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ABBREVIATIONS

AD	Anaerobic Digestion
HRT	Hydraulic Retention Time
SRT	Solid Retention Time
OLR	Organic Loading Rate
TS	Total Solids
VS	Volatile Solids
VFA	Volatile Fatty Acids
PVC	Polyvinyl Chloride
PE	Polyethylene
EPDM	Ethylene Propylene Diene Monomer
VSD	Variable Speed Drive
HDPE	High Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
PLC	Programmable Logic Computer

1 Overview of Anaerobic Digestion

Anaerobic digestion is referred to as the breakdown of organic matter without the presence of oxygen (or without oxygen being consumed). Biogas produced from the anaerobic digestion it is primarily composed of methane 55 – 70%, carbon dioxide 30 – 40%, and a very low quantities of other gases like hydrogen sulfide 1 -2% and traces of carbon monoxide, hydrogen, nitrogen, and saturated carbohydrates (Silwadi, et al., 2023). Biogas can be produced at different processing temperatures. Psychrophilic temperature which ranges from 25 degrees Celsius and below, mesophilic temperature which ranges from 37 - 42 degrees Celsius and thermophilic processing temperature which ranges from 50 - 60 degrees Celsius. To produce biogas different feedstock can be used which includes the primary settling tank sludge, waste activated sludge, food waste and co-digestion of various substrates (Tabatabaei & Ghanavati, 2018).The generation wastewater sewage sludge is directly proportional to urbanization as it increases with it increases with urbanization. AD is very a viable process as it assists in reduction of municipal sewage sludge.

Different feedstocks have different potentials and characteristics which includes volatile solids (VS), Biological oxygen demand (BOD), Chemical oxygen demand (COD), and C/N ratio, the mentioned parameters are very important (Akunna. 2019). Biogas production can also be considered as method for recycling the biowastes as it can be used for fuel, electricity, and heat generation. Electricity generation from the biomass has increased significantly (Ardebili, 2020).The application of anaerobic digestion to wastewater treatment sewage sludge is a promising approach and a solution to energy crisis and environmental problems (Wang , et al., 2020). Biogas technology is beneficial to the environment, as it serves as an alternative to fossil fuels for energy generation and reduces greenhouse gas emissions and can increase energy security. The digestate after the AD process it can be used for agricultural applications as a fertilizer (Paolini, et al., 2018)

The biogas production through AD process occurs in 4 steps which are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

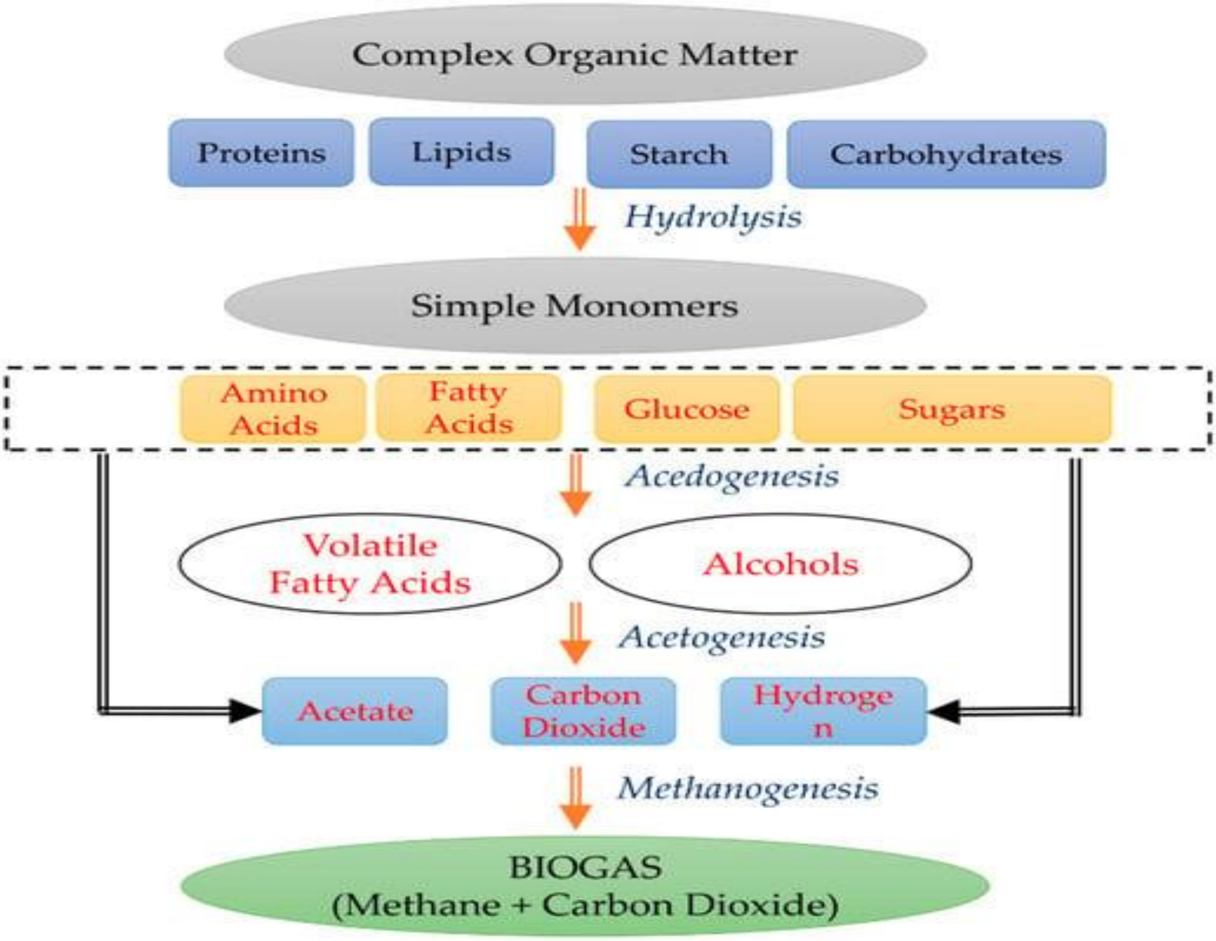

Figure 1: Summarized AD steps of Biogas production (Bhatt & Tao, 2020).

Hydrolysis

Hydrolysis is the first step of the AD process, and it is responsible for breaking down the insoluble complex polymers, lipids, and protein into simple and soluble monomers compounds (Sawyerr, et al., 2019). Hydrolysis is a very essential step because without it the microorganisms would not be able to consume the macromolecules of the waste material. The hydrolytic microorganisms release hydrolytic enzymes which are responsible for changing the polymers into simple soluble monomers (Mekonen, et al., 2023)

Acidogenesis and acetogenesis

Following Hydrolysis is Acidogenesis whereby the acidogenetic microorganisms utilize the monomers from hydrolysis and turn them into butyric, acetic, propionic acids and alcohols. These acids and alcohols are then transformed into hydrogen, carbon dioxide and acetic acid in the acetogenesis step (Tabatabaei, et al., 2020).

Methanogenesis

Methanogenesis is the final step of biogas production, the microorganism called the methanogens are the ones responsible for step. The methanogens are grouped into three: Acetoclastic, hydrogenotrophic, and methylotrophic. Acetoclastic methanogens transform acetate to methane and carbon dioxide gases, hydrogenotrophic uses hydrogen or formate to lower carbon dioxide to methane and methylotrophic methanogens uses methyl compounds such as methanol, methylamines, and methyl sulfides to produce the majority of the methane (Venkiteshwaren, et al., 2016).

1.1 Factors affecting biogas and anaerobic digestion.

1.1.1 pH

The microorganisms require a pH of in the range of 6.5 -8.5, for them to be efficient in biogas generation (Sorathia, et al., 2012). The methanogenic bacteria are effective at a pH of approximately 6.8 – 8.2 which is also prescribed for biogas generation and recommended as an optimal pH. The availability of different acids and bases in the digester results in the final pH of the digester. The volatile fatty acids generated during the acidogenesis stage result in a pH drop in the digester. The reactions that occur inside the digester induce their own buffering system which resists the pH to 6.3, this includes bicarbonate ion and carbon dioxide. However, excess alkalinity or ability to control pH must be present to guard against the accumulation of excess volatile acids. The acid builds up in the digester can be detected by a pH decrease from 6.8 and below, which is affected by changes in factors such as loading rate, temperature of the digester, introductions of toxins, and changes in feedstock material. When the loading rate is increased the acidogenesis and acetogenesis will increase, this will result in the formation of more acids. Methanogenesis has a slow growth rate and cannot be able to use all the acids available and this might result in acids accumulation (Khune *et al.,*2021).

1.1.2 Temperature

Temperature is one of the factors that influence biogas production. The process operating temperatures for biogas production can be grouped into 3, the first is a low temperature which is the psychrophilic temperature which ranges from15 and 20, the second is the medium temperature which is the mesophilic temperature, and it ranges from15 to40 Degrees Celsius, and the third one is the thermophilic temperature which is the highest temperature and ranges from 50 to 60 Degrees Celsius. Higher temperature ranges result in more biogas yield. Another source of heat might be required to keep the digester at a constant higher temperature.

Anaerobic digestion is efficient at mesophilic and thermophilic temperature ranges. The rate of methane production approximately doubles for each 10 degrees Celsius temperature change in the mesophilic range. The temperature also has an impact on the retention time. Operating a digester at a stable temperature is very important, because the methanogens are very sensitive to temperature changes, so the digester should be well insulated to, prevent loss of heat, and keeps the digester at the desired temperature (Khune, et al., 2021).

Temperature	Process temperature	Minimum Retention time(days)
Psychrophilic	$< 20^0\text{C}$	70 - 80
Mesophilic	$30 - 40\ ^0\text{C}$	30 - 40
Thermophilic	$43 - 55\ ^0\text{C}$	15 - 30

Table 1: Thermal conditions and their typical retention time (Tabatabaei et al.2018).

1.1.3 Mixing/Agitation

The mixing of the raw materials in biogas production is one very important as it results in a homogenous mixture that promotes biogas generation. Agitation also plays an important role in pH control and maintenance of uniform environmental conditions as the feedstock and the microorganism are distributed uniformly in the digester. This process stops the accumulation of the concentrate intermediate metabolic products which might slow down the methanogenesis process. Agitation can be done in many ways, which include, feeding daily can have a good mixing effect, mixing can also be done by installing stirring tools such as a scraper, piston and a pump and biogas recirculation is effective for mixing and enhancing the production of biogas (Khune, et al., 2021). If the mixture is not mixed it will settle to the bottom of the digester and generate a hard scum on the surface of the digester, which hinders the release of the biogas, this problem is more likely to occur with (Sorathia, et al., 2012).

1.1.4 Hydraulic and Solid Retention times

There are two essential retention times discussed in this section the Hydraulic and Solid retention times. Solids retention time (SRT) is defined as the time required for the organic material to degrade or break down completely, while the hydraulic retention time (HRT) is defined as the amount of time the fluid spent in a reactor.

The retention time is affected by factors such as temperature, organic loading rate (OLR), and composition of the feedstock, for example a plant feedstock that is rich in cellulose requires more retention time for the bacteria to degrade the material and result in effective hydrolysis.

HRT can be evaluated with equation (Mao, et al., 2015) . $HRT = \frac{V}{Q}$, V is the volume of the digester and Q is the feed flow rate per time. The HRT and SRT are very important parameters in the design of biological treatment processes (Tabatabaei & Ghanavati, 2018). The hydraulic retention time is defined as the time in which the feed material is contained inside the digester. The feedstock which has the easily degradable material has short HRT, while material that are not easily degradable have longer HRT (Dobre, et al., 2014). Short HRT could result in wiping out of the active biomass and methanogens, which could result in low biogas production in the digester, so the HRT should be well monitored.

The SRT is very important for the AD process because it controls the biological characteristics, function, and stability of the digester. If the SRT is extended more than the optimal it could result in low biogas production, while short SRT is not enough for the decomposition of VS and result in a decrease in biogas production, some of the digester designs are designed in such a way that they have longer SRT compared to HRT, and this is to hinder the biomass loss and to increase the biogas production efficiency, these reactors include UASB, EGSB, and AFBR (Tabatabaei & Ghanavati, 2018). The SRT is defined by the formular below.

