (Turovskiy and Mathai, 2006, Qasim et al., 2018)

The use of vacuum filters has declined in recent years because it consumes the most considerable energy per unit of dewatered sludge. Besides, it requires continuous operators attention and only performs if feed sludge dry solids content is 3% or higher. The vacuum filter is considered a continuous process. Vacuum filters consist of a horizontal cylindrical drum covered with porous filter media.

Table 1-2 Performance Data for a Fixed-Volume Filter Press (Turovskiy and Mathai, 2006)

Sludge Type	Feed Solids Concentration % DS	Conditioning Chemical[a]		Cake Solids Content %DS[c]	Cycle Time (h)[d]
		Ferric Chloride ($FeCl_3$) %	Lime (CaO) %		
PS	5 - 10	5	10	45	2
PS + WAS (50:50)	3 - 6	5	10	40 - 45	2.5
PS + WAS (50:50)	1 - 4	6	12	45	2.5
PS + TFS	5 - 6	6	20	38	2
PS + Ferric chloride (FC)[b]	4	-	10	40	1.5
PS + WAS (FC)[b]	8	5	10	45	3
WAS	5	7.5	15	45	2.5
PS + two stage high lime	7.5	-	-	50	1.5
ANDS (PR)	8	6	30	40	2
ANDS (PR + WAS)	6 - 8	5	10	45	2
ANDS (PR+WAS) FC[b]	6 - 8	5	10	40	3
ANDS (PS + WAS) (50 :50)	6 - 10	5	10	45	2
ANDS (PS + WAS) (50 :50)	1 - 5	7.5	15	45	2.5

a % dry solids
b Ferric chloride used as a coagulant aid in the secondary process.
c Include conditioning chemicals.
d Time exclude cake discharge time

Table 1-3 Performance Data for Variable-Volume Diaphragm Filter Press (Turovskiy and Mathai, 2006)

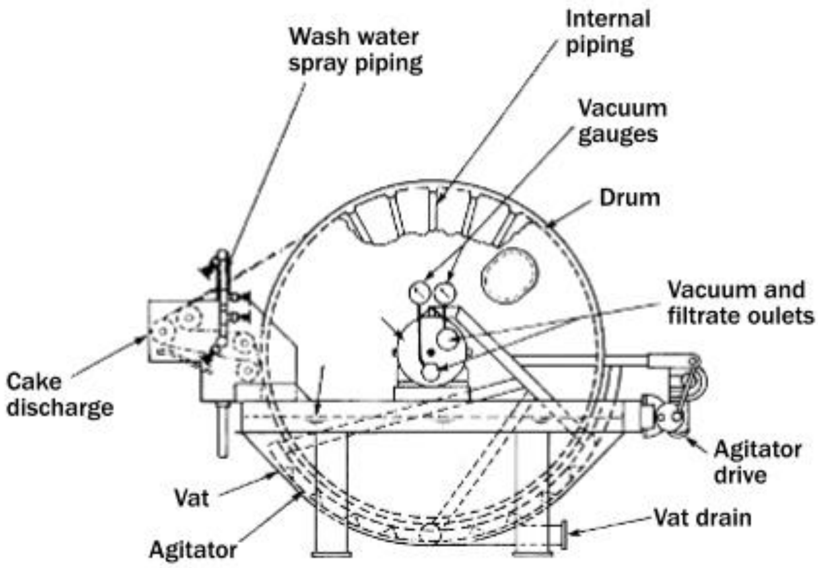
Sludge Type	Feed Solids Concentration % DS	Conditioning Chemical[a]		Cake Solids Content %DS	Cycle Time (min)
		Ferric Chloride ($FeCl_3$) %	Lime (CaO) %		
PS	12	2.9	13	48	21
PS[b] + WAS (25:75)	12 - 16	0	0	52	22

a % dry solids
b Heat treated primary sludge

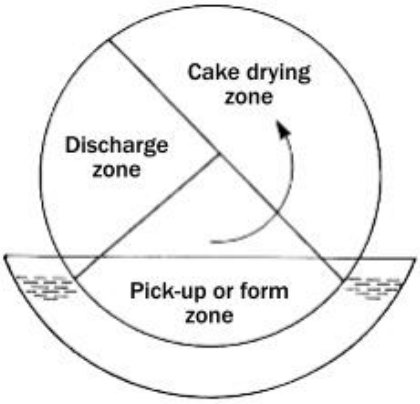
The filter media is typically cloth made of natural or synthetic fabric; in some designs, woven stainless steel mesh or coil springs are used. The vacuum applied downstream of the filter media drives the water to move through the filter media. The drum rotates slowly while partially submerged in a vat of conditioned sludge. As the drum rotates while the vacuum is applied, the sludge moves in sequence between the three distinct zones: cake forming, cake drying, and cake discharging. In the cake discharge zone, the cake is removed from the filter media. After cake discharge, the filter media is washed. Figure 1-2 is a typical cross-sectional view of a rotary vacuum filter. The vacuum filter performance is dependent on; (1)type of feed sludge, (2) dry solids concentration in the feed sludge, (3) type and quality of conditioning chemicals, (4) level of vacuum applied, (5) degree of drum submergence, (6) type of filter media, and (5) cycle time. Typically Ferric chloride and lime are used as conditioning chemicals. The drum submergence time in sludge is referred to as the form time, and the time spent in the air is referred to as dewatering time. The form time usually is 40–60% of the cycle time. A 70 kPa of vacuum is typically applied inside the drum, producing a cake with a 20–35% dry solids concentration. The vacuum filter solids loading rate is typically between 5 – 25 kg/m^2·h with a conditioning chemical dose of 20–40 g/kg for ferric chloride and 100–150 g/kg for lime as CaO on a dry solids basis. Typical vacuum filter performance data is presented in Table 1-4.

1.5 Rotary press (Metcalf & Eddy/AECOM, 2014, Qasim et al., 2018)

The rotary press is considered a relatively new technology if compared to other dewatering systems. The feed sludge is typically conditioned using an organic polymer. The polymer is injected upstream of the inlet into the rotary press. The conditioned sludge is then fed to the rotary press inlet rectangular feed channel; from there, the sludge flows into a peripheral channel formed by two parallel slow rotating stainless steel screens installed in a containment vessel. The water flows through the screens on either side and collected in a common channel, and exit at the bottom of the unit.



(a) Cross-section of vaccum filter



(b) Operation zones

Figure 1-2 Vacuum filter (a) Cross-section view , (b) Operation zones (Reprinted with permission from Johan Wiley & Sons-Books)

Table 1-4 Typical Performance Parameters of Vacuum Filters (Turovskiy and Mathai, 2006)

Sludge Type	Feed Solids Concentration % DS	Solids Loading[a] Kg/m^2.h	Cake Solids Content %DS
Raw sludge:			
PS	4.5 - 9	20 - 50	25 - 35
WAS	2.5 - 4.5	5 - 15	15 - 20
PS + TFS	4 - 8	15 - 30	15 - 25
PS + WAS	3 - 7	12 - 30	10 – 20
ANDS:			
PS	4 - 8	15 - 34	25 - 35
PS + TFS	5 - 8	20 - 34	15 - 20

Sludge Type	Feed Solids Concentration % DS	Solids Loading[a] $Kg/m^2.h$	Cake Solids Content %DS
PS + WAS	3 - 7	17 - 24	15 - 25

The dewatering takes place because (1) free water is drained through the screens, (2) the friction created by the slow-moving screens at 1–3 rpm, and (3) the unit has a restricted outlet that creates backpressure. A schematic of a typical rotary press is shown in Figure 1-3.

The principal parameters that affect the design of the rotary press are; (1) feed sludge concentration between 2 to 6% DS, (2) hydraulic loading, typically 2.5–3.5 $m^3/m^2 \cdot h$ (vary with feed sludge concentration), (3) average solids loading typically 250 $kg/m^2 \cdot h$, and (d) polymer dosage 2–17.5 g/kg. The typical performance parameter of the rotary press is presented in Table 1-5. The amount of wash water required is relatively low, typically 200 L/min for 5 min per channel per day. The rotary press is supplied in standard channels of 1-, 2-, 4- and 6-unit configurations. The effective dewatering area varies from 0.2 to 7 m2 per unit based on the number of channels and the diameter of the screen. A typically rotary press system consists of sludge feed pumps, polymer feed equipment, a conditioning mixing system (either inline or tank designs can be used), the rotary press, power supply, process monitoring, and operational control.

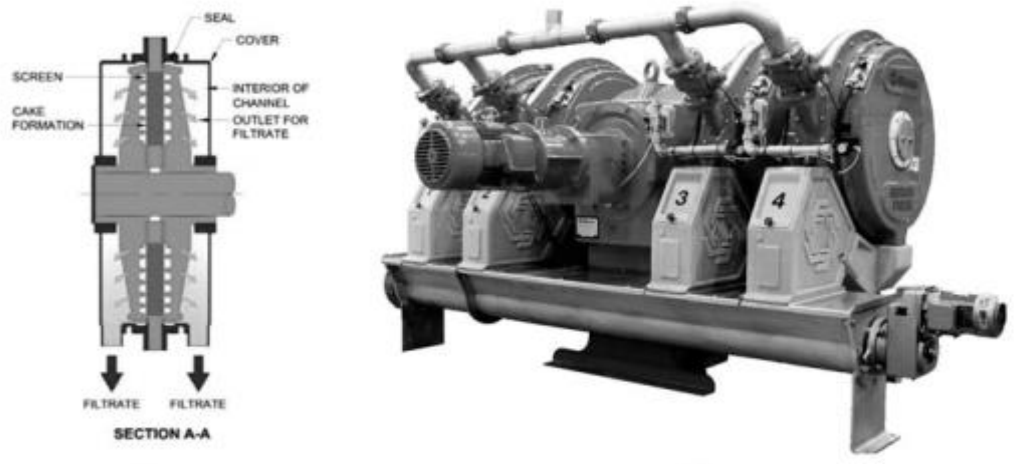


Figure 1-3 Rotary Press Typical Schematic (Reprinted with permission from Taylor & Francis Group LLC-Books)

Table 1-5 Typical Performance Parameters Of The Rotary Press (Metcalf & Eddy/AECOM, 2014)

Sludge Type	Polymer use g/Kg DS	Cake Solids Content %DS	Solid Capture %
Raw sludge:			
PS	2 - 6	28 - 45	95+
PS + WAS	7.5 - 10	20 - 32	92 - 98
WAS	12.5 - 17.5	13 - 18	90 - 95
ANDS:			
PS	7.5 - 10	22 - 32	90 - 95
PS + WAS	10 - 15	18 - 25	90 - 95

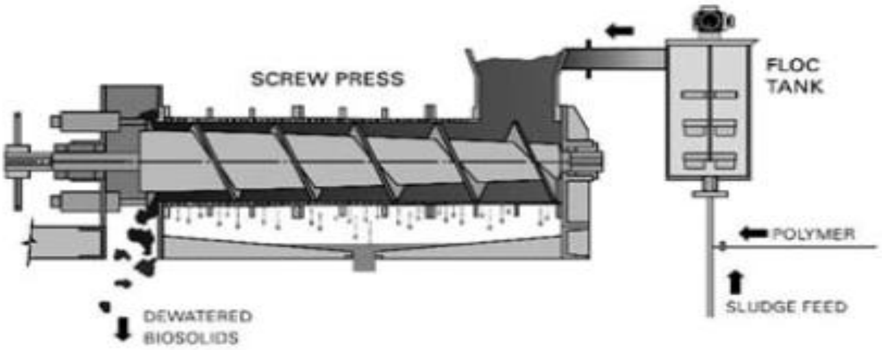
Sludge Type	Polymer use g/Kg DS	Cake Solids Content %DS	Solid Capture %
WAS	10 – 17.5	12 - 17	85 - 90
ADS: WAS	8.5 – 17.5	28 - 45	90 - 95

The advantages of the rotary press are; (1) low power requirements, (2) low maintenance, (3) low O&M costs, (4) enclosed vessel for containing odour, (5) relatively low vibration and noise levels, (6) compact and expandable configuration, (7) low wash water, and (8) low operator attention requirements. The major disadvantages are; (1) relatively sensitive to sludge quality, (2) high polymer requirements, (4) limited capacities, require a high number of units for large plants, and (5) high capital cost. It is recommended that a pilot test be conducted to establish the design parameter, specifically the relationship between polymer dosage, solids capacity, and cake dryness.

