Addis Ababa University

School of Graduate Studies

Faculty of Technology

Chemical Engineering Department

Environmental Engineering Stream

ANAEROBIC CO-DIGSTION OF SEWAGE SLUDGE AND ABATTOIR WASTES TO ENHANCE BIOGAS PRODUCTION

By

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OPTIMIZATION AND DESIGN OF BIOGAS DIGESTER FOR THE CO-DIGESTION OF SEWAGE SLUDGE AND ABATTOIR WASTES

A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the Degree of Masters of Science in Environmental Engineering

By

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Advisor: Eng. Teshome Worku

June, 2010

Addis Ababa, Ethiopia

DECLARATION

I, the undersigned, declare that this thesis entitled "Optimization and Design of Biogas Digester for the Co- Digestion of Sewage Sludge and Abattoir Wastes" is my original work, and has not been presented by any other person for an award of a degree in this or any other University.

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Date of submission: June, 2010

Place: Addis Ababa, Ethiopia

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Acronym

AAAE	Addis Ababa Abattoirs Enterprise
AAWSA	Addis Ababa Water Supply Authority
AD	Anaerobic digestion
APHA	American Public Health Association
AU	African Union
AW	Abattoir Waste
BOD	Biochemical Oxygen Demand
BOD_5	5-day Biological Oxygen Demand
BOD_u	Ultimate BOD
BMP	Biochemical Methane Potential
Btu	British thermal unit
COD	Chemical Oxygen Demand
DAF	Dissolved air floatation
DM	Dry matter
DO	Dissolved oxygen
EB	Energy balance
EGSB	Expanded Granular Sludge Bed
EPA	Environmental protection agency
GA	Gas Analyzer
GHG	Greenhouse gas
HRT	Hydraulic retention time
Kcal	kilocalories
MB	Material/mass balance
NBP	National Biogas Program
OLR	Organic loading rate
OM	Organic matter
OMR	Organic matter reduction
pH	Negative logarithm of hydrogen ion concentration
POP	Persistent organic pollutant

PVC	Poly vinyl chloride
RMP	Red mud plastic
SRT	Solids retention time
SS	Sewage Sludge
TDS	Total dissolved solids
TOC	Total organic carbon
TOD	Total oxygen demand
TS	Total solid
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNICEF	United Nations Children's Fund
UNIDO	United Nations Industrial Development Organization
UNEP	United Nations environment program
USEPA	United States Environmental protection agency
UV	Ultra violet
VFA	Volatile fatty acids
VOCs	Volatile organic carbons
VS	Volatile solid
VSS	Volatile suspended solids
WT	Wet matter

Abstract

Concerns about the managing of sewage sludge for an ever increasing trends of sewage sludge generation coupled with the complex sludge characteristics is a big challenge for Addis Ababa Water Supply Authority. Accumulation of large volumes of dried sludge (cake) in treatment compound has become common. Since sewage sludge contains toxic pollutants and disease-causing organisms and the failure to properly manage sewage sludge may have adverse effects on human health and the environment. As a result, the city water supply authority has to search for holistic and systematic ways of managing it. In this study, a lab scale batch anaerobic co-digestion of sewage sludge and abattoir wastes under mesophilic condition for 20 days was used to digest sewage sludge taken from Kaliti dump site and reduction in volume of the wastes as a result of anaerobic digestion, production of methane and soil conditioner potential were analyzed. Abattoir wastes were co-digested with sewage sludge so as to enhance its nutrient values. 100% SS, 80%SS:20%WA and 60%SS: 40%AW mix ratio were used to analysis the biogas productivities of different mix ratios and 33.8%, 48.3% and 56.9% methane were obtained for SS alone, 80%SS:20%AW and 60%SS: 40%AW respectively. Reductions in volume of the sludge after digestion were also seen as the mix ratio increases. The obtained results are generally consistent with the data from literature where co-digestion of sewage sludge with other substrates rather than abattoir wastes were used.