1.1.5 Start-up inoculum/seeding

Starting the AD process with an inoculum that is rich in bacteria increases biogas production and reduces the retention time. It also increases the degradation rate of the feedstock, sources of inoculum include the digested from the functioning biogas plant, or cow dung (Khune, et al., 2021). The performance and stability of the anaerobic process depend on the quality and availability of methanogens in the system. Active anaerobic microorganisms inoculate anaerobic systems during the start-up to reduce the delay in the development of a balanced microbial consortium. The availability of microbes in the inoculum depends on the type of substrate used and the operational conditions it was operated. Good inoculum can be found in active anaerobic reactors preferably those are digesting similar types of wastes or sewage sludge(bio-solids). Anaerobic digesters are usually started by heavy seeding or maintaining wastewater pH in the range of 6.8 and 7.2 to encourage the growth of microbial populations. A low inoculum-to-feed ratio may result in acidogens dominating over methanogens and can result in low pH (Akunna. 2018).

1.2 Generic Municipal Wastewater Treatment

Wastewater treatment is a process of eliminating the contaminants from wastewater. It comprises of physical, chemical, and biological processes to remove impurities. After the contaminants are eliminated, water is then released to the environment. Sludge is the by-product of wastewater treatment processes (Demirbas, et al., 2017). The wastewater treatment is divided into three stages, primary level, secondary level, and tertiary level. Solid materials are removed at the primary level through screening and sedimentation process. Organics (soluble and organic) are removed in the secondary level. Tertiary level is responsible for elimination of organics and other diluted organics (Poblete, et al., 2023)

1.3 Anaerobic Co-digestion of Sewage Sludge

Co-digestion is another approach to optimizing the production of biogas whereby two substrates are combined as a feedstock and as a result, the digestion becomes more efficient (Lacodivou et al.,2012). Co-digestion serves as a solution to the problems faced or/ related to mono digestion which include lack of nutrients, imbalanced C/N ratio, and unfavorable OLR which might be too high or very low (Xie et al.,2017). Municipal solid wastes consist of easily biodegradable organic fractions up to 40%, whereby these wastes are disposed of in landfills, The digestion of sewage sludge and municipal waste seems to be an attractive technique (Sosnowski et al.,2003). Municipal solid waste consists of various components which include food wastes, kitchen wastes, leaf, grass clippings, flower trimmings, and yard wastes, yard wastes consist of lignocellulosic structures which are not easily biodegradable. Food wastes that are very high in protein consist of macromolecules which have limited biodegradable capacity which can result in high concentrations of ammonia in the digester causing accumulation of the VFAs, and a decrease in pH and this results in low methane production (Leitao et al.,2022). Different co-substrates can be used for biogas production, but the selection of the co-substrates is very important because selecting the right co-substrates can result in effective solids reduction and an increase in biogas production while selecting the wrong co-substrates can result in instability and eventually system failure, the selection of the co-substrates is based on the economic and technical factors (Azarmanesh et al.,2023).

2 Plant operation description

2.1 Plant description

The pilot plant is designed for a hydraulic retention time of 15 days, it will run continuously for 15 days, utilising a continuous stirred suspended growth reactor type. The feed (a mixture of primarily sewage sludge and other organic co-substrate(s)) will be fed semi-continuously into the reactor at 6-hour intervals to allow pumps to cool down. Tank T1 will contain the sewage sludge, Tank T2 will contain the organic co-substrates, both tank T1 and T2 will be fed into the balancing tank T3 at 6-hour intervals. Tank T3 will feed into the reactor (ADR) at 6-hour intervals. The biogas will flow into Tank T5 where it will be scrubbed by a hydrogen sulphide reduction unit before it can either be utilised or disposed under strict NEMA regulations. The wasted feed from the reactor will be discarded into Tank T4 as digestate. Occasionally as the process might require, we may need to add macro nutrients such as nitrogen and phosphorus and/or add minor nutrients such as calcium and/or add micronutrients such as various organic vitamins and to adjust pH back to optimal value by adding a basic or acidic solution depending on the pH level.

2.2 Process flow diagram

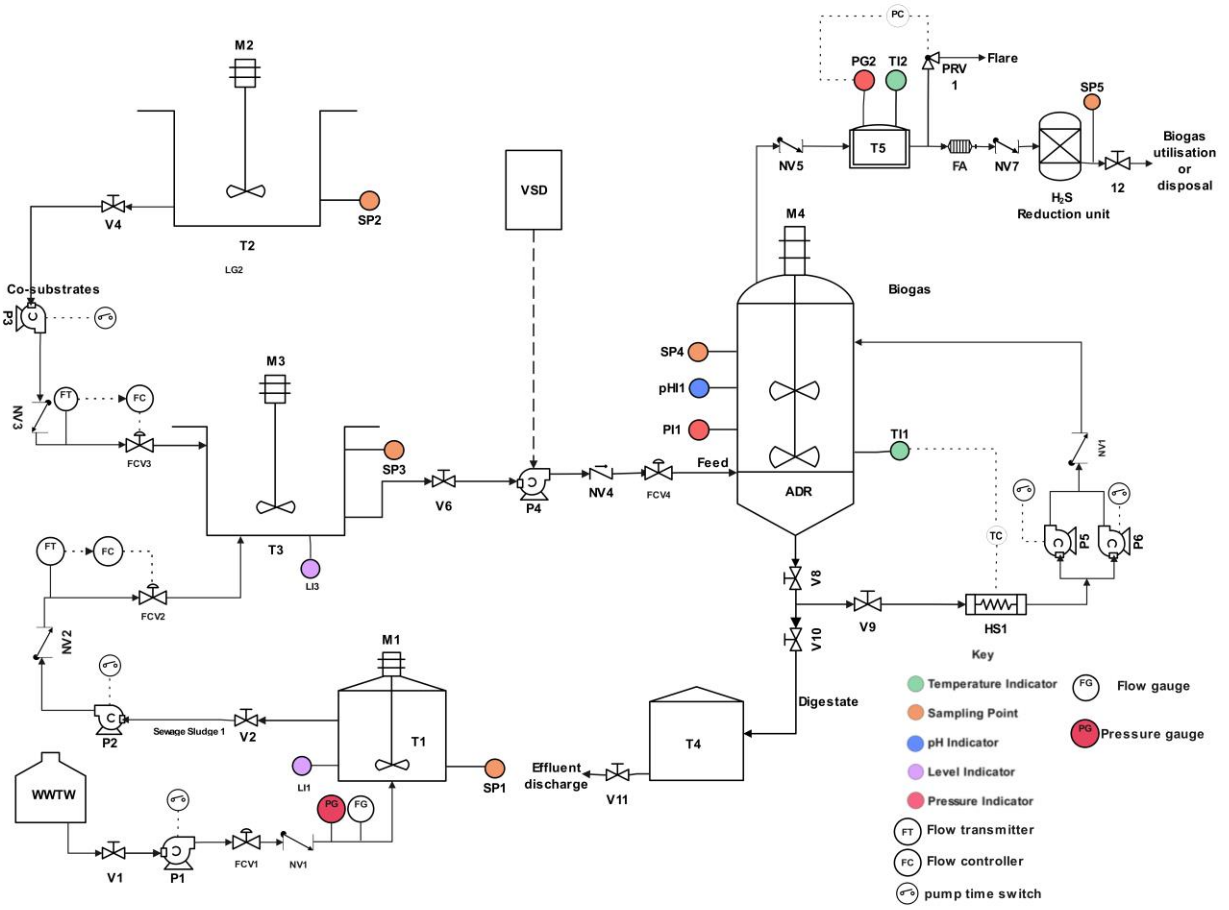

Figure 2: Process flow diagram of the mobile anaerobic digestion unit for testing the biogas potential of municipal sewage sludge and other organic co-substrates.

2.3 List of equipment and instruments.

Table 2 below lists the equipment and instruments and their description and functionality process operation:

Equipment and instruments tag name	Description and functionality
T1	Sewage sludge storage tank
T2	Co-substrate holding tank
T3	Flow equalisation or balancing tank
T4	Digestate holding tank
T5	Biogas storage tank
V1-V11	Compact ball valves (40mm)
NV1-NV7	Non-return valves
P1-P4	Pumps
P5 and P6	Feed recirculation pump
FCV1-FCV4	Flow control valves
PG	Pressure gauge
FG	Flow gauge
LI1	Level indicator
SP1-SP3	Sampling point
FT	Flow transmitter
FC	Flow controller
M1-M4	Electric stirrer
PI1	Pressure indicator
pH1	pH indicator
TI1	Temperature
TC	Temperature controller
FA	Flame arrestor
VSD	Variable speed drive for pump P4

Table 2: List of system equipment and instruments and their description and functionality.

2.4 Process description

The sewage sludge from the wastewater treatment works (WWTW) will be pumped by the pump (P1) into the sewage sludge storage tank (T1) via the (sewage sludge) pipeline. The flow will be measured by a flow gauge (FG) and the pressure will be measured by the pressure gauge (PG). A flow control valve (FCV1) will be fitted to the (sewage sludge) pipeline to ensure a constant flow rate of sewage sludge is discharged into tank (T1). The sludge level in the sewage sludge tank will be measured by level meter (LG1). Pump P1 will have a timer automatic pump switch set to 6 hour ON/OFF cycle so that pump P1 switches off automatically giving the pump enough time to cool off and then switch on again after cooling period. A check valve (NV1) will be fitted ahead of the raw sludge pump (P1) to ensure there is no backflow to the pump.

The sewage sludge will then be pumped into the equalising tank (T3), through the pipeline (sewage sludge1) by pump (P2). A flow control valve (FCV2) will be used to ensure a constant flow rate of sewage sludge is discharged into the balancing tank. Pump P2 will have a timer automatic pump switch set to 6 hour ON/OFF cycle so that pump P2 switches off automatically giving the pump enough time to cool off and then switch on again after cooling period A check valve (NV2) will be fitted ahead of the raw sludge pump (P2) to ensure there is no backflow to the pump.

The co-substrates will be loaded manually into the co-substrate tank (T2) until it is full. The co-substrates will be pumped by pump (P3) into the balancing tank (T3) via the (sewage sludge) pipeline. The flow will be measured by flow gauge (FG) and the pressure will be measured by pressure gauge (PG2). A flow control valve (FCV2) will be used to ensure a constant flow rate of co-substrates is discharged into the balancing tank. The liquid level in the balancing tank will be measured by level meter (LG2). Pump P3 will be fitted with an automatic pump switch so that when tank (T3). Pump P3 will have a timer automatic pump switch set to 6 hour ON/OFF cycle so that pump P3 switches off automatically giving the pump enough time to cool off and then switch on again after cooling period. A check valve (NV3) will be fitted ahead of pump (P3) to ensure there is no backflow to the pump.

The equalising tank minimises the fluctuations in the biomass feed characteristics to the reactor, preventing overloads or underloads of biomass feed to the reactor, while maintaining continuous flow to the digester and can serve as a pH and nutrient corrections operations point (Akunna, 2018).

The sewage sludge, and co-substrates will be mixed with stirrers (M1 and M2) respectively to control fermentation, keep the particulate material in suspension and prevent the biosolids from settling. The feed in the equalising tank will be mixed with the stirrer (M3) to thoroughly mix the sewage sludge and co-substrates for uniformity, control fermentation, keep the particulate material in suspension and prevent the biosolids from settling.

The mixed feed from the balancing tank will then be pumped into the digester (ADR), through the (feed) pipeline by the feed pump (P4). The flow control valve will ensure that the feed is discharged at a constant flow rate in the reactor. Pump P4 will have a timer automatic pump switch set to 6 hour ON/OFF cycle so that pump P4 switches off automatically giving the pump enough time to cool off and then switch on again after cooling period. The fluid to the feed pump (P4) will be regulated by a check valve (NV4) to ensure no backflow of feed to the pump occurs and the pump will also be connected to a variable speed drive (VSD).

In the anaerobic digestion digester (ADR) the feed will be heated to a desired set point temperature by an external heat exchanger (HS1) via a recirculation pump (P5) and pump (P6). Pump (P6) and (P5) will take 6 hours operating turns in circulating the fluid and will not work simultaneously to allow each pump to cool down. The digester (ADR) will be insulated to minimise heat loss and thus minimise temperature fluctuations. A stirrer (M5) will be placed inside the digester for agitation, reduce thermal stratification, increase the area of bioreaction, and reduce the scum build-up layer on top of the active bioreaction area. The ADR will have a sampling point (SP4) where sludge samples can be collected for analysis, it will also be fitted with temperature (TI1) indicator and pH (pH1) indicator to monitor process parameters.