1.6 Screw Press (Metcalf & Eddy/AECOM, 2014, Qasim et al., 2018)

The screw press consists of a low speed rotating screw inside a wedge-wire screen basket, and both are contained in a long cylindrical enclosed vessel. The screw press available types are; (1) horizontal, (2) inclined and (3) vertical. The spacing of the wedge-wire screen is typically 0.2 to 0.3 mm, and the screw rotational speed is approximately 0.5 RPM. In the inclined and horizontal arrangement, the chemically conditioned sludge is fed at low pressure into the basket from one end of the vessel. The inclined arrangement (appx. 20 degrees) allow the lower section of the basket serves as a pre-dewatering zone, where free water drains by gravity, while the upper section of the basket serves as a pressure zone. As the sludge moves forward by the slow rotating screw, the filtrate flows out through the screen. The applied backpressure to complete the dewatering process is controlled by an adjustable restriction located at the outlet side of the screw press. In some designs, narrowing the flights spacing at the end of the screw is used to increase the backpressure. In the vertical arrangement, the chemically conditioned sludge is fed from the bottom of the screw, and the cake becomes progressively drier as it is pushed to the top toward the discharge side. The adjustable backpressure system is located just below the discharge chute and gives the cake a final squeeze before discharge. A schematic of a typical rotary press is shown in Figure 1-4. The screw press typical capacity is between 7 to 45 l/min at an operating pressure between 280 and 560 KPa. However; The hydraulic capacity of one unit can reach about 10 m3/h, and the solids capacity is about 275 kg/h. The polymer is the typical conditioning chemical used. It is typically added to the sludge upfront of the screw press and mixed in a static inline mixer or a pre-mixing tank (flocculation tank). The screw press can achieve a cake with a dry solids concentration of 15 - 40%; typical screw press performance parameters are presented Table 1-6. The screw flights are equipped with brushes for continuous internal cleaning of the wedge section basket. A spray nozzles system is also provided for periodic cleaning of the basket from the outside with spray water.

The principal parameters that affect the design of the screw press are; (1) feed sludge concentration between, (2) Sludge type and characteristics, (3) average solids and hydraulic loading, and (d) polymer dosage. The advantages of the screw press are similar to those of the rotary press; (1) low power requirements, (2) low maintenance, (3) low O&M costs, (4) enclosed vessel for containing odour, (5) relatively low vibration and noise levels, (6) compact and expandable configuration, (7) low wash water, and (8) low operator attention requirements. The major disadvantages are; (1) relatively sensitive to sludge quality, (2) high polymer requirements, (4) limited capacities, require a high number of units for large plants, and (5) high capital cost. It is recommended that a pilot test be conducted to establish the design parameter, specifically the relationship between polymer dosage, solids capacity, and cake dryness.



(a) Horizontal Screw press

(b) Inclined screw press

Figure 1-4 Screw Press Schematic (a) Horizontal, (b) Inclined

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Table 1-6 Typical Performance Parameters Of The Screw Press (Metcalf & Eddy/AECOM, 2014)

Sludge Type	Polymer use g/Kg DS	Cake Solids Content %DS	Solid Capture %
Raw sludge:			
PS	4 - 10	30 - 40	90+
PS + WAS	5 - 10	25 - 35	90+
WAS	8.5 - 11	15 - 22	88 - 95
ANDS:			
PS	10 - 17.5	22 - 28	90+
PS + WAS	10 - 17.5	17 - 25	90+
WAS	8.5 - 17.5	15 - 25	88 - 95
ADS: WAS	8.5 – 17.5	15 - 20	88 - 95

2. Natural dewatering systems

Natural dewatering systems refers to the processes that utilise natural evaporation and gravity drainage to achieve sludge dewatering (McFarland, 2001). Although some mechanical assistance may be involved, such as mixing and turning, the dewatering process is controlled primarily by natural forces (McFarland, 2001). It is also called air-drying (McFarland, 2001). The most common natural dewatering processes are; (1) drying beds and (2) sludge lagoons (Qasim et al., 2018). Natural dewatering systems are easier to operate, requires less equipment maintenance and consume less energy (McFarland, 2001). However, these systems require large land areas and typically more labour-intensive to remove the dried sludge (McFarland, 2001) . These factors make natural dewatering systems best suited for small to medium-sized wastewater treatment works treating 7500 m3/day of sewage or less (Turovskiy and Mathai, 2006). However, if land and labour are available at a reasonable cost, especially in arid and semiarid climates areas, the natural dewatering systems should be considered(McFarland, 2001) .

2.1 Drying Beds (Turovskiy and Mathai, 2006, Qasim et al., 2018)

Sludge drying beds are the oldest and the most widely used to date for sludge dewatering. Although drying beds are expected to be used in small plants and warmer, sunny regions, they are also used in several large plants and cold climates. Sludge drying beds are typically used for dewatering of digested sludge and WAS from the extended aeration process without pre-thickening. The principal advantages of sludge drying beds are; (1) low capital cost, (2) low energy consumption, (3) low to no chemical consumption, (4) low operator skill and attention required, (5) less sensitivity to sludge variability, and (6) produce a dried sludge with a higher dry solids content compared to most mechanical methods. Disadvantages include; (1) large area requirements, (2) requires prior sludge stabilization, (3) susceptible to climate conditions, (4) odour potential, (5) sludge removal is usually labour intensive, (6) visible to the public and (7) potential groundwater contamination due to subsurface infiltration. The design and performance of drying beds are mainly affected by; (1) feed sludge characteristics, (2) sludge conditioning, (3) climate conditions, and (4) Soil permeability. The common sludge drying beds types are; (1) sand drying (conventional), (2) paved drying, (3) artificial media drying, and (4) vacuum-assisted drying.

Sand Drying Beds; The sand drying bed is the most common drying bed among the other types. The sand drying bed is divided into sections. Each section is rectangular, with a width of 6 to 7.5 m and a length of 30 to 60 m. A perforated pipe underdrain system covers the bottom of each section underneath the sand and graded gravel layers to collect the drained water. The sand layer is typical 20 – 45 cm in depth (effective diameter: 0.3–0.75 mm; uniformity coefficient: $\leq$ 4), and placed on the top of a graded gravels layer with a typical depth of 20 – 30 cm (effective diameter: 3 – 25 mm). The perforated pipe drainage system is typically made of plastic pipes or vitrified clay pipe laid with open joints (without gaskets). The underdrain pipe diameter should be 150 to 200 mm diameter, slopped at a minimum of 1% and spaced 2.5 – 6 m centre-to-centre. The underdrain pipes material should consider the type of sludge removal vehicles to be used to avoid damage to the pipes. The collected drainage water typically returned to the head of warks. If mechanical sludge removal is employed, a greater gravel depth may be required to protect the underdrain network structurally. The drying beds outer walls may be earth embankments, treated wood, concrete blocks, or reinforced concrete. The partitions between sections may be constructed of concrete blocks, reinforced concrete, or planks extended between slots in concrete posts. The planks can be made of wood or precast concrete. If the loader is used for cake removal, at least one solid vertical wall in each section against which the loader can push will speed bed cleaning. Each section should have a freeboard of 0.3 to 0.9 m above the sand layer or ground level, whichever is higher. The bottom of the bed should have a liner layer with at least 0.3 m thickness, permeability less than 1×10^7 cm/s, and a minimum slope of 1% toward the drain. However, an impermeable concrete liner is required if the groundwater table is within 1.2 m of the bottom of the liner. A basic sand drying bed schematic diagram is shown in Figure 2-1.

Each section of the drying bed will be fed the sludge to a depth of 20–30 cm and allowed to dry for 10–20 days. Typically, the dewatering occurs by drainage for about two days, and the drying occurs by evaporation for 2–3 weeks. The drying time is shorter in regions that experience low rainfall and humidity and greater sunshine. The typical solids capture rate of sand drying bed is 90%. At the end of the drying period, a dried sludge with a 20 -30 % dry solids concentration is formed. Dried sludge has a coarse, cracked surface and is dark brown. The dried sludge can be either removed manually by shovelling or mechanically by scraper or front-end-loader. Odour problem may be caused by poorly digested sludge. Sludge drying beds may be open or covered depending on weather conditions; and to control insects and odour. The design criteria for open sand drying beds are presented in Table 2-1. The amount and quality of the filtrate removed by drainage are strongly influenced by the type and concentration of the feed sludge; for example, a well anaerobically digested sludge produce filtrate with BOD5 and COD of 40 mg/L and 350 mg/L, respectively. The parameters that influence the sand drying bed performance are; (1) required dewatered sludge dryness, (2) Feed sludge solids concentration, (3) type of sludge applied (e.g., Raw, stabilized, thickened, conditioned, etc.), and (4) drainage and evaporation rates.