Key words: Biogas, Sewage sludge, abattoir waste, co-digestion

1. Introduction

1.1. Background

Sewage sludge is a thick sludge of solid materials which settle out from wastewater during the treatment process, whether the wastewater is being moved through a home septic system or a commercial sewage treatment plant. Sewage is created by residential, institutional, and commercial and industrial establishments and includes household waste liquid from toilets, baths, showers, kitchens, sinks and so forth that is disposed of via sewers. It is the mix of water and whatever wastes from domestic and industrial life are flushed into the sewer [1].

Every waste produced in our society that can be got rid of down toilets, through dislodging vehicles and drains and that can also be got out of the sewage by a given treatment process will be in the sludge. Sludge is thus inevitably a noxious brew of vastly various and incompatible materials unpredictable in themselves and in the toxicity of their amalgamation, incalculably but certainly wildly dangerous to life.

Fully processed sludge must be disposed of or utilized in some way, and there is a great deal of debate in some regions of the world about appropriate handling for sewage sludge. One major component of sludge is, of course, fecal material, complete with accompanying bacteria. Sewage sludge also contains everything else which ends up in a septic or sewer system, including toilet paper, tampons, and a wide variety of other materials such as food, chemical waste, and so forth. This is one of the problems with sewage sludge; pure fecal material can be processed and reused fairly easily, but sludge can be heavily contaminated, which may make it dangerous to handle.

Under normal conditions, sewage sludge will rapidly undergo anaerobic fermentation, with bacteria which thrive in an oxygen-free environment breaking down the sludge. This is sometimes used alone for processing, but sewage sludge can also be chemically treated. The treatment process also involves allowing evaporation to occur so that the sludge becomes more solid, with less liquid, making it lighter and easier to handle. Evaporated sludge may be palletized for convenience.

One use of sludge is in agriculture. Although the use of fecal material on food crops may be restricted in some areas, sludge can be used to fertilize landscaping, and can in fact make an excellent alternative to chemical fertilizers which might otherwise be used to fertilize landscaping. Sewage sludge is, after all, rich in nutrients, and there is a long history of using human waste in agriculture throughout the world. Sludge can also be containerized, or buried, with burial involving dried sewage sludge to limit the amount of space required.

Concerns about the use of sewage sludge revolve around ingredients other than fecal material which it might contain. For example, sludge often contains traces of prescription medications such as antibiotics, which could breed antibiotic resistance if untreated sludge was introduced to the environment, along with hormones and other drugs which may be harmful. It can also contain heavy metals, toxic chemicals, and a variety of other substances which could be dangerous. Heavy treatment can potentially make sludge more dangerous by adding chemicals, and deplete it of nutrients, making it less suitable as a fertilizer. [2]

Addis Ababa, a chartered City, located at the coordinates of 9°1′48″N 38°44′24″E/ 9.03°N 38.74°E/ 9.03; 38.74, is the capital of Africa in general and that of Ethiopia in particular, having 527,685,943 m^2 areas with an average temperature of 16^oC, diplomatic capital for Africa (AU, ECA), regional head quarters like UNDP, UNICEF, UNHCR, and FAO. The population of the city is estimated to be 3 to 4 million living in 10 sub-cities and 204 kebeles divided for administrative purpose (AASBPA, 2003). The fast population growth, uncontrolled urbanization and industrialization, poor sanitation situation, uncontrolled waste disposal etc...are causing somber health problems on the population of the city and neighboring [3].

Modern sewerage service started since 1974 during which wastewater treatment plant at Kaliti was constructed and has been giving service for sewer system; the treatment plant was designed to have capacity of 7500 m^3/ d. During 1990 seven sludge drying beds with design capacity of 30,000 m^3, eight ponds and one lagoon were constructed.

At present, water supply for the city accounts 230,000 m^3/d; from this 30% is expected to be lost in different ways and only 161,000m^3 is used. 80% of the used water estimated to be wastewater which is 128,800$m^{3.}$ [1,5] .From this amount of wastewater generated in Addis Ababa, 7000m^3 through sewer system, 844m^3 private and government dislodging service for Kaliti and 225 m^3 for Kotebe; totally 8, 629 m^3 wastewater is collected and disposed at these two sites [4].