A gas sampling point (SP2) will be fitted on the biogas pipeline for the collection of biogas samples for analysis. Part of the feed will be converted to biogas by anaerobic bacteria and the other part will turn into digested sludge or digestate. The digestate will be discharged by gravity into the digestate holding tank (T4) after 15 days (HRT) with the opening of valve V10.

The biogas will bubble through the feed and keep any solid granules suspended to avoid settling of biosolids. The biogas will pass through the pipeline (biogas) and will be stored in a storage tank (T5), where the volume, temperature (TI2) and pressure (PI2) of the gas will be taken for the determination of the biogas quantity produced. A non-return valve (NV5) will be installed on the biogas pipeline to make sure the biogas does not return to the digester. The biogas storage tank will be fitted with a pressure relief valve (PRV1) to alleviate pressure build-ups. The biogas may contain hydrogen sulphide and will be removed by the H_2S reduction unit. The flame arrestor (FA) will be fitted between the H_2S reduction unit and the biogas storage tank to prevent accidental ignition of the biogas.

2.5 Process Control Philosophy

2.5.1 Tank (T1) – Sewage sludge tank

Tank (T1) will hold the sewage sludge from the primary settling tank of the wastewater treatment plant. The process variable (PV) will be the flow of the sewage sludge into tank T1, the set point (SP) is a flowrate of 7 L/h for “ratio 1” and 8.4 L/h for “ratio 2” and it will be compared against the PV and the error will be sent to the flow controller to manipulate FCV1 as/if necessary. The signal or control value (CV) will be sent to the flow controller by the flow transmitter. The control system will be a single input-single output (SISO) negative feedback loop. The pump (P1) will be automated for a 6 hour ON/OFF cycle, the level indicator-level transmitter-level controller interlock system will be connected to the pump switch to make sure there is no over flow in tank T1 or the tank does not get completely empty. For the initial start-up of the plant (day 1), tank T1 must be filled up before setting the pumps to switch cycles The pressure gauge fitted on the pipeline from WWTW to tank T1 will be connected to an alarm and automatic system shutdown switch for excessive pressure build up in the pipeline. The tank will be continuously agitated.

2.5.2 Tank (T2) – Co-substrates tank.

Tank (T2) will be filled up with organic co-substrates manually by the plant operator(s). The co-substrates should be mixed with enough water to ensure that the mixture is less than 10% solids. The level indicator-level transmitter-level controller system will be connected to the pump switch to make sure that pump P3 does not switch ON when the tank is empty and to also make sure the tank does not overflow when being filled up. The pressure gauge on the “co-substrates’ pipeline will be connected to an alarm and automatic system shutdown switch for when there is excessive pressure build up in the system. The tank will be continuously agitated.

2.5.3 Tank (T3) – Balancing Tank

Tank (T3) will hold the mixed feed (sewage sludge and organic substrates from tank T1 and tank T2 respectively) for mixing and flow equalisation before discharging into the reactor.

The first process variable (PV) will be the flowrate of the sewage sludge into the balancing tank. The set point is a flow of 7 L/h for “ratio 1” and 8.4 L/h for “ratio 2” of the sewage sludge and it will be compared against the PV and the error will be sent to the flow controller to manipulate FCV2 as/if necessary. The pump (P2) will be automated for a 6 hour ON/OFF cycle, the level indicator-level transmitter-level controller system will be connected to the pump switch to make sure there is no over flow in the balancing tank or the tank does not get completely empty.

The second process variable (PV) will be the flowrate of organic co-substrates into the balancing tank. The SP is a flowrate of 7 L/h for “ratio 1” and 5.6 L/h for “ratio 2” of the organic co-substrates and it will be compared against the PV and the error will be sent to the flow controller to manipulate FCV3 as/if necessary. The pump (P3) will be automated for a 6 hour ON/OFF cycle, the level indicator-level transmitter-level controller system will be connected to the pump switch to make sure there is no over flow in the balancing tank or the tank does not get completely empty.

The signal or control value (CV) will be sent to the flow controller by the flow transmitters. The control systems will be single input-single output (SISO) negative feedback loops. The tank will be continuously agitated.

2.5.4 Reactor Tank (ADR) – Digester tank

Digester tank (ADR) will be the reactor where the anaerobic co-digestion process will take place. The process variable (PV) will be the flow of the mixed feed into the reactor, the set point (SP) is a flowrate of 7 L/h and it will be compared against the PV and the error will be sent to the flow controller to manipulate FCV4 as/if necessary. The signal or control value (CV) will be sent to the flow controller by the flow transmitter. The control system will be a single input-single output (SISO) negative feedback loop.

The pump (P4) will be automated for a 6 hour ON/OFF cycle, the level indicator-level transmitter-level controller interlock system will be connected to the pump switch to make sure there is no over flow in reactor or the tank does not get completely empty. The pressure indicator-transmitter fitted on the pipeline from the balancing tank to the ADR will be connected to an alarm and automatic system shutdown switch for excessive pressure build up in the pipeline and an additional pressure indicator-transmitter will be fitted to the reactor and connected to an alarm system for when there is an excessive pressure build-up/drop in the reactor. The tank will be continuously agitated.

The second process variable (PV) will be the temperature of the mixed feed in the reactor, the set point (SP) is a temperature of 35℃ under mesophilic conditions and it will be compared against the PV and the error will be sent to the temperature controller to manipulate HS1 as/if necessary. The signal or control value (CV) will be sent to the temperature controller by the temperature transmitter. The control system will be a single input-single output (SISO) negative feedback loop.

The pumps P5 and P6 will be synchronised to work at 6 hours alternate cycles where pump P5 will be ON for 6 hours while pump P6 is OFF and after the six hours the opposite will happen, this will be automated by pump the time switches.

2.5.5 Tank (T4) – Digestate holding Tank

The flow into the digestate after 15 days of operation will be controlled manually by the compact ball valve (V10), no automation necessary.

2.5.6 Tank (T3) – Biogas storage Tank

The biogas from the digester (ADR) will be allowed to flow freely into the biogas storage tank (T5). The process variable (PV) will be the pressure of the biogas in the tank, the set point (SP) will depend on the specification of the tank used (the maximum pressure the tank can withstand) and it will be compared against the PV and the error will be sent to the pressure controller to manipulate pressure relief valve (PRV1) as/if necessary to make sure there is no excessive pressure build up. The signal or control value (CV) will be sent to the pressure controller by the pressure transmitter. The control system will be a single input-single output (SISO) negative feedback loop. The flame arrestor will be fitted to avoid accidental ignition of the biogas.

3 Design Information

Hydraulic retention time (HRT) and solids retention time (SRT) are two important design parameters. The hydraulic retention time is the amount of time needed for biological materials to completely degrade (Mao, et al., 2015). It is related to the rate at which microorganisms grow and is influenced by the process temperature, organic loading rate (OLR), and sludge feed composition (Mao, et al., 2015).

According to (Akunna, 2015), the retention can be related to the reactor volume and average feeding rate as follows:

$$\mathrm{HRT} = \frac{\mathrm{V}}{\mathrm{Q}} \qquad (1)$$

HRT = Retention time, day

V = Reactor volume, m^3

Q = Average feeding rate, $\mathrm{m}^3/\mathrm{day}$

Hydraulic retention times of 15-20 days are ideal for the treatment of wastewater under mesophilic conditions and hydraulic retention times below 10 days may lead to low biogas production for anaerobic digestion using algal biomass (Mao, et al., 2015). VFA accumulation increases with shorter HRTs, which presents inhabitation effects problems (Meegoda, et al., 2018).

For an AD reactor with HRT = 15 days and V = $2.5\ \mathrm{m}^3$

Average daily feeding rate (Q) $= \frac{2.5}{15} = 0.166667\,\frac{\mathrm{m}^3}{\mathrm{day}}$

$$0.166667\,\frac{\mathrm{m}^3}{\mathrm{day}} \times \frac{\mathrm{day}}{24\mathrm{h}} \times \frac{1000\mathrm{L}}{\mathrm{m}^3} = 6.944\ {}^{L}\!/_{h}$$

The pumping cycle will be set to 6 hours ON/OFF cycle a day, therefore the volumetric flow rate to the reactor will be 14 L/h per cycle for a 12-hour operation a day.

SRT or the average time solids (particulate substrates and microorganisms) are held in the process vessel, is a crucial parameter in the functioning of an AD system, as it controls the amount of time available for substrate breakdown and microbial growth/development (Vanwonterghem, et al., 2015).

One other important parameter affecting the biogas yield is how much volatile solids are being fed to the reactor per day known as the organic loading rate (OLR) (Bhatt & Tao, 2020). Organic loading rate indicates how much biodegradable matter is present in the system and it is expressed in terms of COD or BOD daily, per volume of the system (Akunna, 2015).

To maintain a constant liquid level in the feed balancing tank, and avoid overfill and running out of feed, the **sum** of the volumetric flow rates from the sludge storage tank (T1) and co-substrate tank (T2) into the balancing tank (T3) must be equal to the feeding rate to the digester (14 L/h).

According to (Chow, et al., 2020), the optimal mixing ratio of sewage sludge and organic co-substrate is 60:40, therefore by volumetric basis, the volumetric flow rate of the sludge and co-substrates will be fed into the feed balancing tank at varying ratios as follows:

Table 3: Different mixing ratios and respective flowrates for raw sludge and co-substrates.

Feeding ratios To the balancing tank	Raw sludge (%volume)	Co-substrate (%volume)	Raw sludge Volumetric flow rate (L/h)	Co-substrate Volumetric flow rate (L/h)
Ratio 1	50	50	7	7
Ratio 2	60	40	8.4	5.6

3.1 Storage Vessels

According to the heuristics for process equipment design for a vessel (pressure tank), the design temperature is set 30℃ above the operating temperature between -30 and 350℃ (Peters, et al., 2003). The design pressure is 10 percent or 70 to 175 kPa (0.7 to 1.75 bar) above the maximum operating pressure, whichever is greater (Peters, et al., 2003). Therefore, for a sludge holding tank operated at room temperature (25℃) and atmospheric pressure (101.325 kPa or 1.01 bar), the design temperature is 55℃ and the design pressure is 276.325 kPa (2.76 bar).

According to the heuristics for a vessel (storage tanks) under internal pressure with a capacity of less than $1.9\mathrm{m}^3$, freeboard is 15% and for a capacity less than $4\mathrm{m}^3$ use vertical tanks on legs, for capacity between 4 and $40\mathrm{m}^3$, use horizontal tanks on concrete supports; beyond $40\mathrm{m}^3$, use vertical tanks on concrete foundations (Peters, et al., 2003; Couper, et al., 2012).

The height-to-diameter ratio (H/D) of a cylindrical tank is between 0.5 to 1.5 (Agboola, et al., 2020).

3.1.1 Sludge Tank (T1)

Sludge will be pumped from the sludge tank (T1) by pump (P2) while flow will be controlled by valves (V4 and V7).

The highest drainage flow rate from the sludge storage tank will be experienced under “Ratio 2”, where the flow rate will be 8.4 L/h. To minimise and smooth out any variations, take residence time as 24h then the volume of the sludge storage tank $= 8.4\ \mathrm{L/h} \times 24\mathrm{h}\ =\ 202\mathrm{L}\ (0.202\mathrm{m}^3)$.

The storage tank will have a design volume of $233\mathrm{L}\ (0.233\mathrm{m}^3)$, for a H/D ratio of 1.4, the height is 0.6m and diameter is 0.84m as shown in figure 4.1, 4.2 and 4.3 in the appendices. Table 3 below presents dimensions for the sludge tank.

Table 4: Sludge holding tank design parameters.

Sludge holding tank	
Required Volume (L)	202
Design Volume (L)	233
Residence time (h)	24
Sludge holding tank total height (mm)	840
Sludge holding tank total diameter (mm)	600
H/D	1.40
Inlet diameter (mm)	40
outlet diameter (mm)	40
Volumetric flow (L/h)	7 – 8.4
Orientation	Vertical tank on legs
Design temperature (℃)	55
Design pressure (bar)	2.76
Material of construction	LLDPE (food grade approved)

3.1.2 Co-substrates Tank (T2)

There will need to be enough co-substrates for the HRT of 15 days at this flow rate of 7 L/h every 6 hours pumping cycle per day (2 times a day), therefore the co-substrates holding tank will have the following volume:

$$\mathrm{V} = 7\,{}^{\mathrm{L}}/_{\mathrm{h}} \times 6\mathrm{h} \times 2/\mathrm{day} \times 15\mathrm{days}$$

$$= 1260\mathrm{L}\ (1.26\mathrm{m}^3).$$

The co-substrate holding tank will have a design volume of 1450 $(1.450\mathrm{m}^3)$. For a H/D ratio of 1.4, the height is 1.54m and diameter is 1.1m as shows in figure 4.2-1 in the appendices. Table 4 below presents the co-substrate holding tank dimensions.