Table 2-1 Typical Design Criteria for Open Sand Sludge Drying Beds (Turovskiy and Mathai, 2006)

Type of digested sludge	Area [a] m^2/Capita	Sludge Loading Kg DS/m^2.yr
PS	0.09 – 0.12	120 - 150
PS + TFS	0.12 - 0.17	90 - 120
PS + WAS	0.16 - 0.23	60 - 100
PS + Chemical sludge	0.18 - 0.23	100 - 160

[a] Area requirements for covered sand drying beds is about 70 to 75% of those for open sand drying beds

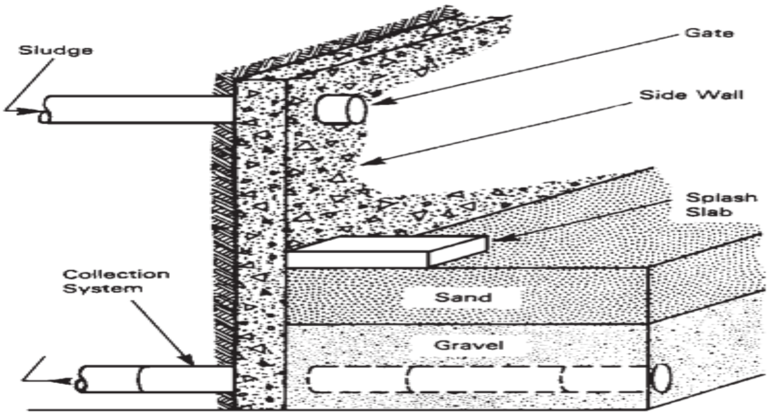
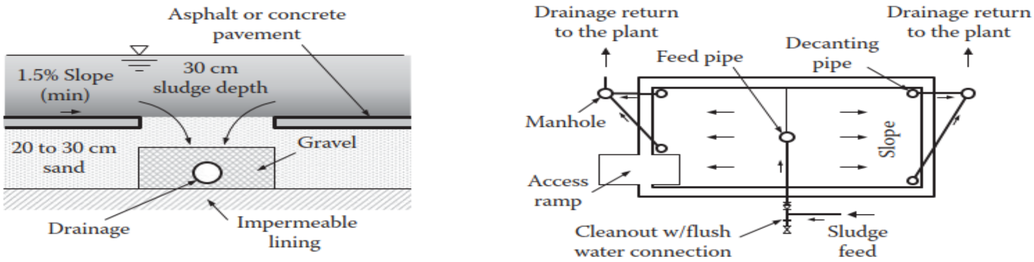


Figure 2-1 Basic sand drying bed schematic diagram (Reprinted with permission from Johan Wiley & Sons – Books)

Paved Drying Beds; The paved drying beds are typically rectangular in shape and are 6 – 15 m wide and 20-45 m long with vertical sidewalls. The paved drying beds are categorised to (1) drainage type and (2) decanting type. The drainage-type drying beds have either concrete or bituminous concrete paved tracks. The paved tracks rest on 0.2 – 0.3 m sand or gravel base and have a minimum slope of 1.5% toward the drainage area. The drainage area is 0.6 to 1 m wide and located on either side or in the middle. The overall design and operation of the paved drying beds are similar to that of sand drying beds. A minimum 150 mm diameter pipe, located in the middle of the drainage area, conveys drainage water away. Paved drying beds facilitate the use of a frond-end-loader to remove dried sludge. It also allows the use of mobile equipment to agitate the percolation area to improve drainage. For the same amount of sludge and drying period, paved drying beds require more area than sand beds as pavements inhibits drainage. The solid concentration in the dried cake may range from 20% to 40%. However, the solid concentration in the dried cake may range from 40% to 50% under hot climate conditions.

The decanting type drying beds typically have paved impermeable base of soil-cement mixture. They are also equipped with a vertical supernatant decanting pipe located at the four corners. The typical depth of the applied feed sludge is 0.3 m. 20% to 30% of the water is removed by decanting; the remaining water is removed by evaporation within 30 to 40 days. A schematic for both types of paved drying beds is shown in Figure 2-2.



(a) Drainage type bed (b) Decanting type bed

Figure 2-2 Paved drying bed: (a) drainage type bed and (b) Decanting type bed

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Artificial-Media Drying Beds; This type of drying beds is equipped with a false floor that is typically made of artificial media such as stainless-steel wedge wire or high-density polyurethane panels. The wedge wire drying bed is a shallow and narrow watertight rectangular basin with a false floor of wedge wire panels with slotted openings of 0.25 mm. On the other hand, the high-density polyurethane media system has 30 cm square interlocking panels with slotted area. However, both systems operate in a precisely similar manner. A schematic of the artificial-media drying beds is shown in Figure 2-3. A control valve is installed below the false floor to control the drainage. The dewatering process starts by closing the outlet valve and feeding plant effluent to the bed surface to a depth of 2.5 cm. The plant effluent works as a cushion and aid the sludge distribution across the wedge wire. Upon reaching the desired sludge depth on the top of the false floor, the control valve opens, allowing water to drain out of the drying bed. Once the initial wastewater is drained, the sludge starts to concentrate by drainage and evaporation. Upon reaching the desired solids concentration, the dried sludge can be removed by a front-end loader, and the panels are washed with a high-pressure water jet. The principal advantages of the artificial-media drying over the sand drying beds are; (1) low media clogging, (2) high and constant drainage rate, (3) easier sludge cake removal, (4) easier to maintain, and (5) better handling to dilute and difficult-to-dewater sludge, such as aerobically digested sludge. The typical solids loading rates are 2–5 kg/m^2 per cycle or 750–1800 kg/m^2·year. The typical operating cycle is 24 h and can achieve dry sludge solids of 8–12%.

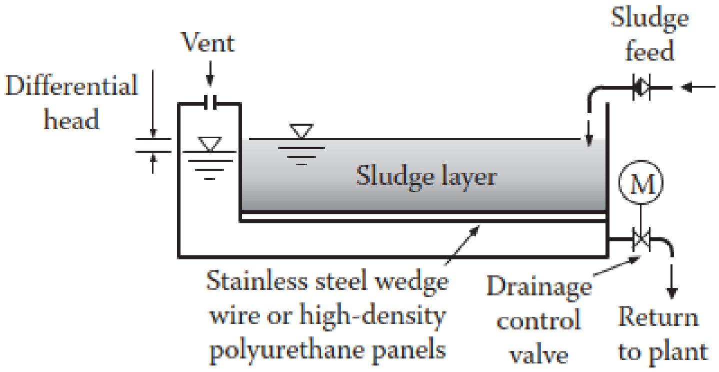

Figure 2-3 Artificial-Media Drying Beds (Reprinted with Permission from Taylor & Francis Group LLC – Books)

Vacuum-Assisted Drying Beds; This type of drying beds accelerate dewatering by applying vacuum to the underside of the porous filter plates. The bed is typically rectangular and has a reinforced concrete slab at the bottom. A gravel layer of several millimetres thick is placed on top of the concrete slab to support the porous filter plates. The gravel layer is also used as the vacuum chamber where the vacuum pump is connected. The main components of this type of drying beds are; (1) porous media plate used as a false floor in a concrete housing, (2) gravel support media, (3) polymer dosing and mixing equipment, (4) vacuum pump, (5) sludge cake removal equipment, and (6) high-pressure surface washing equipment. The operation sequence starts with the feed sludge being conditioned with a polymer. Conditioned sludge is then fed by gravity to the drying bed at a solids rate of 5 to 30 Kg/m^2, and a depth of 0.3 to 0.75 m. After the sludge feeding is over, the sludge is allowed to drain by gravity for an hour. The vacuum system started at the end of the drainage period, and the vacuum is maintained at 30 to 48 KPa. The vacuum pump stops when the dried solids (cake) crakes and the vacuum is lost. The dry solid content at this stage is 10 – 26%. The dried sludge is then allowed to air till the end of the cycle; the typical cycle time is 1 to 2 days. The cake is removed from the bed using a front-end loader. The final step is to wash the porous media using a high-pressure water system. Table 2-2 presents performance data for vacuum-assisted drying beds. Compared to other drying beds types, the principal advantages of this system are (1) short dewatering cycle time, thereby reducing the effects of weather, and (2) requires a smaller area. The small area makes it easy to cover this type of drying bed and protect it from unfavourable weather conditions. The principal disadvantage is that polymer conditioning of sludge is required for successful operation.

Table 2-2 Typical Performance Data for Vacuum-Assisted Sludge Drying Beds (Turovskiy and Mathai, 2006)

Sludge Type	Feed Sludge %DS	Solids loading Kg DS/m^2	Polymer use g/Kg DS	Cycle time h	Cake Solids Content %DS
ANDS:					
PS	1 - 7	10 - 20	2 - 20	8 - 48	12 - 26
PS + WAS	1 - 4	5 - 20	15 - 20	18 - 48	15 - 20
PS + TFS	3 - 10	15 - 30	20 - 26	18 - 48	20 - 26
ADS:					
WAS (conventional)	1 - 4	5 - 15	1 - 17	8 - 48	10 - 23
WAS (Oxidation ditch)	1 - 2	5 - 10	2 - 7	8 - 48	10 - 20

2.2 Drying Lagoons (Turovskiy and Mathai, 2006)

Sludge drying lagoons are another cheap method that can replace drying beds for dewatering stabilized sludge when sufficient land is available. The principal sludge dewatering mechanisms for dry lagoons include subsurface infiltration, decanting supernatant and evaporation. However; evaporation is the most critical dewatering factor. Lagoons are not suitable for dewatering raw sludge due to odour and nuisance potential. The drying lagoons are typically considered if the annual evaporation rate exceeds the annual precipitation. The subsurface infiltration is a function of the soil permeability where drying lagoons are located. The subsurface infiltration may decreases over time as the sludge depositions will clog the soil. However, the dried sludge removal method may reduce the clogging of the soil. The potential impact of subsurface infiltration on the environment, especially groundwater, should be evaluated. If necessary, a lagoon lining and underdrain system may be utilised to mitigate the problem.

Drying lagoons are generally rectangular shallow earthen basin enclosed by earthen dikes 0.6 to 1.2 m high, as shown in Figure 2-4. The principal equipment required includes sludge feed pipelines, supernatant decant pipelines and removal equipment such as a bulldozer, dragline, or front-end loader. The dewatering cycle starts with pumping stabilised sludge into the lagoon to a depth of 0.6 – 1.2 m. The stabilised feed sludge is then allowed to settle. The formed supernatant is decanted from the surface either contentiously or intermittently and returned to the head-of-works. More stabilised feed sludge is to be added gradually in proportion to the decanting to ensure that the sludge depth reaches 0.7 to 1.4 m. Then the sludge is left for moisture to evaporate. The surface crust may be removed periodically to ensure continuity of moisture evaporation. The feed sludge depth and the climate conditions dictate the time required for dewatering. Typically, 3 to 12 months are required to reach a dry solids concentration of 20% to 40%. Once the required dry solids concentration is reached, the dewatered sludge is removed from the lagoon using the mechanical equipment described above. After emptying the lagoon, the cycle may restart. The factors affecting the drying lagoons design and performance are ; (1) precipitation, (2) evaporation, (3) Solids loading 32 - 40 kg/m^3·year of lagoon capacity, (4) Per capita design criteria 0.3 - 0.4 m^2/capita in areas with 900 mm of annual rainfall. The main advantages of sludge drying lagoons are; (1) Low energy cost, (2) low to no chemical cost, (3) relatively less sensitive to feed sludge characteristics, (4) can be used as a buffer during plant shock loading, (5) aid further stabilisation of organic matter, (6) low operation attention required, (7) doesn't require skilled labour to operate, (8) low capital cost, if the land is available, and (9) low operation cost. The principal disadvantages are; (1) potential release of odour, (2) may cause groundwater contamination (environmental impact), (3) attracts vectors, (4) visible to the public, and (5) requires a large footprint.