1.2 Sewage Sludge treatment methods

Sewage can be treated close to where it is created (in septic tanks, biofilters or aerobic treatment systems), or collected and transported via a network of pipes and pump stations to a municipal treatment plant. Sewage collection and treatment is typically subject to local, state and federal regulations and standards.

Conventional sewage treatment may involve three stages, called primary, secondary and tertiary treatment. Primary treatment consists of temporarily holding the sewage in a quiescent basin where heavy solids can settle to the bottom while oil, grease and lighter solids float to the surface. The settled and floating materials are removed and the remaining liquid may be discharged or subjected to secondary treatment. Secondary treatment removes dissolved and suspended biological matter. Secondary treatment is typically performed by indigenous, water-borne micro-organisms in a managed habitat. Secondary treatment may require a separation process to remove the micro-organisms from the treated water prior to discharge or tertiary treatment. Tertiary treatment is sometimes defined as anything more than primary and secondary treatment. Treated water is sometimes disinfected chemically or physically (for example by lagoons and microfiltration) prior to discharging into a stream, river, bay, lagoon or wetland, or it can be used for the irrigation of a golf course, green way or park. If it is sufficiently clean, it can also be used for groundwater recharge or agricultural purposes [5].

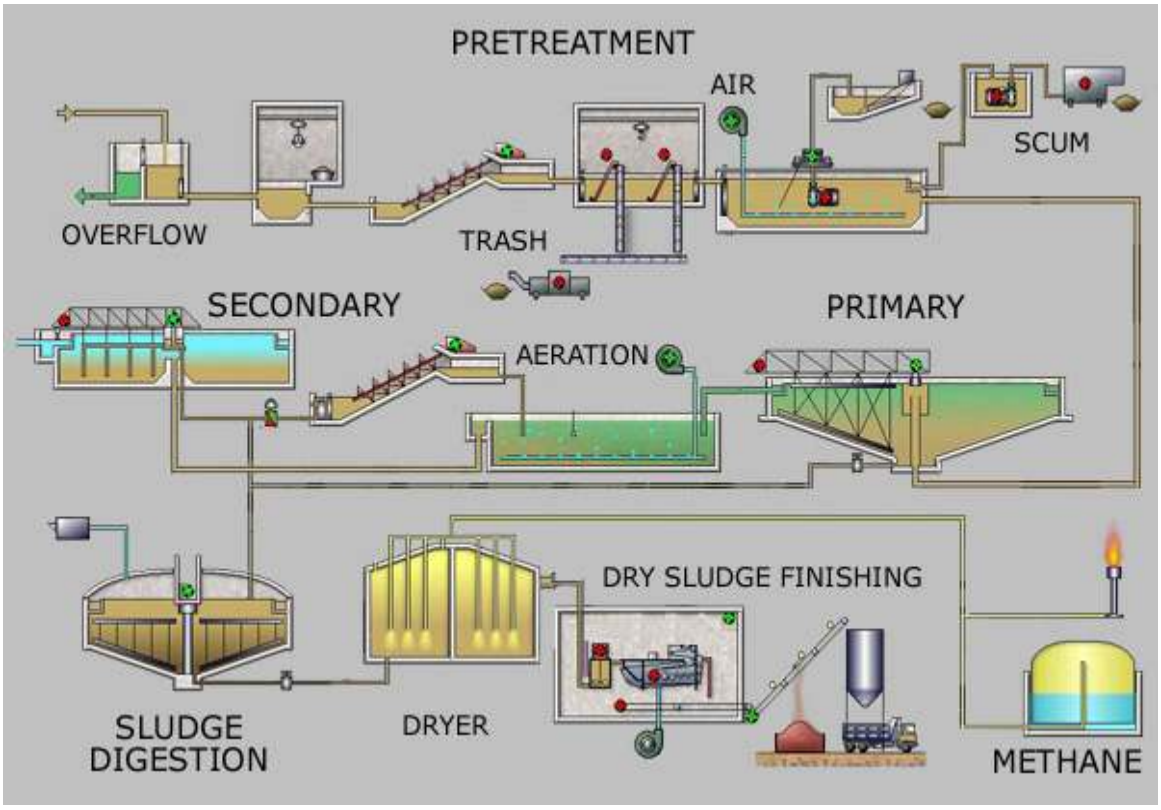

Fig. 1.1. Process Flow Diagram for a typical large-scale treatment plant

As sewage often contains toxic chemicals and pathogens, safe disposal of wastewater treatment sludge is important. Typically disposal consists of treating the sludge through anaerobic digestion, dewatering the resulting biosolids to form sludge cakes, and then sending the sludge cakes to a landfill. Anaerobic digestion occurs in an airtight tank wherein bacteria feed on the organic matter in the sludge in an oxygen-free environment. The gases produced by this digestion process can sometimes be harnessed to create biogas, a renewable energy source used in heating or vehicle propulsion [6].

Aerobic digestion or bacteria-aided decomposition in an oxygenated environment, of wastewater treatment sludge can also be used. While faster than anaerobic digestion, aerobic digestion is more expensive to operate because it is so energy intensive. On small scale sites, composting can also be used to treat sludge. Composting mixes waste with organic materials high in carbon, such as wood or straw, and allows aerobic bacteria

digestion. The process results in heat production and biosolids that can sometimes be used as fertilizer, depending on the content of the waste and the local regulations.

Anaerobic wastewater treatment uses biological agents in an oxygen-free environment to remove impurities from wastewater. After undergoing such a treatment, water can be safely released back into the environment. The biological agents used in the process are microorganisms that consume or break down biodegradable materials in sludge, or the solid portion of wastewater following its filtration from polluted water [1].