Table 5: Sludge holding tank design parameters.

Co-substrate holding tank	
Required Volume (L)	1260
Design Volume (L)	1450
Sludge holding tank total height (mm)	1540
Sludge holding tank total diameter (mm)	1100
H/D	1.40
Inlet diameter (mm)	40
outlet diameter (mm)	40
Volumetric flow (L/h)	5.6 – 7
Orientation	Vertical tank on legs
Design temperature (℃)	55
Design pressure (bar)	2.76
Material of construction	Food grade polyethylene, BPA-free

3.1.3 Feed Balancing Tank (T3)

The rate of drainage from the feed balancing tank will be the same as the feeding rate to the reactor (14 L/h for 4 hours 3 times a day = 168L/day). The required volume taking into consideration 24h residence time = 14×24h = 336L (0.336m^3).

The design volume is 387L (0.387m^3). For a H/D ratio of 1.4, the height is 1m and diameter is 0.714m as show in figure 4.3-1 in the appendices. Table 5 below presents the dimensions for a balancing tank.

Table 6: Balancing tank design parameters.

Sludge holding tank	
Required Volume (L)	336
Design Volume (L)	387
Residence time (h)	24
Sludge holding tank total height (mm)	1000
Sludge holding tank total diameter (mm)	714

H/D	1.4
Side opening diameter (mm)	25
Bottom opening diameter (mm)	25
Volumetric flow (L/h)	14
Orientation	Vertical tank on legs
Design temperature (℃)	55
Material of construction	LLDPE (Food grade approved)

3.1.4 Digestate Holding Tank (T4)

The digested sludge from the digester will be drained into the sludge holding tank at a constant flow rate. The digestate holding tank must be able to hold the sludge for a period of at least 48h before discharging the sludge as effluent.

The digestate holding tank will be conical with a volume $(\mathrm{V}) \geq 2.5\mathrm{m}^3$.. The digestate holding tank will have a design volume of 2875L ($2.875\mathrm{m}^3$). For a H/D ratio of 1.33, the height is 1.87m and diameter is 1.4m.

Table 6 below presents the dimensions for the sludge holding tank.

Table 7: Sludge holding tank design parameters.

Co-substrate holding tank	
Required Volume (L)	2500
Design Volume (L)	2875
Sludge holding tank total height (mm)	1870
Sludge holding tank total diameter (mm)	1400
H/D	1.33
Inlet diameter (mm)	40
outlet diameter (mm)	40
Volumetric flow (L/h)	-
Orientation	Vertical tank on legs
Design temperature (℃)	55
Design pressure (bar)	2.76
Material of construction	HDPE

3.1.5 Biogas Storage Tank (T5)

The biogas can be stored in different methods which include gas bags, water sealed gas holders, and weighted gas bags, (Tabatabaei et al.,2018), HDPE is the most commonly used material when it comes to the construction of biogas storage tank because they are cheaper and have a permeability resistance for a very long time, however, it has a limitation as it is not strong enough to be operated at high pressures that are exceeding 2 – 3 mbar.

A floating gas holder will be used as the biogas storage tank for this project. Floating gas holders are easy to install, operate and understand and the position of the gas is a visual indicator of the amount of gas produced (Nzila, et al., 2012).

The weight of the gas holder per unit area will indicate the pressure of the biogas and is normally between 4 and 8cm of water (Tiwari, et al., 1996) . Water-jacket floating gas holder tanks are usually clean and easy to maintain, since water is cleaner the gas holder cannot get stuck in a scum layer (Nzila, et al., 2012). The tank is usually fitted with internal/external guide frames to keep it upright and provide stability (Nzila, et al., 2012). Figure 4.7 in the appendices presents the conceptual view of the storage tanks.

The biogas storage tank will be designed for a 1 L/h flow rate of biogas and a storage time of 15 days (360 hours).The gas holder will be cylindrical with a total capacity of $1\,\mathrm{L/hr} \times 360\mathrm{hr} =$ 360L ($0.36\mathrm{m}^3$).The biogas storage tank will be operated at room temperature (25℃) and atmospheric pressure (101.325 kPa or 1.01 bar), the design temperature is set at 55℃ and the design pressure is set at 276.325 kPa (2.76 bar).

The biogas storage inner tank will have a design volume of 414 L ($0.414\mathrm{m}^3$). For a tank with an H/D ratio of 1.5, the diameter is 0.706m and the height is 1.06m.
The outer tank will be slightly taller and have a slightly larger diameter than the inner tank and there will be a clearance between the inner tank and the outer tank where the channelising and stoppers will meet. Table 7 below presents the dimensions of a biogas holding tank.

Table 8: **Biogas holding tank parameters.**

Biogas Production	
Flow rate (m^3/hr)	0.001
Storage time (days)	15
Inner Tank dimensions	
Design capacity (L)	414

L/D ratio	1.5
Diameter (mm)	700
Height (mm)	1076
Material of construction	HDPE
Outer tank dimensions	
Design capacity (L)	440
Height (mm)	1081
Diameter (mm)	720
H/D	1.5
Material of construction	HDPE

3.2 Digester (ADR)

Materials such as PVC, HDPE, and LLDPE have been used successfully for the construction of biogas tank digesters (Khune et al.,2021). Biogas digesters are mostly constructed from materials such as cement, concrete, and bricks, whereby in some instances the biogas holders are made up of fiberglass, however, there are disadvantages with different materials for the digester construction. Digesters constructed from the metals, usually face corrosion problems which makes metals less suitable for the construction of the biodigester. Constructing a biodigester using bricks and cement is very costly due to the labor and equipment required. Besides the high costs this kind of digester usually faces leakage problems through the bricks which results in biogas loss (Obileke et al.,2020).

The digester is a suspended growth type CSTR bioreactor, made from HDPE and will have three regions as pictured below:

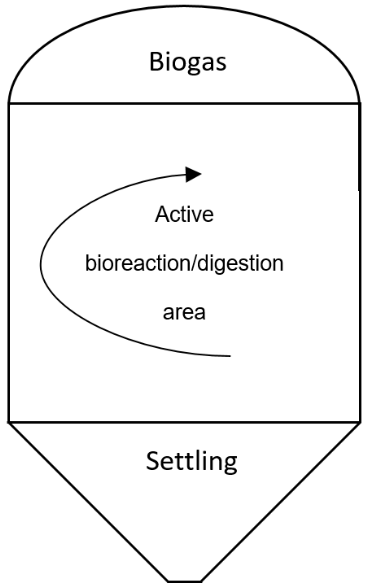

Figure 3: Digester tank regions.

The digestion will occur in the active digestion region where organic solids will be turned into biogas by enzymatic and metabolic processes involving a variety of microorganisms in the absence of oxygen. Appendices 4.4-2 presents the cross-sectional views of the digester tank.

Table 8 below presents the dimensions for the digester tank/reactor.

Table 9. Digester tank dimensions.

Digester	
Required Volume (L)	2500
Design Volume (L)	2742.3
Material of construction	HDPE
Digester total height (mm)	3132
Digester diameter (mm)	700
Feed inlet diameter (mm)	40
Recirculation inlet diameter (mm)	40
Discharge outlet diameter (mm)	40

3.3 Heating systems

Typical heating systems for reactors are provided by internal or external heat exchanger coils or pipes, steam injection into the tank, or passing hot combustible gas through the sludge (Peters, et al., 2003; Turovskiy & Mathai, 2006). External heat exchangers provide better heat transfer efficiency and are mostly used (Turovskiy & Mathai, 2006). The anaerobic bacteria responsible for the digestion of the sludge is sensitive to temperature fluctuations or thermal shock which could lead to a reduction in COD removal efficiency, an increase in volatile fatty acids (VFA) and a reduction in biogas yield (Mei, et al., 2016).

The wasted sludge from the reactor will pass through an external heat exchanger set to a desired temperature set point suitable for the anaerobic bacteria. To break up the scum layer and minimize the supernatant and help mix the sludge in the reactor, the sludge will be recirculated by a recirculation pump and enter the reactor at the top.

3.3.1 Heating requirement

3.3.1.1 Heat energy is required.

According to (Turovskiy & Mathai, 2006), primary sludge has a density of $1000 \text{ to } 1030 \text{ kg/m}^3$ and has the following thermophysical characteristics:

Table 10. Sludge thermophysical properties.

Raw primary and waste activated sludge	
Thermal conductivity	$0.4 - 0.6 \text{ W/m} \cdot \text{K}$
Specific heat capacity	$3.5 - 4.7 \text{ KJ/kg} \cdot \text{K}$

$\dot{Q}_{req} = \dot{m}\overline{C_p}(T_2 - T_1)$

Where:

- $\dot{Q}$ = specific energy required
- $\dot{m}$ = the mass flow rate of the sludge fed into the tank
- $\overline{C_p}$ = average heat capacity over a temperature range in kJ/kg.k
- T_2 = design temperature in ℃ or K
- T_1 = minimum sludge temperature in ℃ or K

$\dot{m} = \rho\dot{V}$

$\rho \text{ (Sludge density) } = 1030 \text{ kg/m}^3$

$\dot{V} \text{ (Volumetric flow rate of the feed into the reactor) } = 14 \text{ L/h}$

$= 3.889 \times 10^{-6}\ \mathrm{m^3/s}$

$\dot{m} = 1030 \times 3.889 \times 10^{-6}$

$= 4.056 \times 10^{-3}\ \mathrm{kg/s}$

According to (Turovskiy & Mathai, 2006), municipal wastewater treatment plant raw sludge feed temperature can be as low as 12.8℃.

$\dot{Q}_{req} = 4.056 \times 10^{-3} \times 4.7(55 - 12.8)$

$\dot{Q}_{req} = 0.7945$ kJ/s (0.8kW)

3.3.1.2 Heat loss

3.3.1.2.1 Heat loss via conduction (without insulation):

The sludge will be in contact with the tank sides which will be in contact with the atmosphere.

Under steady-state conditions heat conduction in plane walls can be modelled as one-dimensional, driven by a temperature gradient and the surface is considered isothermal (Çengel & Ghajar, 2015).

According to (Çengel & Ghajar, 2015), "*The rate of heat conduction through a plane wall is proportional to the average thermal conductivity, the wall area, and the temperature difference, but is inversely proportional to the wall thickness*", and can be estimated by the following equation:

$$\dot{Q}_{conduction} = -kA\frac{(T_1 - T_2)}{L}$$

Where:

$\dot{Q}_{conduction}$ = specific energy lost by the sludge via conduction

k = average thermal conductivity

A = reactor wall area

L = reactor wall thickness

$T_1 - T_2$ = temperature gradient

Assuming a minimum of 20 mm thickness of the tank wall.

Pure HDPE has a thermal conductivity of about $0.51 \pm 0.02\ \mathrm{W/m \cdot K}$ (Yang, et al., 2016).

The following table presents the thermophysical properties of HDPE.

Variable	data
k	$0.53\ \mathrm{W/m \cdot K}$
A	$2.56\mathrm{m^2}$ (See Appendix A.2)
L	20mm
T_1	12.8℃ (Lowest possible sludge temperature)
T_2	55℃ (Design temperature)

Table 11: **HDPE thermophysical properties**

$$\dot{Q}_{\text{conduction}} = -0.53 \times 2.56 \frac{(12.8 - 55)}{20 \times 10^{-3}}$$

$= 2.8628$ kJ/s (2.8628 kW) lost.

Therefore, the total specific duty $\dot{Q}$ of the heat exchanger is:

$$\dot{Q} = \dot{Q}_{\text{req}} + \dot{Q}_{\text{conduction}}$$

$\dot{Q} = 0.8 + 2.8628 = 3.67$ kW (Without insulation).