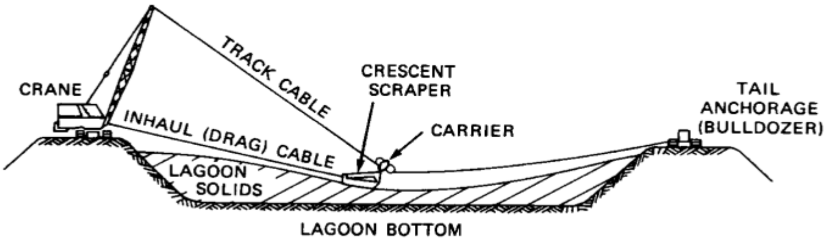

Figure 2-4 Typical Sludge Drying Lagoon (Reprinted with Permission from Springer)

Appendix 10 – Thermal drying

1. Mechanical dewatering systems

The mechanical dewatering systems are used for large wastewater treatment facilities (Qasim et al., 2018). These systems are typically installed inside a building along with a chemical conditioning feed system (Qasim et al., 2018). The conditions that favour the use of mechanical dewatering systems include (1) aesthetics, (2) climate, (3) costs, and (4) site limitations (McFarland, 2001). All mechanical dewatering systems use filtration as a mechanism for water removal (McFarland, 2001). The pressure drop required for filtration is significant (McFarland, 2001). The mechanical dewatering systems archive the required pressure drop through (McFarland, 2001); (1) creating a centrifugal force, (2) placing a vacuum on one side of a porous medium and (3) Raising the pressure on one side of a porous medium. At present, belt filter presses and solid-bowl centrifuges are the mechanical dewatering systems most frequently used(McFarland, 2001, Qasim et al., 2018).

1.1 Centrifugal dewatering (Qasim et al., 2018)

Besides sludge thickening, centrifuges are also used for sludge dewatering. The main advantages of using centrifugal dewatering are; (1) continuous operation, (2) the produced cake has a high solid concentration,(3) enclosed system, clean with no spills and minimal odours, (4) wash water requirement is very low, and in some designs not required, (5) suitable for thin sludge dewatering like WAS (< 0.5% solids), (6) easy to install, (7) small footprint, (8) low initial capital costs, and (9) easy startup and shutdown. On the other hand, the centrifuges major disadvantages are; (1) high power consumption, (2) the centrate has a relatively high TSS concentration, (3) high operation and maintenance costs, and (4) prone to produce noise and vibration. Chemical conditioning before the centrifuge is required to aid its performance. The organic polymer is the typical chemical used for conditioning. The organic polymer dosage is in the range of 1 to 25 g/kg of dry solids. The dry solid concentration of the sludge cake produced by the centrifuges is 20–30% solids with an 85–95% solids capture rate. The available unit capacity is between 5–280 m3/h. The principal operating parameters controlling the centrifuge performance are; the sludge feed rate, rotational speed, type of polymer used, and feed sludge characteristics (concentration, particle size, shape, density, temperature and liquid viscosity). For more details, please see section **Error! Reference source not found.Error! Reference source not found.**

1.2 Belt filter press (BFP) (Turovskiy and Mathai, 2006, Qasim et al., 2018)

The belt filter press is a continuous-feed sludge dewatering machine where the dewatering occurs by compressing the sludge between two tensioned porous moving belts. It is presently the most widely used dewatering equipment in the world. The BFP operation involves four basic processes (1) chemical conditioning, (2) gravity drainage, (b) low-pressure compression, and (c) high-pressure compression. The chemical conditioning occurs in a vertical column, a chemical conditioning tank, or a long pipe with a static mixer. The mixing time between the polymer and sludge should be between 15 to 45 sec for efficient mixing. The conditioned sludge is then fed into the gravity zone of the moving porous belts. The gravity zone allows a significant amount of the free water to drain through the belt and collected in a pan and routed to a sump. The gravity zone is equipped with plows. The plows significantly increase the gravity drainage process by clearing spaces for water to drain and by turning the solid mass on the belt. The liquid sludge is stopped from running off the sides of the belt by restrainers and rubber seals. At the end of this zone, the sludge is typically a loosely structured cake. From the gravity drainage zone, the sludge falls into the low-pressure zone (also called wedge zone) where the sludge is introduced between the two belts then passes to the high-pressure zone where a series of rollers apply pressure to expel nearly all the free water from the sludge. A schematic of a belt filter press is shown in Figure 1-1.

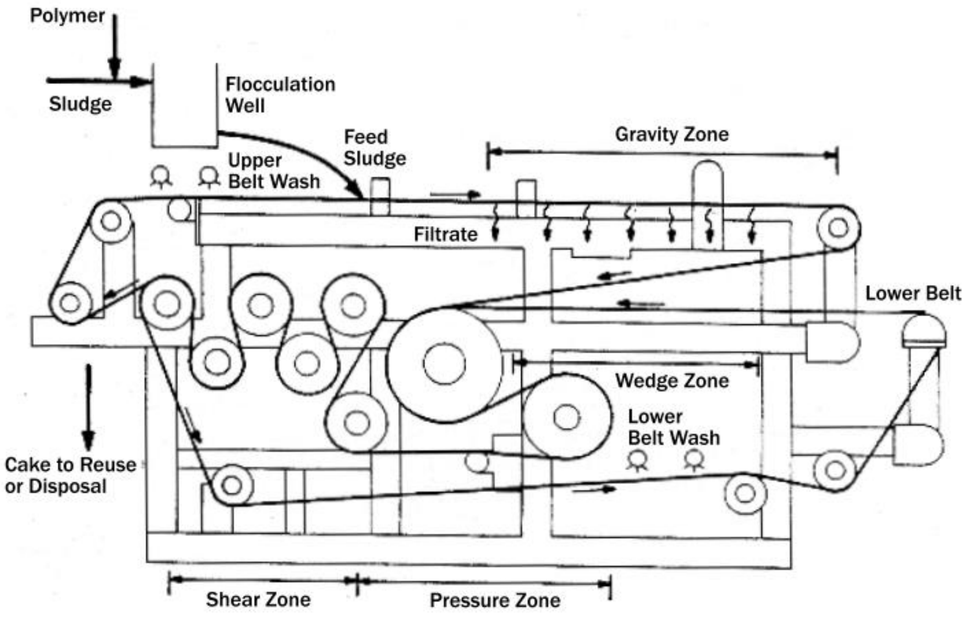

Figure 1-1 Belt Filter Press Schematic (Reprinted with permission from Johan Wiley & Sons-Books)

The principal advantages of the belt filter press are (1) simple operation and maintenance; (2) easy startup and shutdown; (3) continuous operation, (4) low power requirement, (5) Produced cake with high solids content; and (6) low noise level. On the other hand, the major disadvantages are (1) uses a large volume of wash water, (2) screening, grinding, or degritting of sludge is required to protect the belt from damages, and (3) high operation cost, and (4) requires enclosure for odour control. BFP typically produces sludge cake with dry solids concentration between 15% and 30% at a solids capture rate of 95–98%. The wash water supply is continuous and typically in the range of 150 to 300 L/m.min at 12 to 17 KPa. The typical performance data of the belt filter press is presented in Table 1-1.

Critical auxiliary systems required for the operation of the BFP are; (1) belt wash water supply and (2) compressed air for pneumatic or hydraulic belt tensioning systems. The major component of the BFP are; (1)dewatering belts, (2) rollers, (3) drive unit with control, (4) belt tracking (or steering) system, (5) belt tensioning system, (6) belt washing system, and (7) automatic shutdown system for belt misalignment, insufficient belt tension, belt drive failure; sludge conditioning tank failure; loss of pneumatic or hydraulic system pressure; low belt wash water pressure; and emergency stop.

The most common size of the belt width is 2m. However, BFP is available with a belt width between 0.5 to 3.5 m. BFP units with 2-belts and 3-belts are currently available for dewatering of thickened and unthickened sludges with solids contents of 2–6% and 1.5% or less, respectively. The typical number of rollers is 6 to 24 arranged in series. The arrangements of the these rollers categorise the BFP to a horizontal and vertical belt.

Table 1-1 Typical Design and Performance Parameters of Belt-Filter Presses (Qasim et al., 2018)

Sludge Type	Feed Solids Concentration % DS	Solids Loading[a] Kg/m.h	Hydraulic loading[a] L/m.min	Polymer Dose g/Kg DS (Polymer/Feed Sludge)	Cake Solids Content %DS
Raw or TFS:					
PS	4 - 8	1000 - 1500	250 - 600	1.5 - 2.5	25 - 35
WAS	1 - 4	200 - 350	200 - 350	3 - 7.5	15 - 20
PS + WAS	3 - 6	350 - 800	350 - 800	5 - 10	15 - 25
SBR/MBR sludge	1 - 2	250 – 400	250 - 350	5 - 10	10 – 20
ANDS:					
PS	2 - 5	700 - 900	250 - 600	2 - 5	25 - 35
WAS	2 - 3	250 - 400	100 - 350	4 - 10	15 - 20
PS + WAS	2 - 4	300 – 550	150 - 450	4 - 8	15 - 25
ADS:					
WAS	1 – 3	250 - 400	150 - 350	6 - 10	10 - 20
TFS	2 - 5	350 - 600	100 - 500	2 – 12.5	10 - 20