Anaerobic wastewater treatment is also known as anaerobic digestion due to the action of the microorganisms. That is, they are essentially "digesting" the polluted parts of the water. An excellent way to decrease the amount of organic matter leftover in things such as sewage and leftover food, anaerobic digestion is typically a component of any biological wastewater treatment system. It is this treatment method of sewage sludge which is in focus in this experimental study.

Usually, the anaerobic process takes place in sealed tanks, located either above or below the ground. During the initial stages of the sludge breakdown, the microorganisms, which are mostly bacteria, convert the waste into organic acids, ammonia, hydrogen and carbon dioxide. In the final stages of anaerobic wastewater treatment, the remains of the sludge are converted, by a single-celled microorganism known as a methanogens, into a biogas consisting of methane and carbon dioxide.

An additional benefit of anaerobic wastewater treatment is its reduction of gas emissions. The biogas that results from the anaerobic wastewater treatment may actually be harnessed and used as an alternative power source for cooking, lighting, heating and engine fuel. In other words, by capturing and utilizing the methane and carbon dioxide produced by anaerobic digestion, the biogas is not released into the atmosphere.

Two types of sludge disposal systems are in operation at Kaliti site of AAWSA wastewater treatment. The first one is the sewage sludge that comes through sewer line with daily capacity of 7500m^3. The second one is the sewage sludge dislodging service by government and non-government vehicles. At Kaliti site, dumping of the sludge (from the

2nd type) takes place at two different dumping sites depending from where the sludge is sucked. Those sewage sludge sucked from the toilet are directly dumped on to drying beds while those taken from septic tanks are dumped in to aerobic digester.

The treatment process for sewage through sewer is pond system having screen, grit chamber, stabilization ponds, and recirculation station. The two line stabilization pond each has four stages: facultative pond, maturation pond, polishing I pond, and polishing II pond. The effluent from such treating system directly released in to little Akaki river and the sludge stored in the compound on open field as dry cake.

Addis Ababa Abattoirs Enterprise discharges about 31,639 kg of solid and liquid wastes per year. Analysis of the effluents of Addis Ababa Abattoirs Enterprise indicated that, the wastewater is highly contaminated with organic compounds analyzed by using the parameters chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), total dissolved solids (TDS), and volatile suspended solids (VSS). In addition, the concentrations of nutrients were analyzed (ammonium nitrogen NH_4-N, phosphate PO_4^{3-} , nitrate NO_3^-). This waste, however, contain substantial nutrients and organics which can be considered as a recoverable natural resource [3, 4].