- To minimize heat-loss, reduce energy consumption by the heat exchanger and allow the usage of an affordable heat exchanger with lower duty, the reactor will be insulated.
- The most affordable insulation material in the market available at the time of writing is SABS-approved polyester with a thermal conductivity of $0.046 \text{W/m} \cdot \text{K}$.

3.3.1.2.2 Heat loss via conduction (with insulation).

$$\dot{Q}_{\text{cond(insulation)}} = -kA \frac{(T_1 - T_2)}{L}$$

Where:

$\dot{Q}_{\text{cond(insulation)}}$ = specific energy lost by the sludge via conduction with insulation applied on the reactor

k = average thermal conductivity

A = reactor wall area

L = insulation material thickness

$T_1 - T_2$ = temperature gradient

The polyester insulation material is sold with 40mm thickness.

The following table presents the thermophysical properties of polyester insulator.

Variable	data
k	$0.046\ \text{W/m} \cdot \text{K}$
A	2.56m^2 (See Appendix A.2)
L	40mm
T_1	12.8℃ (Lowest possible sludge temperature)
T_2	55℃ (Design temperature)

Table 12: Polyester insulation material thermophysical properties

$$\dot{Q}_{cond(insulation)} = -0.046 \times 2.56 \frac{(12.8 - 55)}{40 \times 10^{-3}}$$

= 124.24 J/s (124.24 W) lost.

Therefore, the total specific duty $\dot{Q}$ of the heat exchanger is:

$$\dot{Q} = \dot{Q}_{req} + \dot{Q}_{cond(insulation)}$$

$\dot{Q} = 0.8 + 0.12424 = 0.93\ \mathrm{kW}$ (With insulation).

3.3.1.3 Tube side flow rate

The circulating fluid in the tube side will be water.

$$\dot{Q}_{water} = \dot{m}_{water} \overline{C_p}_{water} (T_2 - T_1)$$

$$\dot{m}_{water} = \frac{\dot{Q}_{water}}{\overline{C_p}_{water} (T_2 - T_1)}$$

Duty ($\dot{Q}$) = $0.93\mathrm{kW}$

The average specific heat capacity of saturated liquid water over $12.8 - 55℃$ is $4.18 \mathrm{kJ/kg \cdot k}$ and the average density over $12.8 - 55℃$ is $993.93\ \mathrm{kg/m^3}$ (Çengel & Ghajar, 2015).

$$\dot{m}_{water} = \frac{0.93}{4.18(55 - 12.8)} = 5.273 \times 10^{-3}\ \mathrm{kg/s}$$

The specifications for the heat exchanger are tabulated below.

HEAT EXCHANGER (HS1)	
Identification: • Item: Hot water bath tank heat exchanger • No. required: 1	
Function: Heat the sludge in the reactor (ADR) to a desired temperature.	
Operation: Continuous.	
Type: • Horizontal • Fixed tube • **Duty:** 0.52kW • Area:	
Tube Side: • **Fluid:** Water • **Flow rate:** 5.273×10^{-3} kg/s • **Pressure:** 101.325 kPa • **Temperature:** 12.8℃	**Tubes:** • 2 passes • **Tube material:** copper • **Pipe Material:**
Shell Side: • **Fluid:** Water. • **Flow rate:** 0 kg/s • **Pressure:** 101.325 kPa • **Temperature:** Set point (SP)	**Shell:** • 1 pass • **Longitudinal baffles:** 0 Required
Utilities: untreated heating water **Controls:** Tube heating water controlled by a peristaltic pump **Tolerances:** Tubular Exchangers Manufacturers Association (TEMA) standards. **Comments and drawings:**	

Table 13: **Specification sheet for a heat exchanger (HS1).**

3.4 Mixing/Agitation

Mixing in the digester helps create uniformity in the digester/tank, prevent the formation of a scum layer and prevent deposition of suspended matter at the bottom of the tank (Turovskiy & Mathai, 2006). According to (Turovskiy & Mathai, 2006), mechanical mixing, pumped recirculation, and gas mixing are the three forms of mixing that are frequently utilized in biogas pilot plants. Inlet flow baffling, turbine mixing, mild diffused aeration with air, or mild diffused aeration with biogas can all be employed to accomplish mixing (Akunna, 2018).

Mechanical mixing will be used in the sludge storage tank, co-substrate tank, equalising tank, and reactor. Low-speed flat-blade turbines or high-speed propeller mixers are used in mechanical mixing and mechanical mixing has the advantage of providing mixing efficiency and breaking up scum layer buildup (Turovskiy & Mathai, 2006).

Common agitators in mixing are propellers, turbines, pitched turbines, paddles, anchor type and helical ribbon type (Peters, et al., 2003).

According to (Towler & Sinnott, 2021) power rating for electric stirrers of baffle agitated tanks under severe agitation for slurry suspensions is about $1.5 - 2.0\,\mathrm{kW/m^3}$ of the tank volume.

- The raw sludge holding tank will require an electric stirrer with a power rating of at least, $2\,\mathrm{kW/m^3} \times 0.233\mathrm{m^3} = 0.47\,\mathrm{kW}$.

Sludge Tank Electric Stirrer(M1)	
Type	Propeller
Power Required	$0.47\,\mathrm{kW}$
Working Temperature	-30 to 200℃
Voltage	230-240V/50Hz
Tank Volume	0.3233

Table 14:Sludge Tank Electric Stirrer properties

- The co-substrate holding tank will require an electric stirrer with a power rating of at least, $2\,\mathrm{kW/m^3} \times 1.25\mathrm{m^3} = 2.5\,\mathrm{kW}$.

Co-substrate Tank Electric Stirrer(M2)	
Type	Propeller
Power Required	$2.5\,\mathrm{kW}$
Working Temperature	-30 to 200℃
Voltage	230-240V/50Hz
Tank Volume	$1.25\mathrm{m^3}$

Table 15: Co-substrate tank electric stirrer properties

- The equalising tank will require an electric stirrer with a power rating of at least, $2\,\mathrm{kW/m^3} \times 0.334\mathrm{m^3} = 0.67\,\mathrm{kW}$.

Equalising Tank Electric Stirrer(M3)	
Type	Propeller
Required	$0.67\,\mathrm{kW}$
Working Temperature	-30 to 200℃
Voltage	230-240V/50Hz
Tank Volume	$0.336\mathrm{m^3}$

Table 16:Equalising tank electric stirrer properties.

- The digester will require an electric stirrer with a power rating of at least, $2\,\mathrm{kW/m^3} \times 2.875\mathrm{m^3} = 5.75\,\mathrm{kW}$.

Digester Electric Stirrer(M4)	
Type	2 Propellers
Power Required	$5.75\,\mathrm{kW}$
Working Temperature	-30 to 200℃
Voltage	230-240V/50Hz
Tank Volume	$2.875\mathrm{m^3}$

Table 17: Digester electric stirrer properties

3.5 Piping

Most often, fluids are delivered through closed channels that vary in size, wall thickness, construction material, and cross-sectional geometry, such as pipes or conduits (Jafari & Malekjani, 2022). Pipes or tubes depending on what they are used for, are usually made of metals, metal alloys, plastics, composite plastics, glass, ceramic, and wood (Jafari & Malekjani, 2022). PVC pipes and most recently cast-iron pipes are used for sewage systems and drainage (Jafari & Malekjani, 2022).

3.5.1 Pipe size selection

The polyvinyl chloride (PVC) pipe is used on the inlet and outlet sections of the biogas, and it can also be used as the biogas chamber. The reason for the selection of PVC is that it has a low cost, and it is also effective. PVC is a degradable material, and the life span is estimated to be less than 2 years which is also a disadvantage of using PVC, the selection for PVC is mostly based on its physical properties and also the fact that is cost effective (Obileke et al.,2021).

If the aim is to discharge fluid from one vessel to the other by **gravity**, then the smallest pipe diameter that gives the minimum flow rate is normally chosen (Towler & Sinnott, 2021). For a fluid that must be pumped by a pipe the size of the pipe must be selected to give the least total annualized cost (Towler & Sinnott, 2021). 40 mm diameter PVC pipes will be used on all tank outlets as well as the digester inlet.

3.6 Pump sizing

Liquids and dilute slurries are transported via piping systems. Pumps are classified into two general types:

1. Dynamic pumps such as centrifugal pumps and
2. Positive displacement pumps, such as reciprocating and diaphragm pumps.

In this report, a centrifugal pump will be employed for:

1. Pumping the sludge from the WWTP to the raw sludge holding tank (P1)
2. Pumping the sludge from the raw sludge holding tank into the balancing tank (P2)
3. Pumping the co-substrates into the feed balancing tank (P3).
4. Pumping the mixed feed from the feed balancing tank into the reactor (P4)

A peristaltic pump will be employed for:

1. Circulating hot water in the reactor (P5)

3.6.1 Suction and discharge pressures

$P_{suction} = P_1 + P_{static} - \triangle P_{friction}$

P_1 = pressure at liquid surface = 0, for all tanks

P_{static} = pressure due to the height of the liquid = $\rho g h$

$\rho = 1030 \text{ kg/m}^3$

$g = 9.81\, m/s^2$

$h_{suction\ point} = 0.4$

$P_{static} = 1030 \times 9.81 \times 0.4 = 4041.72\ Pa$, for all pumps 2 to 4.

$P_{discharge}$ = 101325 Pa

3.6.2 Pressure loss

$$\triangle P_{friction} = 8f\left(\frac{L'}{D}\right)\left(\frac{\rho u^2}{2}\right)$$

where f is Darcy friction factor, L' is the total pipe length taking into consideration, the fittings, D is inner pipe diameter, ρ is fluid density and u is fluid velocity.

Friction factor depends on Reynold's number (Re):

$$Re = \frac{\rho D u}{\mu}$$

μ is the dynamic viscosity of the sludge. Assuming it is the same as that of water at $25℃$, $\mu = 0.891 \times 10^{-3}\ kg/m \cdot s$

$$u = \frac{\dot{V}}{A}$$

$\dot{V}$ = volumetric flow rate

A = pipe cross-sectional area

$A = \frac{\pi D^2}{4} = \frac{\pi(0.04)^2}{4} = 1.257 \times 10^{-3} m^2$, for all pipelines connected to pumps 1 to 5.

For Re<2100, the flow is laminar, and the friction factor is calculated as follows:

$$f = \frac{64}{Re}$$

For turbulent flow with Re>4000, the friction factor is calculated by the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right)$$

The effective roughness (ε) of PVC is 0.0015 https://www.pipeflow.com/pipe-pressure-drop-calculations/pipe-roughness.

Fitting/valve	K, number of velocity heads	Equivalent pipe diameters

3 90° elbows	0.8×3	40×3
1 non-return valve	0.4	18
2 gate valves	0.15×2	7.5×2
1 Sudden reduction (tank outlet)	0.5	25
1 Sudden expansion (tank inlet)	1.0	50
Total	4.2	228

Table 18: Pump 1 to 4 miscellaneous losses.

Contribution of fittings to the total length (L') = $228 \times 0.025 = 5.7m$, for all pipelines.

$$\triangle P_{friction} = 8f\left(\frac{L'}{D}\right)\left(\frac{\rho u^2}{2}\right)$$

Parameter	Pump 2	Pump 3	Pump 4
$\dot{V}$ (m^3/s)	2.33×10^{-6}	1.944×10^{-6}	3.889×10^{-6}
u (m/s)	1.854×10^{-3}	1.547×10^{-3}	3.094×10^{-3}
Re	85.73 (Laminar flow)	71.53 (Laminar flow)	143.07 (Laminar flow)
f	0.75	0.895	0.447
L (m)	8	8	10
L' (m)	13.7	13.7	15.7
$\triangle P_{friction}$ (Pa)	**3.64**	**3.022**	**9.54**

Table 19: Pump 1 to 4 friction pressures.

Suction and discharge pressures of pumps 1 to 4.

Parameter	Pump 2	Pump 3	Pump 4
$P_{suction}$ (Pa)	4003.9	4003.9	4020
$P_{discharge}$ (Pa)	101325	101325	101325
Flow (L/h)	8.4	7	14

Table 20: Pump 1 to 4 discharge and suction pressures.

3.6.3 Power

$$g\Delta z + \Delta P/\rho - \Delta Pf/\rho - W = 0$$

W = work done by the fluid, J/kg

Δz = difference in elevations ($z_1 - z_2$), m

ΔP = difference in system pressures ($P_1 - P_2$), Pa

ΔP_f = pressure drop due to friction, including miscellaneous losses, and equipment losses, Pa

ρ = liquid density, kg/m^3

g = acceleration due to gravity, m/s^2

$Power = \frac{W \times \dot{m}}{\eta_p}$ in Watts

Where:

W = work done by the fluid, J/kg

$\dot{m}$ = is the mass flow rate, kg/s.