a. Based on belt width in meter

1.3 Filter Press (Turovskiy and Mathai, 2006 , Qasim et al., 2018)

Filter press is also called plate and frame filter press or recessed plate filter press. It operates in batches in which dewatering is achieved by applying high pressure to force the water out from the sludge. The cake produced using filter press is the drier if compared with other dewatering alternatives. The filter press generally consists of a series of plates, each equipped with a recessed section. When the plates come together, it forms a chamber into which the sludge is pumped for dewatering. The chamber walls are covered by filter media (cloth) that permit the filtrate to pass through. There are two common types of filter press (1) fixed-volume recessed plate, and (2) Variable volume recessed plate. The typical filtration area for either type ranges from 0.3 to 6 m^2 per chamber with a plate size of 0.5–2 m. A filter unit may consist of 20 – 200 chambers. Chemical conditioning of the feed sludge is required for both types of filter-presses. The typical chemicals used for conditioning are ferric chloride and quick lime with a typical dosage of 50 g/kg for ferric chloride and 100 g/Kg for quick lime on a dry solids basis. The typical solids loading rate is 5 Kg/m^2 h. The operation sequence of both types of filter press are; (1) Feed; conditioned sludge is pumped to the chamber, (2) apply and maintain the desired pressure for the required period, (3) the filtrate passes through the filter cloth and plate to outlet ports, (4) separate the plates and remove the cake, and (5) wash the cloth and close the press for the following operating cycle. In the fixed-volume recessed-plate filter press, the sludge is pumped into the chamber between the plates at relatively high pressure between 700 to 1550 KPa and maintained for 1 to 3 hours. The plates are then moved away mechanically from each other, and the cake is dropped from the chambers onto a truck or conveyor belt for disposal of further processing. The cake thickness varies from 25 to 38 mm, with a dry solids concentration between 35 and 42%. Following cake removal, the filter press is washed and ready for the next cycle. The overall cycle time varies from 1.5 to 5 hours. In the variable-volume recessed-plate filter press, a diaphragm is added behind the filter media. The sequence starts with feeding the conditioned sludge to the chamber at a lower pressure between 690 and 860 KPa. Once the chamber is filled, the sludge feed pump is stopped. Water or air are pumped between the diaphragm and the media, squeezing the already formed cake and releasing more water from the cake. Typically the water or air pressure applied is between 1380 to 2070 KPa for a period of 15 to 30 minutes. The diaphragm is then deflated, and the press opens, and the cake is dropped from the chambers onto a truck or conveyor belt for disposal of further processing. The cake thickness varies from 25 to 38 mm, with a dry solids concentration between 38 and 50%. Following cake removal, the filter press is washed and ready for the next cycle. The overall cycle time varies from 1 to 3 hours. The variable-volume filter press offers several advantages over the fixed-volume filter press such as, (1) It produces a dryer sludge cake, (2) shorter operation cycle, therefore a higher daily production, (3) lower O & M for the feed pumps, and (4) the ability to dewatered marginally conditioned sludge. On the other hand, the principal disadvantage of the variable-volume filter press is the higher initial capital cost, which can be as much as two to three times compared to a fixed-volume filter press with the same daily capacity. Performance data for both types of filter presses is presented in Table 1-2 and Table 1-3.

The advantages of plate and frame filter press compared to other dewatering systems are: (1) high cake dryness, (2) high solids capture rate, (3) low TSS concentration in filtrate, and (4) simple operation. The major disadvantages are (1) batch operation only, (2) Higher capital and O&M costs, (3) labour-intensive, (4) large footprint, (5)requires high-pressure washing system, (6) an acid wash system is required to remove lime scales, (7) cake shredder is required mainly if the dewatered sludge to be incinerated, and (8) Increase sludge quantity considerably due to the high inorganic chemical for conditioning. The filter presses may be more suitable for dewatering water treatment sludge where metal salt and/or lime are already added as coagulants in the treatment processes. The performance of both types of filter presses is affected by several operational parameters, including (1) feed sludge dry solids concentration, (2) chemical conditioning dosage, (3) required cake solids content, (4) total cycle time, (5) solids capture, and (6) sludge load kg/m^2 .h).

1.4 Vacuum filter (Turovskiy and Mathai, 2006, Qasim et al., 2018)

The use of vacuum filters has declined in recent years because it consumes the most considerable energy per unit of dewatered sludge. Besides, it requires continuous operators attention and only performs if feed sludge dry solids content is 3% or higher. The vacuum filter is considered a continuous process. Vacuum filters consist of a horizontal cylindrical drum covered with porous filter media.

Table 1-2 Performance Data for a Fixed-Volume Filter Press (Turovskiy and Mathai, 2006)

Sludge Type	Feed Solids Concentration % DS	Conditioning Chemical[a]		Cake Solids Content %DS[c]	Cycle Time (h)[d]
		Ferric Chloride ($FeCl_3$) %	Lime (CaO) %		
PS	5 - 10	5	10	45	2
PS + WAS (50:50)	3 - 6	5	10	40 - 45	2.5
PS + WAS (50:50)	1 - 4	6	12	45	2.5
PS + TFS	5 - 6	6	20	38	2
PS + Ferric chloride (FC)[b]	4	-	10	40	1.5
PS + WAS (FC)[b]	8	5	10	45	3
WAS	5	7.5	15	45	2.5
PS + two stage high lime	7.5	-	-	50	1.5
ANDS (PR)	8	6	30	40	2
ANDS (PR + WAS)	6 - 8	5	10	45	2
ANDS (PR+WAS) FC[b]	6 - 8	5	10	40	3
ANDS (PS + WAS) (50 :50)	6 - 10	5	10	45	2
ANDS (PS + WAS) (50 :50)	1 - 5	7.5	15	45	2.5

a % dry solids
b Ferric chloride used as a coagulant aid in the secondary process.
c Include conditioning chemicals.
d Time exclude cake discharge time

Table 1-3 Performance Data for Variable-Volume Diaphragm Filter Press (Turovskiy and Mathai, 2006)

Sludge Type	Feed Solids Concentration % DS	Conditioning Chemical[a]		Cake Solids Content %DS	Cycle Time (min)
		Ferric Chloride ($FeCl_3$) %	Lime (CaO) %		
PS	12	2.9	13	48	21
PS[b] + WAS (25:75)	12 - 16	0	0	52	22

a % dry solids
b Heat treated primary sludge

The filter media is typically cloth made of natural or synthetic fabric; in some designs, woven stainless steel mesh or coil springs are used. The vacuum applied downstream of the filter media drives the water to move through the filter media. The drum rotates slowly while partially submerged in a vat of conditioned sludge. As the drum rotates while the vacuum is applied, the sludge moves in sequence between the three distinct zones: cake forming, cake drying, and cake discharging. In the cake discharge zone, the cake is removed from the filter media. After cake discharge, the filter media is washed. Figure 1-2 is a typical cross-sectional view of a rotary vacuum filter. The vacuum filter performance is dependent on; (1)type of feed sludge, (2) dry solids concentration in the feed sludge, (3) type and quality of conditioning chemicals, (4) level of vacuum applied, (5) degree of drum submergence, (6) type of filter media, and (5) cycle time. Typically Ferric chloride and lime are used as conditioning chemicals. The drum submergence time in sludge is referred to as the form time, and the time spent in the air is referred to as dewatering time. The form time usually is 40–60% of the cycle time. A 70 kPa of vacuum is typically applied inside the drum, producing a cake with a 20–35% dry solids concentration. The vacuum filter solids loading rate is typically between 5 – 25 kg/m^2·h with a conditioning chemical dose of 20–40 g/kg for ferric chloride and 100–150 g/kg for lime as CaO on a dry solids basis. Typical vacuum filter performance data is presented in Table 1-4.

1.5 Rotary press (Metcalf & Eddy/AECOM, 2014, Qasim et al., 2018)

The rotary press is considered a relatively new technology if compared to other dewatering systems. The feed sludge is typically conditioned using an organic polymer. The polymer is injected upstream of the inlet into the rotary press. The conditioned sludge is then fed to the rotary press inlet rectangular feed channel; from there, the sludge flows into a peripheral channel formed by two parallel slow rotating stainless steel screens installed in a containment vessel. The water flows through the screens on either side and collected in a common channel, and exit at the bottom of the unit.

Appendix 11 – Sludge composting

1. Introduction

The primary parameters that influence the design and operation of a composting facility are;

(1) Moisture content (Qasim et al., 2018); the optimum moisture content for composting process is from 40% to 60%. Typically, dewatered sludge contains 75% to 80% moisture; hence to reduce the moisture content to the optimum level, the dewatered sludge is blended with a bulking agent such as wood chips, sawdust, chipped brush, rice hulls, wood ash, leaves and yard wastes. The moisture content of the bulking agent should be in the range of 30% to 40%. The blending ratio of sludge and the bulking agent is typically 3:1 to 4:1 by volume. In addition to reducing the moisture content, the bulking agent serves as a carbon source and enhance air circulation by increasing the mixture porosity. The volume is used as a unit of measure because it is easier for operators to use a skip or a truck of known volume to measure such bulk material. In addition, knowing the density of the sludge and bulking agent mixture allows the operators to calculate the weight easily. The moisture content should be measured and maintained during the composting process. If the moisture content falls below 40%, the decomposition process will slow down. Also, if the moisture content exceeded 60%, the air circulation will decrease due to water clogging resulting in odour and inferior quality product.

(2) Temperature (McFarland, 2001 , Qasim et al., 2018) ; for effective destruction of pathogens, maintaining the compost temperature between 50°C to 70°C for several days is essential. Under optimum process and operation conditions, this temperature range is achieved within 12 to 24 hours, and it can be sustained for a period exceeding 1 to 2 weeks. The three main stages of composting associated with temperature are; initial mesophilic, thermophilic, and cooling. The thermophilic range is the most important where the maximum decomposition rate of organic matter and pathogen destruction occur. The decrease in temperature is a sign of the cooling phase and that the composting process is in the final stages. It should be noted that; the temperature within the compost pile may vary significantly depending on where measurements are taken. The temperature variation depends on the operation condition (moisture content, aeration rates, size and shape of the compost pile, atmospheric conditions, and nutrient availability) within and around the pile at the point of measure.

(3) pH control (Turovskiy and Mathai, 2006, Qasim et al., 2018); The optimum pH range for the growth of most bacteria is between 6 and 9 and between 5.5 and 8 for fungi. However, the pH will vary throughout the pile with time, and the variation is an indication of the process performance. At the end of the composting process and during the cooling phase, the pH will drop slightly to reach 7 to 7.5 in the end product. A drop of pH below 5 indicates aeration deficiency and that anaerobic conditions, and organic acid production.

(4) seeding (Qasim et al., 2018); seeding is the process of blending a portion of the finished compost to the sludge and the bulking agent to accelerate the aerobic decomposition by increasing the initial microbial concentration. The amount of seeding typically doesn’t exceed 20% of the dry solids in the

sludge. Hence, the optimum organic content for the mixture undergoing composting is 55% or higher; the seeding shouldn't negatively influence this percentage.

(5) Nutrient concentration(Turovskiy and Mathai, 2006, Qasim et al., 2018); the availability of nitrogen in the composting mixture is essential for the growth of the microorganisms. The initial optimum carbon-to-nitrogen (C/N) ratio in the composting mixture ranges from 20: 1 to 35: 1 by weight. It has been found that lower ratios increase the nitrogen volatilisation as ammonia decreasing the nutrient value of the compost and causing ammonia odour. However, higher ratios increase composting time leading to organic material remains active until the final composting stage. The lime conditioned sludge may not reach this ratio because lime solubilises nitrogen and increase its volatilisation. The addition of bulking agents and/or seeding are typically effective methods to correct an imbalance C/N ratio. The finished compost should contain C/N ratio of less than 10:1. The optimum nitrogen to phosphorus (N/P) ratio may range from 75:1 to 100:1 by weight.