1.3. Experiences of some countries in treating sewage sludge

Different countries have different sewage sludge treatment policies depending on the end use of the wastewater and sludge. There is no process which completely eliminates the requirements for disposal of biosolids. In South Australia, after centrifugation, the sludge is then completely dried by sunlight. The nutrient rich biosolids are then provided to farmers' free-of-charge to use as natural fertilizers. This method has reduced the amount of landfill generated by the process each year [6].

In the very large metropolitan areas of southern California inland communities return sewage sludge to the sewer system of communities at lower elevations to be reprocessed at a few very large treatment plants on the Pacific coast. This reduces the required size of interceptor sewers and allows local recycling of treated waste-water while retaining the economy of a single sludge processing facility. In the United States, anaerobic wastewater

treatment is usually part of a municipal wastewater treatment plant. Still, anaerobic digestion is also used by single-family homes in areas not connected to a municipal system and by businesses with on-site wastewater treatment facilities.

1. 4. Statement of the Problem

The search for a systematic management of an ever increasing trends of sewage sludge generation coupled with the complex sludge characteristics is a big challenge for Addis Ababa Water Supply Authority (AAWSA) to manage such biosolids. Accumulation of large volumes of dried sludge (cake) in treatment compound has become common. These might have immediate public health implications, which are manifested as frequent outbreak of major epidemic diseases like 'Atet'

Currently, open disposal of sewage sludge dislodged from individual residence after dewatered using evaporative lagoon is the usual main disposal route and is not given an early critical emphasis on its stability and behavior even though it is known to create detrimental environmental consequences, which could affect the health and lives of all living creatures.

The rapid increase and accumulation of sewage sludge in treatment plant compound and its associated risk to human health is principal concern. The waste composition is characterized by high fraction of biodegradable organic material that is potentially recyclable for energy production. At present, there are no recycling programs in place to exploit this organic fraction but instead hauled into the compound and dried on the prepared drying beds nonetheless others are treated through lagoon treatment (specially during rainy seasons) of the incoming sewage, resulting in negative impacts on both human health and the environment.

Uncontrolled anaerobic digestion takes place releasing leachate into groundwater and emission of potential greenhouse gases such as methane and carbon dioxide into the atmosphere. More to the point, disease causing bacteria and foul odour are also released from the decomposing materials into the environment resulting in increased cases of cholera, diarrhoea, intestinal worms and upper respiratory diseases.

At present, the acceptable method of disposal of sludge or residue in the study area is open dumping. The troubling part of such disposal situation is that, they are just dumpsites and are not engineered so wastes are dumped; therefore, these dump sites will not be able to accommodate increased amounts of residue or sewage sludge in the future. The socio-criticism of the near by farmers should also have to be considered. The water from the ponds that join the near by little Akaki river has been causing severe impacts on the heath, and livelihood of the neighboring populations.

Fig.1.2. Waste channel into the Little Akaki River from Kaliti waste water treatment site

1. 5. Objectives

1. 5.1. General Objective

The general objective of this study is to enhance biogas production from anaerobic digestion of sewage sludge using abattoir wastes as nutrient supplementation.

1. 5.2. Specific Objectives

The specific objectives of this study are to:

I. determine raw Sewage Sludge and raw abattoir compositions
II. investigate optimum mixing ratio for maximum methane production
III. design anaerobic digester for optimum production of biogas and
IV. evaluate the organic and nutrient load reduction

1.6. Significance of the Study

By reduction of the organic fraction of sludge stream, it is possible to reduce emissions, leachets and also to recover valuable by-products like biogas for energy conversion. The remaining stabilized material after treatment can be used as soil conditioner or land filled. This study helps to address the critical problems of sewage sludge managements the city has been facing. It also establishes data base for further investigating anaerobic digestion as other option to solve similar problems in other parts of the country. In addition to these significances, the study evaluates the potential value of co-digestion of sewage sludge and abattoir wastes as, a soil conditioner and a fuel.