η_p = is the pump efficiency, assuming 0.7.

$$\dot{m} = \rho\dot{V}$$

ρ $(Sludge\ density) = 1030\ kg/m^3$

$\dot{V}$ $(Volumetric\ flow\ rate\ of\ the\ feed\ into\ the\ reactor)$

Parameter	Pump 2	Pump 3	Pump 4
z_1 (m)	0.4	0.4	0.4
z_2 (m)	4	4	5
P_1 (Pa)	4041.72	4041.72	4041.72
P_2 (Pa)	101325	101325	101325
ΔPf	3.64	3.022	9.54
$g(z_1 - z_2)$	-35.32	-35.32	-45.13
$(P_1 - P_2)/\rho$	-94.45	-94.45	-94.45
$\Delta Pf\ /\rho$	0.00353	0.003	0.0093
W (J/kg)	129.77	129.77	139.60
$\dot{m}\ (kg/s)$	9.93×10^{-4}	9.93×10^{-4}	1.99×10^{-3}
Power (kW)	**0.18**	**0.18**	**0.40**

Table 21: Pumps 1 to 4 require power.

3.6.4 Cavitation

A pump's input pressure needs to be high enough to prevent cavitation inside the pump **(Towler & Sinnott, 2021)**. Cavitation happens when vapour or gas bubbles develop in the pump casing. If the pressure drops below the liquid's vapour pressure, vapour bubbles will start to form **(Towler & Sinnott, 2021)**. The ensuing collapse of these bubbles produces localized shock waves that make noise and may harm the pump **(Towler & Sinnott, 2021)**.

The net positive suction head available ($NPSH_{available}$) is the pressure at the pump suction, above.
The vapour pressure of the liquid, expressed as the head of the liquid (Towler & Sinnott, 2021).

The net positive head available is given by the following equation:

$$NPSH_{available} = P/\rho g + H - P_f/\rho g - P_v/\rho g$$

where $NPSH_{available}$ = net positive suction head available at the pump suction, m
P = the pressure above the liquid in the feed vessel, Pa
H = the height of liquid above the pump suction, m
P_f= the pressure loss in the suction piping, Pa
P_v= the vapour pressure of the liquid at the pump suction, Pa
ρ = liquid density, kg/m^3
g = acceleration due to gravity, m/s^2
The inlet piping must be designed to ensure that $NPSH_{available}$ exceeds $NPSH_{required}$ under all operating conditions to avoid cavitation.

$P_v\ (water)_{@25°C} = 3.17 kPa$ (Çengel & Cimbala, 2018).

Parameter	Pump 2	Pump 3	Pump 4
P (Pa)	101325	101325	101325
$P/\rho g$	10.03	10.03	10.03
H (m)	3.6	3.6	4.6
P_f (Pa)	9.84	9.84	21.72
$P_f/\rho g$	3.74×10^{-3}	3.74×10^{-3}	2.15×10^{-3}
P_v (Pa)	3170	3170	3170
$P_v/\rho g$	0.314	0.314	0.314
$NPSH_{available}$ (m)	13.31	13.31	14.31

Table 22: Pump 1 to 4 Net positive suction available.

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5 Appendices

5.1 Appendix A.1

A.1: Digestor sizing

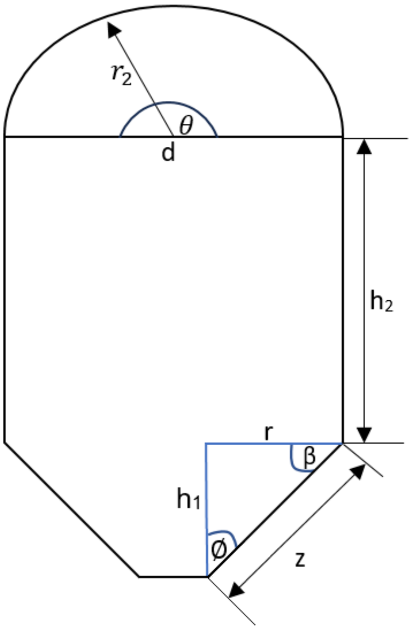

Figure 4: **Digester dimensions.**

1. Sizing the digester bioreaction region

Total Volume (V_T)= 2500L = $2.5m^3$

β = 60°

Volume of cylinder $(V_2) = \pi r^2 h_2$

Volume of Cone $(V_1) = \frac{\pi}{3} r^2 h_1$

$\emptyset = 180 - \beta = 180 - 60 = 30°$

$h_1 = r \tan 60 = r\sqrt{3}$

$h_1(r) = r\sqrt{3}$ .... (1)

$$z = \frac{r}{\cos 60} = 2r$$

$z(r) = 2r$ .... (2)

$$V_T = V_2 + V_1$$

$$V_1 = \frac{\pi}{3} r^2 (r\sqrt{3})$$

$$= \pi \frac{\sqrt{3}}{3} r^3$$

$$V_2 = V_T - V_1$$

$$V_2 = 2.5 - \pi \frac{\sqrt{3}}{3} r^3 \ = \pi r^2 h_2$$

$$h_2 = \frac{\left(2.5 - \pi \frac{\sqrt{3}}{3} r^3\right)}{\pi r^2}$$

$$h_2(r) = \frac{\left(2.5 - \pi \frac{\sqrt{3}}{3} r^3\right)}{\pi r^2} \quad \text{.......} (3)$$

r (m)	$h_1(r)$ (m)	$h_2(r)$ (m)	$z(r)$ (m)
0.1	0.1732	79.52	0.2
0.2	0.3464	19.78	0.4
0.3	0.5196	8.669	0.6
0.4	0.6928	4.743	0.8
0.5	0.8660	2.894	1.0
0.6	1.039	1.864	1.2
0.7	**1.212**	**1.220**	**1.4**
0.8	1.386	0.7815	1.6
0.9	1.559	0.4628	1.8
1.0	1.732	0.2184	2.0
1.1	1.905	0.02258	2.2

Table 23:Tabulated values of radius and the corresponding digester shape heights

$$V_T = \pi r^2 h_2 + \frac{\pi}{3} r^2 h_1$$

Chosen reactor dimensions.

- r = 700mm
- h_1= 1212mm
- h_2= 1220mm

2. Sizing the digester biogas region

$S = r_2 \times \theta$, where S is the arc length and θ in radians.

$$\theta = 180° = \pi$$

$$r_2 = r$$

$S = 700 \times \pi$

$S = 2199.11mm$

Determining the total design volume of the reactor

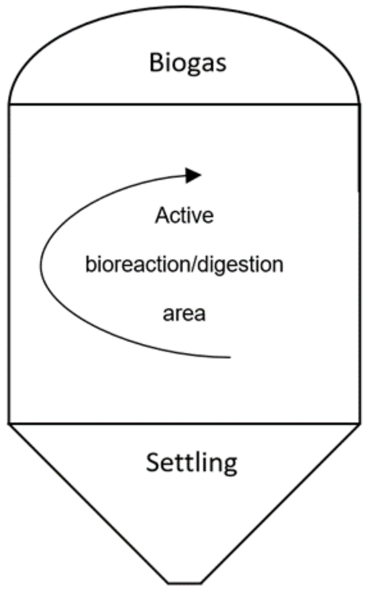

Figure 5: Digester tank regions.

1. **Biogas region volume**
   Volume of half a sphere = $0.5 \times \frac{4}{3}r^3$
   $=0.5 \times \frac{4}{3}(0.7)^3$
   $=0.2287m^3 = 228.7l$

2. **Active bioreaction/digestion region volume**
   Volume of cylinder = $\pi r^2 h$
   $= \pi(0.7)^2 \times 1.220$
   $= 1.878m^3 = 1878l$

3. **Settling region volume**
   Volume of a 60mm cylinder + volume of a cone
   $= \pi r^2 h + \frac{\pi}{3} r^2 h_2$
   $=\pi(0.06)^2 \times 1.212 + \frac{\pi}{3}(0.7)^2 \times 1.212$
   $= 0.6356m^3 = 635.6l$

Total volume of the digester = $(0.2287 + 1.878 + 0.6356)m^3$

$= 2.7423m^3 = 2742.3l$

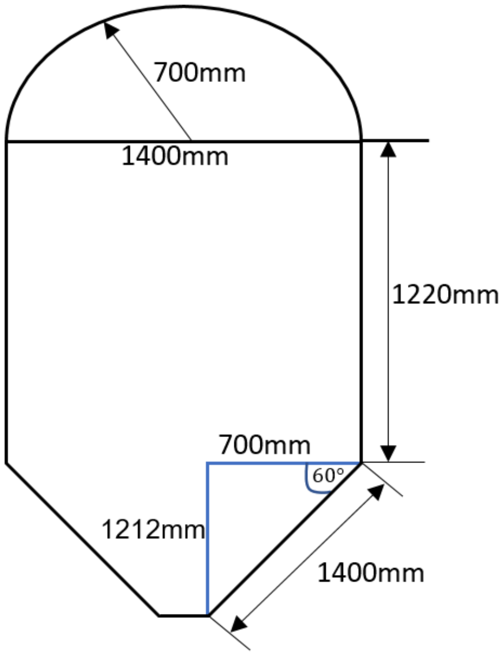

Figure 6: **Digester shape and dimensions**

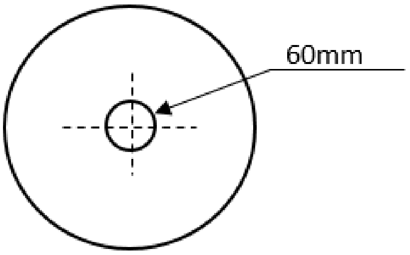

Figure 8: Digester tank top view.

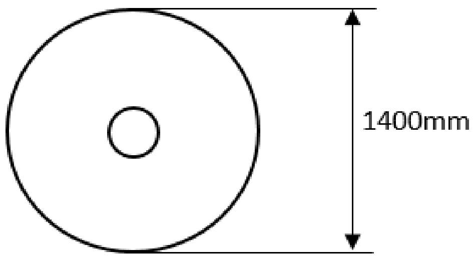

Figure 7: Digester tank bottom view.

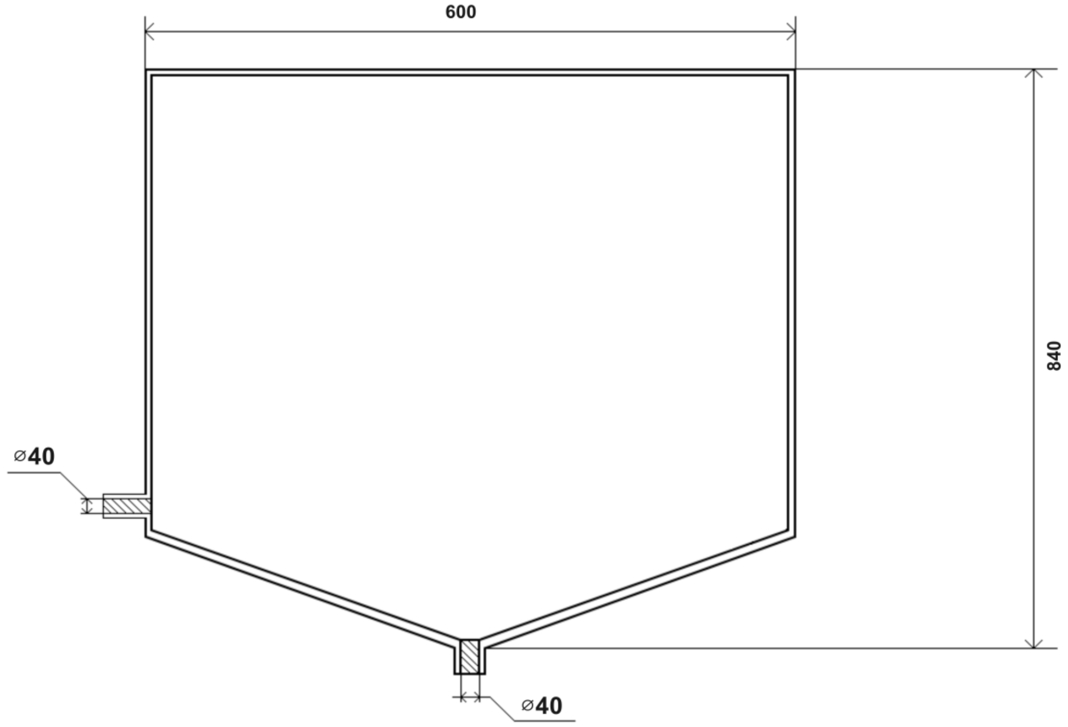

Figure 9: Sludge holding tank side view.