(6) Oxygen concentration (Turovskiy and Mathai, 2006, Qasim et al., 2018); 5% to 15% oxygen by volume is required for an efficient composting process. However, oxygen concentration as low as 0.5% has been reported in some composting process; it is recommended not to allow oxygen concentration to drop below 5% to prevent the possible formation of anaerobic pockets within the compost pile. The addition of oxygen in excess of 15% by blowing air will decrease the composting process temperature due to heat losses through convection. The bulking agents play a critical role in maintaining the required oxygen concentration through the compost pile by increasing the dewatered sludge porosity allowing more air to pass through, leading to higher oxygen transfer.

(7) Odour control (WEF,2010, Qasim et al., 2018); in composting, the major odour problem typically arises from lack of aeration, leading to the development of anaerobic conditions within the pile, surface emission of active piles , leachet puddles from piles, and poor houskeeping. Organic acids are produced through the anaerobic decomposition of organic matter, and many of them are highly odorous. In addition, hydrogen sulphide and other off gases are also released under anaerobic conditions.

The main advantages of the sludge composting process are the following (Turovskiy and Mathai, 2006):

- The high nutrient contents of the compost made it suitable for a wide variety of end uses, such as landscaping, topsoil blending, and growth media.
- The Nitrogen in the compost is released more slowly and is available to plants over a long period, consistent with plant uptake needs.
- Well-composted sludge is safe to be sold to the public.
- Compost improves sand soil quality by increasing its water content and retention.
- Compost increases aeration and water infiltration of clay soils.
- The process can handle the change in feed sludge quality and quantity.
- The process requires relatively simple equipment.
- Operation simplicity.

- Proprietary composting systems (In-vessel composting system) require a relatively small area and can control odour.

The main disadvantages of composting process are the following (Turovskiy and Mathai, 2006):

- The traditional composting processes (windrow and aerated static pile) require relatively large areas, and odour release is a common problem.
- The composting process is influenced by the weather conditions (windrow and aerated static pile).
- The composting process is sensitive to the change in the feed sludge characteristics.
- Compost has less nitrogen from other stabilization processes (except lime stabilisation) due to ammonia loss during composting.
- Site runoff and leachate must be treated on-site or returned to the WWTW.
- Very dry compost is fire hazardous.

Most composting processes occur in the following order (Qasim et al., 2018);

(1) Preparation; where the dewatered sludge is mixed with the bulking agent and/or seeded to form a feedstock with optimum moisture content, porosity, carbon content and nutrients content.

(2) High-rate decomposition: in this phase, the compost pile is aerated by either addition of air or mechanical turning or both to maintain aerobic conditions. The decomposition progress and the temperature rises under the created aerobic condition; this step may take 3–4 weeks to complete.

(3) Curing: where further stabilisation occurs, pathogens are reduced, cooling takes place; this phase takes about 30 days.

(4) Recovery; to reduce operational costs (if practical), bulking agents are typically recovered and recycled using a trommel screen or equivalent device. This step typically occurs at the end of the high-rate decomposition phase or the curing phase.

(5) Drying: this phase is required, especially if the bulking agents are to be recovered; this phase may take anything between few days to a couple of weeks.

(6) Postprocessing: For removing undesired material such as plastics and metals through screening, It may also include grinding for size reduction.

(7) Recycle, where a portion of the final product is recycled for seeding during the preparation phase.

(8) Storage: typically for 30 to 60-d to provide further stabilisation and curing.

2. Windrow (Turovskiy and Mathai, 2006, Qasim et al., 2018)

The windrow is an agitated composting system where the dewatered sludge and bulking agent are mixed and placed in windrows. Seeding using finished compost may also be required. The windrows are typically 1 to 2 m high and 2 to 4.5 m wide at the base. The composting period is about 3–4 weeks, followed by 30 days of curing. The windrows are mechanically turned and mixed periodically.

Typically, turning and mixing are more frequent at the initial stage, starting daily and reduced to three times per week. The turning and mixing of the windrows disturb anaerobic pockets and help maintain aerobic conditions. However, depending on the turning and mixing frequency, the microbial activity within the pile may vary between aerobic, facultative, anaerobic, or various combinations thereof. In addition, turning and mixing may release offensive odour. Some window operations use supplemental mechanical aeration, and it also can be covered or enclosed.

3. Aerated Static Pile (Turovskiy and Mathai, 2006, Qasim et al., 2018)

The aerated static pile composting system consists of a grid of perforated pipes above which a pile of a mixture of dewatered sludge and a bulking agent is placed. Seeding using finished compost may also be required. The pipe grid is typically made of disposable corrugated plastic drainage pipes connected to a blower or exhaust fan that blows or draws air through the pile. The pile is 2–2.5 m. The pipe grid is typically covered with 0.3 m of wood chips. The wood chips facilitate even air distribution during composting and absorb moisture that may condense and drain from the pile. The compost pile is usually covered with a 150 to 200 mm thick layer of wood chips or screened finished compost for insulation. The composting period is 3–4 weeks, followed by 30 days or more for curing. In small facilities, a dedicated exhaust fan or blower is used for each pile. For optimum utilisation of space, especially for large facilities, an extended pile system is used where the fresh mixture is added to the side of the preceding day pile. The pile is typically extended daily for 28 days. It takes 21 days to remove the first section. After seven sections are removed in sequence, there is adequate space to start a new extended pile.

4. In-vessel Composting System (Turovskiy and Mathai, 2006, Qasim et al., 2018)

In-vessel composting system is also known as mechanical or enclosed reactor system. This system is a proprietary system where different suppliers produce a different design. However, all takes place typically inside an enclosed container or vessel. These systems may be either mixed or unmixed process in a horizontal or vertical reactor. The primary advantage of this system over the other composting systems are; (1) It produces a more stable and consistent compost, (2) less process time - 10 to 21 days depending on the system manufacturer, regulatory requirements, and desired product characteristics, (3) ability to control composting conditions such as airflow, temperature, oxygen concentration, (4)better control of odours, (5) lower labour cost, (6) higher throughput, and (7) smaller area requirements compared to other composting processes.

Appendix 12 – Thermal oxidation

1. Incineration

Incineration is a rapid exothermic oxidation process that occurs through the combustion of combustible sludge elements (Turovskiy and Mathai, 2006). It is also known as advanced thermal oxidation (ATO) (Qasim et al., 2018). Incineration is enforced in most European countries (Kelessidis et al., 2012). In this process, the organic matter is completely oxidised into carbon dioxide, water, and ash (Turovskiy and Mathai, 2006). Other gases are also produced as part of the incineration process and are typically referred to as exhaust gases (Turovskiy and Mathai, 2006). The exhaust gases typically include combustion ash, gases, excess air, water vapour, and it requires extensive treatment before releasing to the atmosphere (Turovskiy and Mathai, 2006). Therefore, air pollution control and carbon footprint reduction are essential considerations in designing and operating a sludge incineration system (Qasim et al., 2018). The feed sludge should contain at least 35% dry solids to start (autogenous combustion) and self-sustain the incineration (Andreoli et al., 2007). However, feed sludge with as low as 20% dry solids content may be used; but auxiliary fuel may be required to start and sustain the incineration process(Andreoli et al., 2007). Therefore, thermal drying or dewatering step before incineration is required (Turovskiy and Mathai, 2006). Typically, dewatering process is used due to its lower capital and operation cost. The typically combustible elements in the sludge are carbon, hydrogen and sulphur; these elements are chemically combined in the sludge in the form of grease, carbohydrate and protein (Turovskiy and Mathai, 2006). However, free sulphur is rarely present to a significant extent (Wang et al., 2007). The combustible portion of the sludge has a heat value (also called calorific value or fuel value) equal to the lower grade of coal (Metcalf & Eddy/AECOM, 2014). The heat value is the amount of heat released per unit mass of solids burned (WEF, 2010). Therefore, a proper proportioning between feed sludge characteristics, temperature, time and turbulence (mixing) is required for a successful incineration process. The primary factors that influence the incineration system design are the sludge quantity and composition (Turovskiy and Mathai, 2006). The sludge composition determines the heat value and the quantity determine the size of the system. Each fuel has two heat values, the high heat value - HHV (gross heat value) and the low heat value – LHV (effective heat value) (WEF, 2010). The low heat value is mainly the amount of released heat minus the dry-flue gas loss and the moisture loss (WEF,2010). The high heat values of different fuel is presented in Table 1-1. However, the high heat values of different wastewater sludge/solids is presented in Table 1-2.

Table 1-1 Comparison of Alternative Fuels Calorific Value

Fuel Type	Calorific Value KJ/Kg
Coal	14 600 – 26 700
Plastics, wood, paper, rags, garbage	17 600 – 20 000
Wood	16 000 –20 000
Sewage sludge	12 000 – 20 000
Natural gas	38 000

Fuel Type	Calorific Value KJ/Kg
Synthetic coal gas	10 800
Black liquor	12 500 – 15 000
Coke-oven gas	19 000 – 22 000

Table 1-2 Heat Values of Sewage Sludge (WEF, 2010)

Sludge/Solids Type	Combustible Solids %	High heat value Kj/Kg
Grease and scum	88	38 816
Raw sludge	74	17 678
Fine screening	75	15 700
WAS	60	12 793
ANDS	60	12 317
Chemical Sludge	57	17 430
Grit	30	9 304

The determination of the sludge heat value is vital as it's one of the primary criteria to determine the effectiveness of the sludge as a fuel source and for incineration. I found that the heat value a mixed industrial and municipal sewage sludge (thickened) contained the highest heating value (5040 Kcal/kg = 21 087 Kj/kg) (Kim et al., 2005). The literature contains several methods to calculate the heat value of organic matters using proximate and ultimate analysis (Wang et al., 2007 , WEF, 2010). The Ultimate analysis method is used to determine the basic sludge elemental composition concentration such as oxygen, carbon, hydrogen, sulphur, nitrogen, chloride, and ash (Wang et al., 2007). In addition, it is typical to determine other elements that may contribute to air emissions or ash disposal problems (Wang et al., 2007). The results of the ultimate analysis are then used to calculate the high heat value on a moisture and ash-free (MAF) basis using empirical formulas such as Dulong's formula, modified Dulong'd formula, Chang formula and Boie's formula; all presented below;

Dulong's formula (Wang et al., 2007);

$\text{HHV (kJ/kg)} = 33950\,C + 144200\,(H - O/8) + 9400\,S$

Modified Dulong's formula (Wang et al., 2008);

$\text{HHV (kJ/kg)} = 328\,C + 1503.4\,(H - O/8) + 93\,S + 50\,O + 24\,N$

Boie's formula(Wang et al., 2008);

$\text{HHV (kJ/kg)} = 348\,C + 1152.6\,H - 107.9\,O + 104.6\,S + 63\,N + 39.33\,Cl + 77.4\,F + 272\,P + 51\,Fe$

Chang's formula (Wang et al., 2008);;

$\text{HHV (kJ/kg)} = 35819.7\,C + 751.95\,H - 267.32\,S - 465.14\,O - 376.56\,Cl - 280.1\,N$

Where; C : % carbon content, H: % hydrogen content, O: % oxygen content, S: % Sulfer content, N: % Nitrogen content, Cl: % chloride content, F: % floride content, P: % phosphate content and Fe: % Iron content.