2. Literature Review

Sewage is created by residential, institutional, and commercial and industrial establishments and includes household waste liquid from toilets, baths, showers, kitchens, sinks and so forth that is disposed of via sewers. In many areas, sewage also includes liquid waste from industry and commerce. Sewage treatment, or domestic wastewater treatment, is the process of removing contaminants from wastewater and household sewage, both runoff (effluents) and domestic. It includes physical, chemical, and biological processes to remove physical, chemical and biological contaminants. Its objective is to produce a waste stream (or treated effluent) and a solid waste or sludge suitable for discharge or reuse back into the environment. The implementation of wastewater treatment plants has been so far a challenge for most countries. Economical resources, political will, institutional strength and cultural background are important elements defining the trajectory of pollution control in many countries [6].

Technological aspects are sometimes mentioned as being one of the reasons hindering further developments. However, the vast array of available processes for the treatment of wastewater should be seen as an incentive, allowing the selection of the most appropriate solution in technical and economical terms for each community or catchments area. For almost all combinations of requirements in terms of effluent quality, land availability,

construction and running costs, mechanization level and operational simplicity there will be one or more suitable treatment processes.

Compared to convectional aerobic wastewater treatment systems, anaerobic treatment process merely offers advantages. This is especially true for the rate of start-up. The available insight in anaerobic sludge immobilization (i.e. granulation) and growth of granular anaerobic sludge in many respects suffices for practice. In anaerobic treatment, the immobilization of balanced microbial communities is essential, because the concentration of intermediates then can be kept sufficiently low.

Anaerobic wastewater treatment can also profitably be applied in the thermophilic and psychrophilic temperature ranges. Moreover, thermophilic anaerobic sludge can be used under mesophilic conditions. The Expanded Granular Sludge Bed (EGSB) system particularly offers big practical potentials, e.g. for very low strength wastewaters (COD <<1.00g/l) and at temperatures as low as 10° C. In EGSB-systems virtually all the retained sludge is employed, while compared to UASB-systems also a substantially bigger fraction of the immobilized organisms (inside the granules) participates in the process, because an extraordinary high substrate affinity prevails in these systems. It looks necessary to reconsider theories for mass transfer in immobilized anaerobic biomass [6].

2.1. Wastewater Characteristics

Wastewater quality can be defined by physical, chemical, and biological characteristics. Physical parameters include color, odor, temperature, solids (residues), turbidity, oil, and grease. Solids can be further classified into suspended and dissolved solids (size and settleability) as well as organic (volatile) and inorganic (fixed) fractions. Chemical parameters associated with the organic content of wastewater include the biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), and total oxygen demand (TOD). BOD is a measure of the organics present in the water, determined by measuring the oxygen necessary to biostabilize the organics (the oxygen equivalent of the biodegradable organics present). Inorganic chemical parameters include

salinity, hardness, pH, acidity, alkalinity, iron, manganese, chlorides, sulfates, sulfides, heavy metals (mercury, lead, chromium, copper, and zinc), nitrogen (organic, ammonia, nitrite, and nitrate), and phosphorus. Bacteriological parameters include coliforms, fecal coliforms, specific pathogens, and viruses [6, 8].

Table 2.1 shows the typical concentration range of various constituents in untreated domestic wastewater. Depending on the concentrations, wastewater is classified as strong, medium, or weak. Table 2.2 shows typical mineral increases resulting from domestic water use. The types and numbers of microorganisms in untreated domestic wastewater vary widely; examples of such variations are shown in Table 2.3.

Table 2.1. Typical composition of untreated domestic wastewater

Contaminants	units	concentration		
		Weak	Medium	Strong
Total solids (TS)	mg/l	350	720	1200
Total dissolved solids (TDS)	mg/l	250	500	850
Volatile	mg/l	105	200	325
Suspended Solids (SS)	mg/l	100	220	350
BOD_5	mg/l	110	220	400
TOC	mg/l	80	160	290
COD	mg/l	250	500	1000