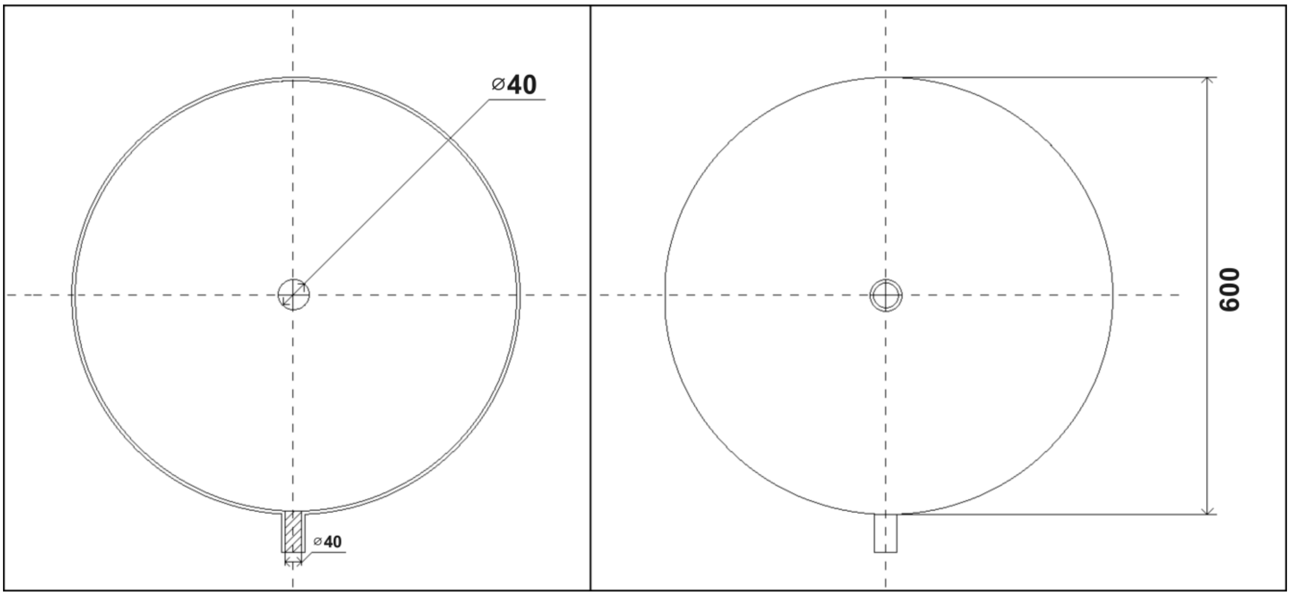

Figure 10: Sludge holding tank top view and bottom cross-sectional views respectively.

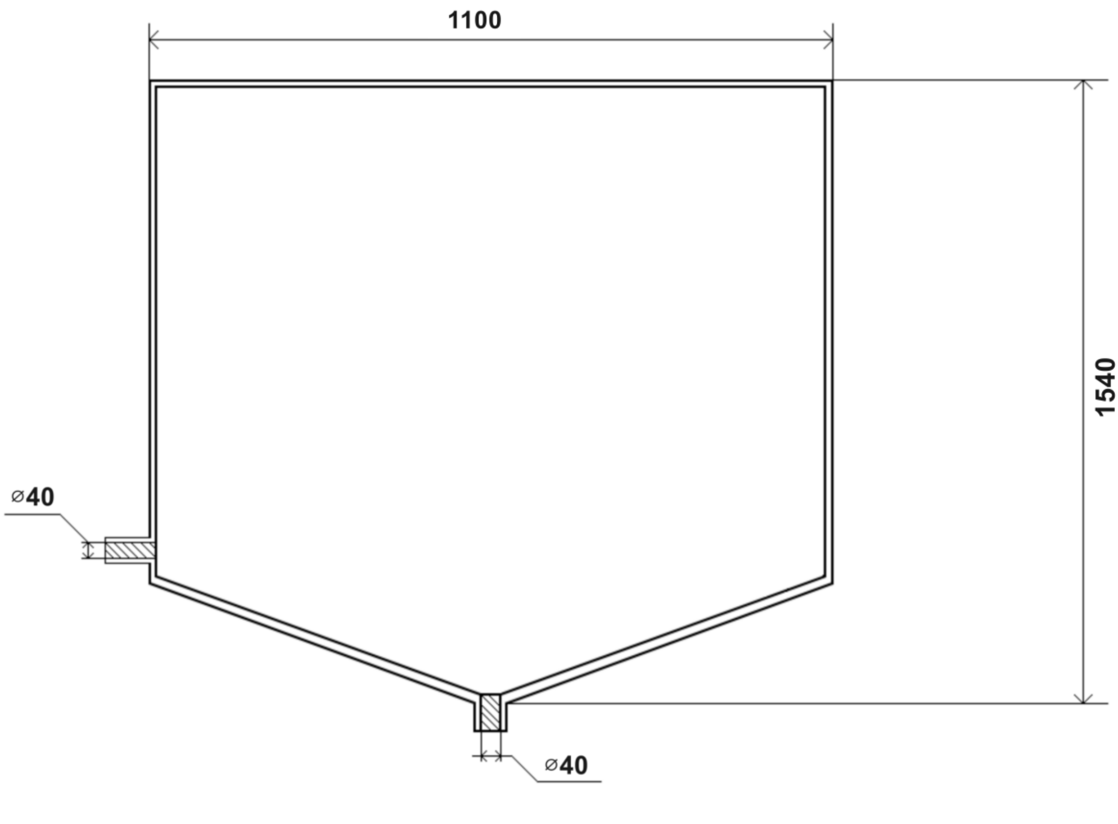

Figure 11: Co-substrates tank cross-sectional view.