Proximate analysis is a relatively low-cost analysis in which moisture content, volatile solid content, and ash are determined (Wang et al., 2007). The heat value of the sludge is then calculated using empirical formulas such as Fair et al. formula and P. Aarne Vesilind's formula. These formulas are presented below;

Fair et al. Formula;

$$HHV\ (BTU/lb) = a\left[\frac{P_v\,100}{100\ - P_c}\ \ - b\right]\left[\frac{100\ - P_c}{100}\right]$$

P. Aarne Vesilind's formula;

$$HHV\ (BUT/lb) = 122\,P_v\ - 660$$

Where;

P_v = proportion of volatile matters (%)

P_c = proportion of chemical, precipitating or conditioning reagent (%)

a, b = coefficients for different classes of waste solids/sludges

For plain-sedimentation municipal waste water sludges (fresh and digested), a = 131 and b = 10, while for fresh activated sludge, a = 107 and b = 5.

Vesilind, P. A. (1979) presented a rule of thumb for sewage sludges is to expect about 5550 cal/g of dry volatile solids. The same rule of thumb range was verified by Zanoni and Mueller (1982). However, caution should be exercised when using this rule of thumb since it is based on the sludge's typical composition of proteins, carbohydrates, and fats (Haug, 1993). This may not always be the case, mainly if there are a significant amount of industrial wastes (Haug, 1993).

The principal advantages of the incineration process are (Turovskiy and Mathai, 2006); (1) Reduces disposal requirements by reducing the volume and weight of sludge cake by approximately 95%, (2) complete destruction of pathogens, (3) reduce or eliminate toxic matter , (4) Potential energy recovery, (5) Small footprint, (6) Suitable for large plants, and (7) well established process. However, the principal disadvantages are (Turovskiy and Mathai, 2006); (1) High capital and operation cost, (2) eliminate the beneficial use of sludge; therefore, it should only be used if beneficial use of the sludge is not feasible, (3) Requires a highly skilled operation and maintenance staff, (4) Ash may be classified as hazardous due to the high concentration of heavy metals, (5) auxiliary fuel system is required regardless of the feed sludge dryness to cater for process upsets and ensure complete oxidation under required temperature at all conditions, (6) Relatively sensitive to feed sludge characteristics deterioration (7) auxiliary fuel consumption increase by increasing the feed sludge moisture content, and (8) extensive treatment of the exhaust gas is required increasing the overall capital and operation cost.

A detailed heat balance must be prepared before commencing with the design of an incineration system to evaluate its effectiveness and feasibility (Metcalf & Eddy/AECOM 2014). Such a balance must include heat losses through the walls and equipment of the incinerator as well as losses in the stack gases and ash (Metcalf & Eddy/AECOM 2014). The ignition temperature of feed sludge with dry solids content 25 -35% is between 420 to 500°C in the presence of oxygen (Turovskiy and Mathai, 2006).

Temperatures of 760 to 820°C are required for the complete combustion of organic matter (Turovskiy and Mathai, 2006). The design temperature in the furnace should not exceed the melting point of ash (usually, about 1050°C) (Turovskiy and Mathai, 2006). Sludge incineration systems should provide complete combustion of the organic fraction of the sludge and recovery of the heat of the exhaust gases (Turovskiy and Mathai, 2006). The incineration process efficiency can be improved using an advanced heat recovery system (HRS) (Metcalf & Eddy/AECOM, 2014). The most used incineration systems are (1) fluidized-bed and (2) multiple-hearth furnace (Qasim et al.., 2018). Both systems are reviewed under thermal drying sections **Error! Reference source not found.** and **Error! Reference source not found.**, respectively. Other types of incinerators are also available, including rotary kilns, electric furnaces, cyclones, or smelting furnaces (Wang et al., 2008). The principal differences between furnaces used for drying and those used for incineration are the temperature range, time, air (oxygen) required and air pollution control system design.

In the multiple-hearth incinerator, the dewatered sludge enters the top hearths, where water evaporation and sludge dryness occur at about 450–650°C (Qasim et al., 2018). In the following hearths, the dry sludge is ignited at 650–820°C (Qasim et al, 2018). In the lower hearths, the slow-burning material is wholly burned, and ash is cooled at a temperature of about 315°C (Qasim et al., 2018). The amount of excess air required for complete combustion is approximately 50–100% of the stoichiometric amount (Qasim et al., 2018). The efficiency of multiple-hearth incinerators is about 55% (Qasim et al., 2018). The multiple-hearth incinerator has the advantage of good internal energy usage because the hot flue gas comes directly into contact with the sludge (Dangtran et al., 2000). However, it is sensitive to the change in feed sludge, and satisfactory performance can only be obtained with the stable feed rate and moisture content (Dangtran et al., 2000). On the other hand, The fluidized-bed incinerator operates at a constant temperature of 760–820°C, with excess air of 20–25% (Qasim et al., 2018). There are two types of fluidized-bed incinerators: bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) (Dangtran et al., 2000). Sand is used as a fluidizing medium, which also enhances heat transfer to create a uniform temperature distribution in the bed (Dangtran et al., 2000). It should be noted that the stoichiometric oxygen requirement for complete combustion is 4.6 kg of air for every kg of oxygen (Andreoli et al., 2007). The design concept of multiple-hearth and fluidized-bed incinerators is different (Dangtran et al., 2000). For a multiple-hearth incinerator, the design is based on sludge drying, combustion, and cooling, while the design of a fluidized-bed incinerator is based on intense mixing, excellent heat transfer, short sludge residence time, long gases residence time, moderate combustion temperature, and low excess air (Dangtran et al., 2000). The difference in design concept provides some advantages to the fluidised-bed incinerators over the multiple-hearth incinerators (Dangtran et al., 2000). These advantages are (Dangtran et al., 2000); (1)lower NO_x formation, (2) lower CO formation, (3) lower total hydrocarbon formation, (4) suitable for intermittent operation, (5) less sensitive feed sludge characteristics and tolerate thermal shocks, (6) easy control and automation, (7) lower auxiliary fuel consumption, (8) reduced maintenance cost, and (9) smaller exhaust gas treatment system.

However, the fluidized-bed incinerators also have a few disadvantages compared to the multiple hearth incinerators (Dangtran et al., 2000); (1) high power requirements, (2) more complicated ash removal from the exhaust gas, (3) sand requirements, and (4) higher ash disposal costs.

Exhaust gas pollution control system; the exhaust gases produced during sludge incineration can carry an excessive amount of particulates (Turovskiy and Mathai, 2006). These particulates consist of solid particles (ex. Ash) and liquid droplets swept along by the gas stream or formed through condensation (Turovskiy and Mathai, 2006, Gurjar et al., 2017). The particulates are typically enriched with volatile traces of heavy metals such as cadmium, lead, and zinc (WEE, 2010). The solid particles are mostly smaller than 2 µm, and the volatile metals are primarily in the submicrometer sizes (WEF, 2010). The exhaust gas will also include NO_x (NO and NO_2) and N_2O (Paul et al., 2012). NO_x is a type of ozone-depleting chemical, while N_2O is known as a greenhouse gas (Paul et al., 2012). NO_x and N_2O are also harmful to human health (Paul et al., 2012). Incomplete combustion due to improper design and operation can also produce exhaust gases with unacceptable intermediate products such as hydrocarbons, volatile organics, and excessive carbon monoxide. Some of these products can produce offensive odours (Turovskiy and Mathai, 2006). The selection of the air pollution control equipment depends on the type of the incinerator, the nature of the particulates, the conditions of the exhaust gases, and emission limits (Turovskiy and Mathai, 2006).

Ash handling and disposal (Turovskiy and Mathai, 2006) ; although incineration provides the most significant reduction in sludge volume, it produces a considerable amount of ashes to be disposed of. The produced amount of ashes are equal to the inert fraction of the sludge. Incineration of grit, screening and scum will affect the quality and quantity of the ashes. The infiltration and inflow during the wet weather period also affect the quantity of inert materials in sludge and subsequently the quantity of ashes produced. Industrial discharge and the use of chemicals in the treatment process affects the quantity and the quality of the produced ash. The typical quantity of ash ranges from 200 to 400 g/kg of dry WAS sludge without consideration of grit. However, the quantity of ash generated from the incineration of digested sludge ranges from 350 to 500 g/kg dry solids due to the lower volatile content of digested sludge. Ash is typically handled by two principal methods: dry ash handling or wet ash handling. In dry ash handling, the ash is lifted from the incinerator furnace with a bucket elevator or pneumatically to a silo for later load-out. The bucket elevator method is typically for small facilities, while the pneumatic method is generally applied for large facilities. In wet ash handling, the ash is mixed with water to form a slurry that is pumped to a lagoon for further treatment and disposal. Therefore, the availability of land to construct the holding lagoon is crucial to the feasibility of this method.

Co-incineration (co-combustion) is a process that is currently not practised by the municipality. There are typically three routes for co-combustion of sewage sludge; (1) in coal-fired power plants, (2) solid waste incineration plants, and (3) cement industry (cement kilns) c. Co-combustion reduces incineration capital and operational and maintenance costs since it is integrated into an existing industrial process train (Andreoli et al., 2007). The characteristics to evaluate the effectiveness of co-combustion of sewage sludge are the same as those to evaluate the incineration processes of sewage sludge (Wang et al., 2008). Co-incineration also requires additional pre-processes to dry the sludge to its autogenous point (Wang et al., 2008). Sewage sludge is a valuable complementary fuel that can be co-incinerated in the power industry (Krol et al., 2019). In large and medium-sized cities where the quality of sewage sludge is compromised by industrial pollution and therefore cannot be used in agricultural, incineration or co-incineration with energy recovery is the best existing alternative (Krol et al., 2019).

The KwaMashu WWTW has an incineration and drying plant for dewatered sewage sludge (Naidoo, 2004). The plant was initially commissioned in the year 2000 (Naidoo, 2004 , Botha et al., 2011). It was designed to incinerate 80 tonne/day of dewatered raw sludge (35% DS) in a fluidised bed reactor (FBR) and dry 100 tonne/day of dewatered digested and WAS (18% DS) in spouted bed reactor (SBR) (Naidoo, 2004, , Botha et al., 2011). The incinerator and dryer were designed to work together, with the incinerator's hot combustion gas being used to dry digested sludge into pellets (Naidoo, 2004, , Botha et al., 2011). Since the calorific value of the wet raw sludge was insufficient to keep the bed temperature at 850°C, the pellets were fed to the incinerator as a supplementary fuel (Naidoo, 2004 , Botha et al., 2011). Complaints from the local residents about the odour forced the plant to shut down. In 2002 the plant was re-commissioned using Regenerative Thermal Oxidiser to remove odour from exhaust gases(Naidoo, 2004, Botha et al., 2011). The plant is currently not in operation due to operational challenges and costs (EWS, 2020).

2. Gasification

The gasification is a partial oxidation process used different gasifying agents, such as air, oxygen, and steam, to produce gases (i.e Syngas) with different heating values (Bridgwater, 2003). The heating value depends on the gasifying agent used (Bridgwater, 2003). Syngas is composed primarily of carbon monoxide, carbon dioxide, hydrogen and methane (Metcalf & Eddy/AECOM, 2014). The operating temperature and pressure of the process influence the products, including syngas, char or slag, oils and reaction water (WEF, 2010). The operating temperature ranges from 815°C to 1815°C and operating pressure up to 200 KPa (WEF, 2010). The process dynamic and products depend on the type of feed sludge used; however, pilot testing is highly recommended to determine operating conditions, products, exhaust gases and residues (WEF, 2010). The process has been proven to be expensive in treating sewage sludge, where the dewatered sludge must be heat-dried to decrease its moisture content and increase the dry solid content before gasification (WEF, 2010). The main drawback of this process is that the resulting syngas has a low heating value of about 4500–5500 kJ/m^3, which is about 10–15% of natural gas (Qasim et al., 2018). Likewise, Char and oils produced have a heating value less than those produced during pyrolysis (WEF, 2010). The higher ash content in the sludge compared to other organic material used in gasification makes ash handling more difficult (Metcalf & Eddy/AECOM, 2014). However, gasification provides better control of air emission if compared to the incineration process (WEF, 2010). Gasifiers are commercially available in either fixed-bed (upflow or downflow), fluidized-bed, or entrained-flow reactor (Qasim et al., 2018).

3. Wet air oxidation (Andreoli et al., 2007, Gurjar et al., 2017)

Wet air oxidation is also called Zimmerman process, named after Fred J. Zimmerman, who commercialised it in the mid 20th century. The process utilises the ability of dissolved or particulate organic matter present in a liquid to be oxidised at high temperatures. Intensive sludge dewatering before wet air oxidation is not required; only thickening to achieve 1% to 10% dry solids keeps the oxidation self-sustained. The process can be carried out either in a conventional system with a vertical reactor or in a deep shaft reactor called the VerTech reactor. In the wet air oxidation process, the temperature and pressure of the thickened sludge are raised to 148 –315°C and 5–225 bar, respectively, in the presence of oxygen, where the decomposition of organic matters take place. The temperature must be maintained below the critical value (374°C) to avoid complete evaporation of the water. The following equation represents the wet air oxidation process;

$$C_aH_bO_cN_dS_eCl_f + O_2 \rightarrow CO_2 + H_2O + NH_4^+ + SO_4^{2-} + Cl^- + \text{Energy}$$

Theoretically, all carbon and hydrogen content can be oxidised to carbon dioxide and water; however, the degree of oxidation is influenced by the reactor temperature, detention time, and feed sludge characteristics. As represented by the oxidation equation above the organic nitrogen is converted into ammonia, sulphur into sulphate, and halogenated elements into their Cl^-, Br^-, $I^-$and Fl^- ions. These ions remain dissolved, and there is no production of sulphur or nitrogen oxides (SO_x and NO_x). The Energy released from the oxidation process is in the form of heat, sufficient to make wet air oxidation a self-sustainable process. The process is also autogenous on a liquid feed if influent COD is not less than 10 g/l.

The mains control variables of the wet air oxidation process are (1) temperature, (2) pressure, (3) air/oxygen supply and (4) feed sludge characteristics and solids concentration. The process is classified according to the working pressure as; (1) low-pressure oxidation, (2) intermediate pressure oxidation, and (3) high-pressure oxidation. The low-pressure wet air oxidation is mainly used as a heat treatment step to improve sludge dewaterability. However, intermediate and high-pressure wet air oxidation are used to reduce the sludge volume significantly through oxidation to water and carbon dioxide. The typical operational range for the wet air oxidation process for sludge is summarized in Table 3-1.

The wet air oxidation process has principal advantages such as; (1) flexibility in achieving any degree of oxidation; (2) can handle different types of sludges; and (3) produces a relatively small amount of rapidly settleable solids, sterile, compacts well and easy to dewater. On the other hand, the principal disadvantages are; (1) require skilled operators and regular maintenance, (2) produces foul odours, (3) susceptible to heavy corrosion of heat exchangers and reactors, (4) High start-up power consumption to initiating the oxidation process, (5) wet oxidation liquors produced by the process contains a considerable amount of biodegradable organic matter that needs to be treated or recycled back through the wastewater treatment processes, which may represent a considerable organic load and the fine ash could plug air diffusers (if used), (6) produced solids are low in nitrogen and rich in metals content which may render its agriculture reuse and add constraints on final disposal, and (6) high capital and operation cost. Figure 3-1 shows a conventional vertical reactor of the wet air oxidation process. The feed sludge is pumped through a heat exchanger to raise its temperature before being fed to the wet air oxidation reactor. The rector effluent goes to a phase splitter, routing the solids for dewatering, the liquid back to the heat exchanger for heat recovery, and the exhaust gases sent to gas treatment systems, such as electrostatic precipitator and filter for solid particles and odorous substances removal.

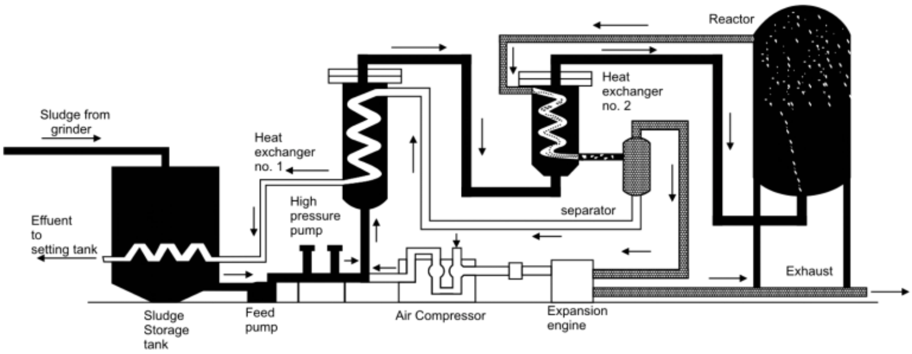

Figure 3-1 Conventional Zimmerman Wet Air Oxidation Process (Reprinted with permission from Taylor & Francis Group – Books)

Table 3-1 Typical Operational Ranges of Wet Air Oxidation Process (Andreoli et al., 2007)

Parameter	Type of wet air oxidation process		
	Low-Pressure (Thermal treatment)	Intermediate-Pressure	High-Pressure
Pressure - bar	5 - 28	28 – 138	138 - 255
Temperature - ^{o}C	148 - 204	204 - 260	260 - 320
Reduction of organic matter - %	5 - 10	10 - 50	50 - 90
Volume Reduction - %	25 - 35	30 - 60	60 - 80
Sludge sterilisation	Yes	Yes	Yes
Autogenous reaction	No	Yes	Yes
Improved dewaterability	Yes	Yes	Yes

4. Pyrolysis (Wang et al., 2008, Yurtsever et al. 2009)

Pyrolysis is a thermal decomposition of organic matter at a high temperature between 300 and 900^{o}C in the absence of oxygen to produce combustible gases, oil and tar, and char. These products are typically used as an energy source. Pyrolysis is a highly endothermic process; for this reason, the pyrolysis process is typically called destructive distillation. Pyrolysis reduces sludge volume significantly and produces sterilised products the same as incineration. Pyrolysis is also considered the first step in the incineration and gasification processes, followed by total or partial oxidation of the primary products. The major products characteristics from sludge pyrolysis can be summarised as follows;

1) A gas stream: typically consists of hydrogen, methane, carbon monoxide, carbon dioxide and various other gases, depending on the organic characteristics of the feed sludge.
2) Tar and/or oil: liquid at room temperatures and typically contains chemicals such as acetic acid, acetone, and methanol.
3) Char: typically consist of almost pure carbon and other inert material that may have entered the process.

The ratio of the three products depends on the operating conditions. The principal operating conditions are temperature, residence time, and heating rate. For example, high temperature and long residence time favour the production of gas and char over oil. However, low temperature and a short residence time favour the liquid products (tar and oil). Pyrolysis is the same as gasification, where feed sludge with a moisture content between 5 - 25% is required to achieve good process efficiency. Therefore, dewatering, and thermal drying steps are required before pyrolysis. The principal advantage of pyrolysis is that all the process products can be commercialised. For example, char, gases and oil can be used as fuel; however, their heating value is sometimes considered low compared with other fuel sources. Oil can also be used as a chemical material in some industries. The parameters to consider in the design of a pyrolysis system are; (1) feed sludge characteristics, (2) particle size, (3) pre-treatment, (4) reactor configuration, (5) heat supply, (6) heat transfer, (7) heating rates, (8) reaction temperature, (9) vapour residence time, (10) secondary cracking, (11) char separation, (12) ash separation, and (13) liquid collection. The pyrolysis liquid products have an additional advantage since they can be easily stored and transported, while heat recovered from incineration and syngas from gasification is used on site. The conversion of sludge to oil, also called bio-oil, is considered a promising technology for sludge disposal through pyrolysis. Pyrolysis processes are typically operated to maximize the bio-oil yield. In addition to the operating conditions of the pyrolysis system, the pyrolysis product ratio and oil properties are also affected by the feed sludge characteristics; for example, the higher the volatile content, the higher the yield of the bio-oil production, and the higher the ash content, the less the bio-oil and char yields. The bio-oil has a boiling point up to 4 00°C and typically used as diesel or boiler fuel. The bio-oil principal advantage is that it does not contain toxic heavy metals, such as lead or mercury. In addition, the bio-oil content of aromatic compounds (benzene, toluene, ethylbenzene, n-xylene and o-xylene) does not exceed the concentrations in the other fuel oils. The calorific value of the bio-fuel is 35,000 - 40,000 kJ/kg. The bio-oil can be used as a fuel source for the pyrolysis process, leading to a significant reduction in operating costs. On the other hand, the solid char formed during pyrolysis can be used as ; (1) sorbent to extract oil and petroleum products from water and absorb oil spills on solid surfaces, and (2) fertilizer as it contains a high concentration of phosphate; however, it’s heavy metals content is to be investigated. Pyrolysis of sludge is still considered innovative technology and not widely practised.