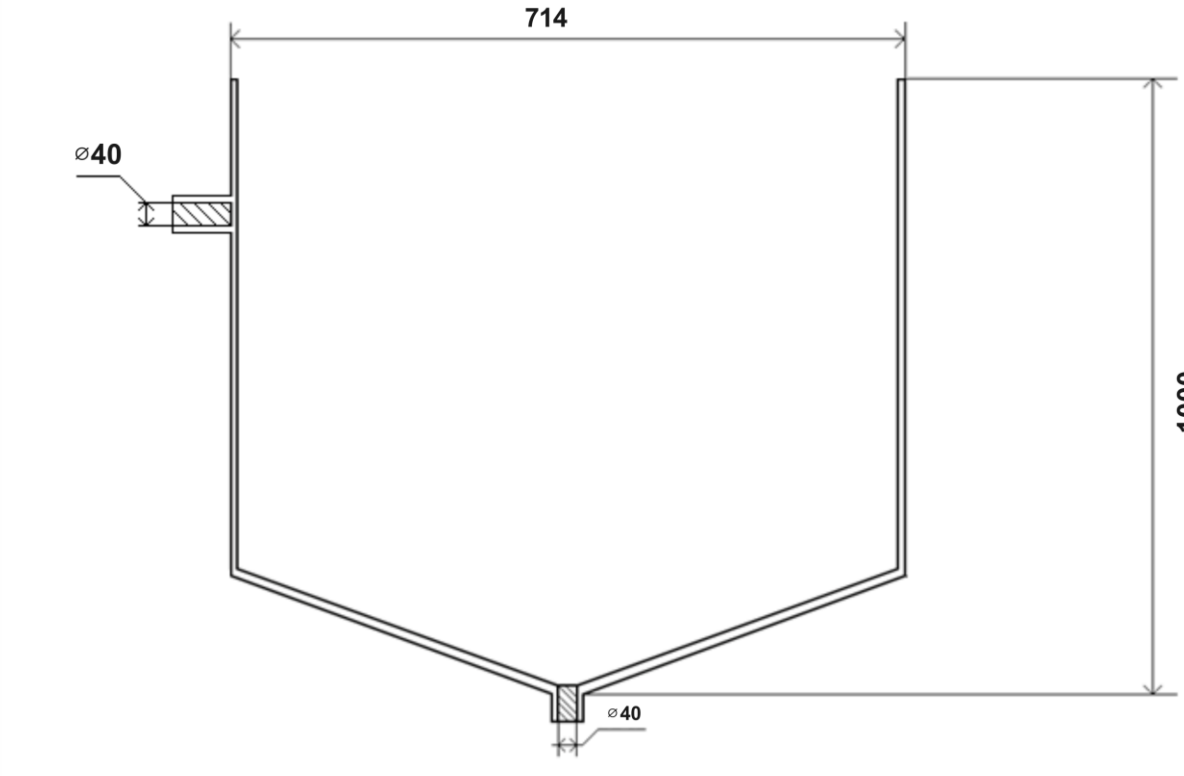

Figure 12: **Feed balancing tank cross-sectional view.**

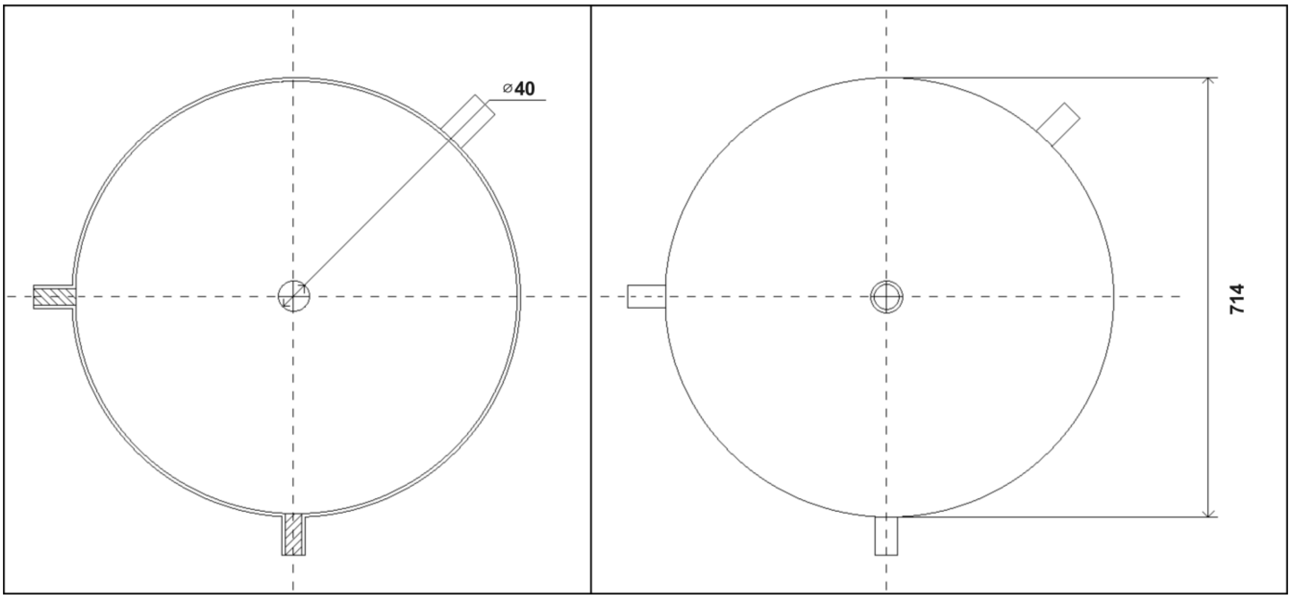

Figure 13: **Feed balancing tank, top and bottom views respectively.**

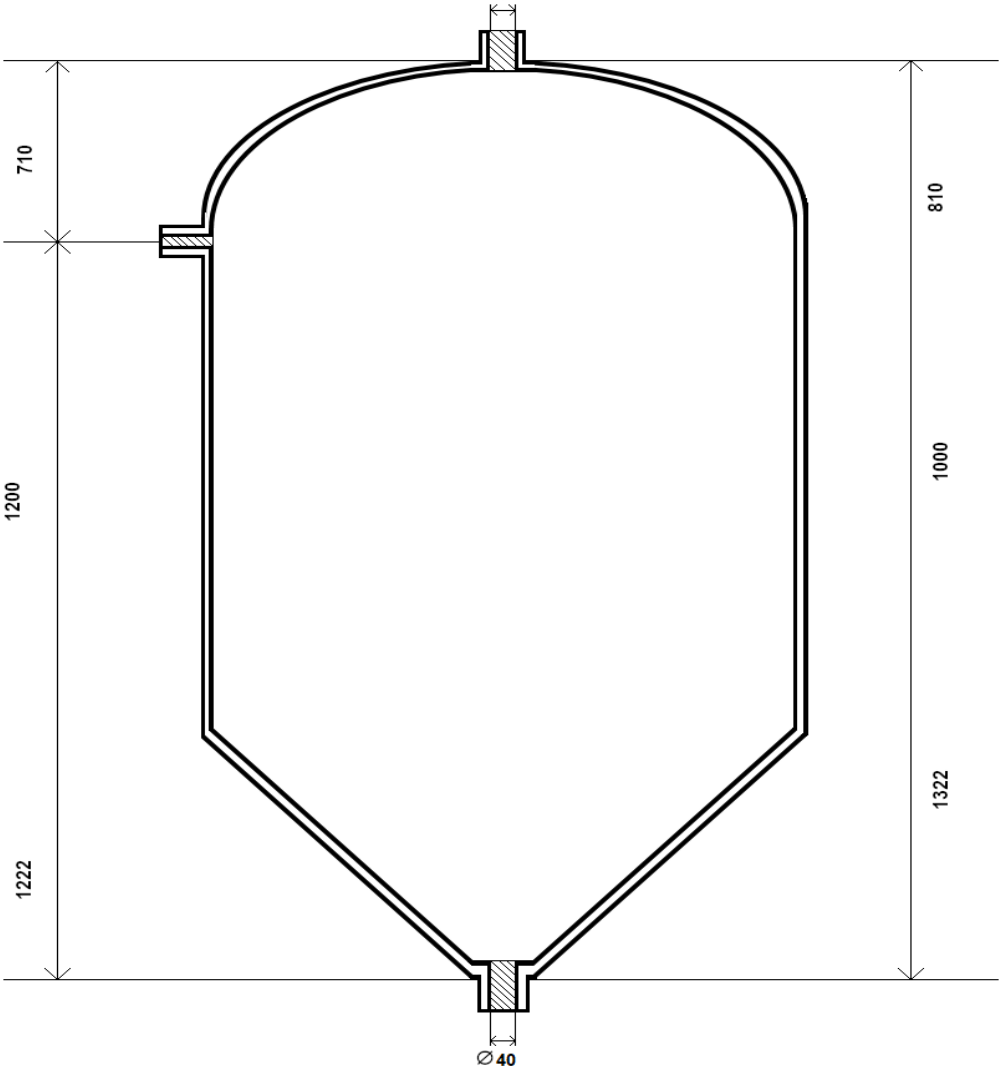

Figure 14: Cross-sectional view of the digester

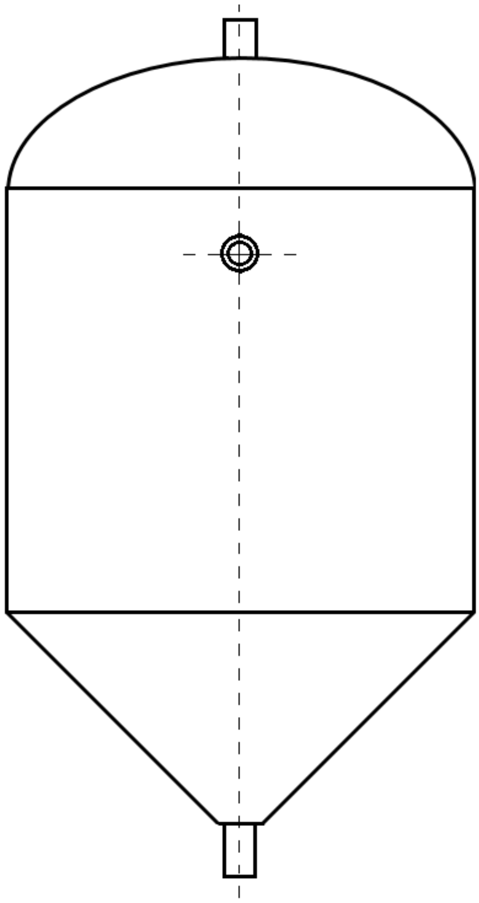

Figure 15: Digester tank front view

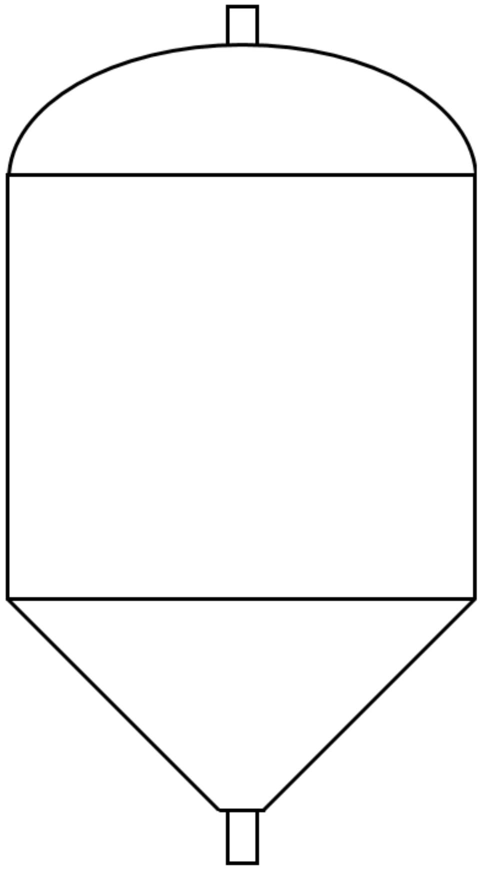

Figure 16: Digester tank back view

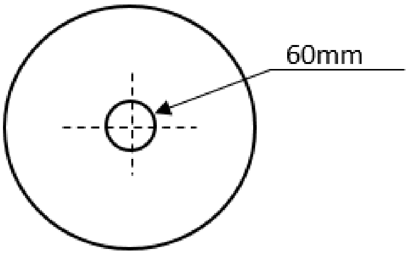

Figure 17: Digester tank Top view

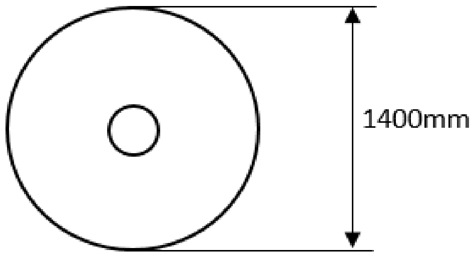

Figure 18: Digester tank bottom view

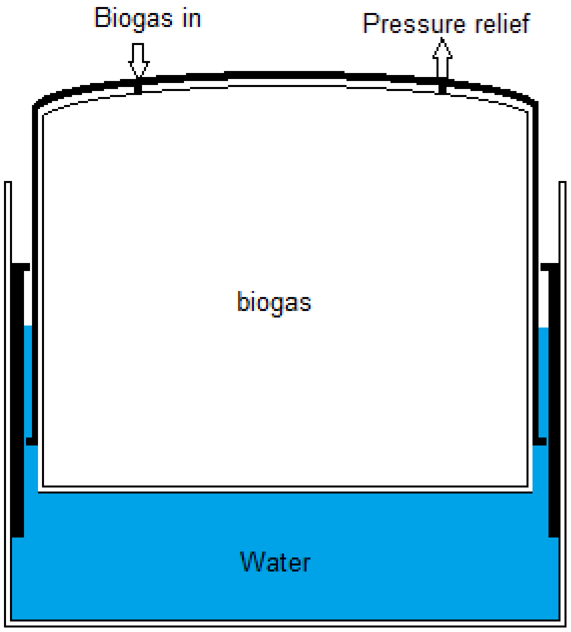

Figure 19: **Biogas storage tank cross-sectional view**

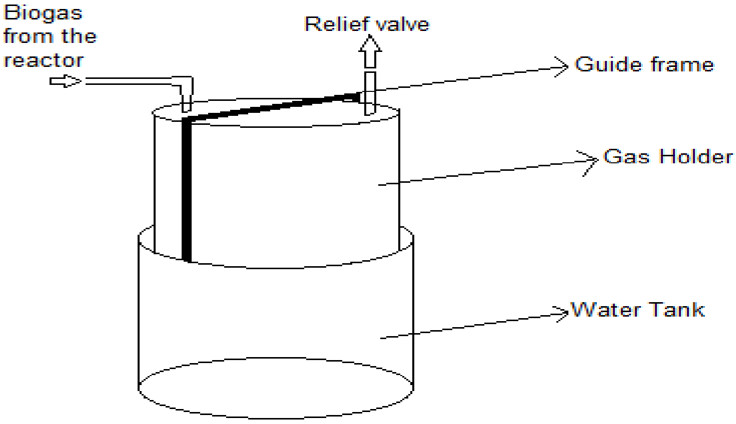

Figure 20: **Floating gas storage tank.**

5.2 Appendix A.2

Contact area for heat conduction:

$$A = A_{\text{digestion region}} + A_{\text{settling region}}$$

$$A = h_2 \times d + \frac{1}{2} d \times h_1$$

$$A = 1.220 \times 1.4 + \frac{1}{2} \times 1.4 \times 1.212$$

$$A = 2.56\ m^3$$

A.3: Feed balancing tank sizing

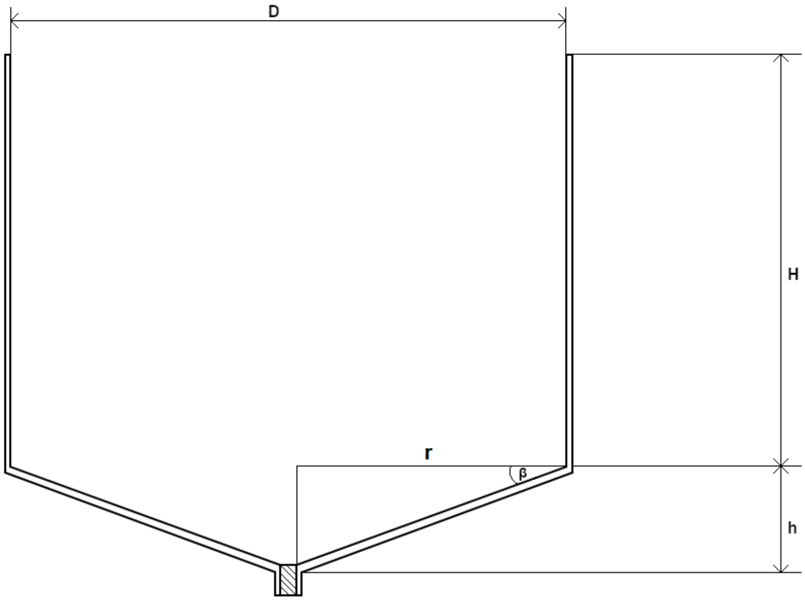

Figure 21: **Feed balancing tank cross sectional view.**

Sizing of the balancing tank

$$V_d = S_d \times R_t$$

$$2.5m^3 = S_d \times 15\ day$$

$$s_d = \frac{2.5m^3}{15\ day} = \frac{2500l}{15day} = \frac{167L}{day}$$

Therefore 1169L/week

$$v_w = 1169L$$

allowance of 10% is given.

$$V_b = 1169 + (0.1 \times 1169) = 1286L$$

$$V_b = V_1 + V_2$$

For v1

$$V_1 = 0.9V_b = 1.17m^3$$

$$H = 1.75D = 1.75(2r) = 3.5r$$

$$V = \pi r^2 H$$

$$1.17 = \pi(r^2)(3.5r)$$

$$1.17 = \pi 3.5r^3$$

$$r = \sqrt[3]{\frac{1.15}{\pi \times 3.5}} = 0.47\ m$$

$$D = 2r = 2(0.47) = 0.94m$$

$$H = 3.5r = 3.5(0.47) = 1.65m$$

For V2

$$V_2 = 0.1V_b$$

$$V = \frac{1}{3}\pi r^2 h$$

$$0.13 = \frac{1}{3}\pi(0.47)^2 h$$

$$h = 0.56$$