Nitrogen (total as N)	mg/l	20	40	85
Nitrogen as organic	mg/l	8	15	35
Nitrogen as free ammonia	mg/l	12	25	50
Nitrogen as nitrites	mg/l	0	0	0
Nitrogen as nitrates	mg/l	0	0	0
Phosphorus (total as P)	mg/l	4	8	15
Phosphorus as organic	mg/l	1	3	5
Phosphorus as inorganic	mg/l	3	5	10
Chloridesa	mg/l	30	50	100
Sulfatea	mg/l	20	30	50
Alkalinity (as $CaCO_3$)	mg/l	50	100	200
Grease	mg/l	50	100	150
Total coliform	no/100 ml	106–107	107–108	107–109
(VOCs)	µg/l	<100	100–400	>400

Table 2.2. Typical mineral increase from domestic wastewater

Constituent	Increment Range, mg/l
Anions	
Bicarbonate (HCO_3^-)	50–100
Carbonate (CO_3^{-2})	0–10
Chloride (Cl^-)	20–50
Nitrate (NO^-_3)	20–40
Phosphate (PO_4^{-3})	5–15
Sulfate (SO^{-2}_4)	15–30
Cations	
Calcium (Ca^{+2})	6–16
Magnesium (Mg^{+2})	4–10
Potassium (K^+)	7–15
Sodium (Na^+)	40–70
Other constituents	
Aluminum (Al)	0.1–0.2
Boron (B)	0.1–0.4
Fluoride (F^-)	0.2–0.4
Manganese (Mn)	0.2–0.4
Silica (SiO_2)	2–10
Total alkalinity (as $CaCO_3$)	60–120
TDS	150–380

Table 2.3. Types and number of microorganisms typically found in the untreated domestic wastewater

Organism	Concentration ,number/ml
Total coliform	10^5–10^6
Fecal coliform	10^4–10^5
Fecal streptococci	10^3–10^4
Enterococci	10^2–10^3
Shigella	Present[a]
Salmonella	100–10^2
Pseudomonas aeroginosa	10^1–10^2
Clostridium perfringens	10^1–10^3
Mycobacterium tuberculosis	Present[a]
Protozoan cysts	10^1–10^3
Giardia cysts	10^{21}–10^2
Cryptosporidium cysts	10^{21}–10^1
Helminth ova	10^{22}–10^1
Enteric virus	10^1–10^2

Note: [a]Results for these tests are usually reported as positive or negative rather than quantified.

The TS content of wastewater can be defined as the matter that remains as residue upon evaporation at 103 to 105°C. Table 2.4 shows particle sizes related to different categories. Clesceri, Greenberg, and Trussell (1989) provide detailed information related to testing procedures.

Table 2.4. General classifications of wastewater solids

Particle Classification	Particle Size, mm
Dissolved	Less than 10^{26}
Colloidal	10^{26} to 10^{23}
Suspended	Greater than 10^{23}
Settleable	Greater than 10^{22}

Odors in wastewater are caused by gases from decomposition or by odorous substances within the wastewater. Table 2.5 lists examples of odorous compounds associated with untreated wastewater. Organic matter in wastewater can be related to oxygen demand and organic carbon measurements. Table 2.6 shows several measures of organic matter. BOD refers to the amount of oxygen used by a mixed population of microorganisms under aerobic conditions that stabilize organic matter in the wastewater. The 5-day BOD is primarily composed of carbonaceous oxygen demand, while the 20-day BOD includes both carbonaceous and nitrogenous oxygen demands.

Table 2.5. Odorous compounds associated with untreated wastewater

Odorous Compound	Chemical Formula	Odor, Quality
Amines	CH_3NH_2, $(CH_3)_3H$	Fishy
Ammonia	NH_3	Ammoniacal
Diamines	$NH_2(CH_2)_4NH_2$, $NH_2(CH_2)_5NH_2$	Decayed flesh
Hydrogen sulfide	H_2S	Rotten eggs
Mercaptans (e.g., methyl and ethyl)	CH_3SH, $CH_3(CH_2)SH$	Decayed cabbage
Mercaptans (e.g., *T* 5 butyl and crotyl)	$(CH_3)_3CSH$, $CH_3(CH_2)_3SH$	Skunk
Organic sulfides	$(CH_3)_2S$, $(C_6H_5)_2S$	Rotten cabbage
Skatole	C_9H_9N	Fecal matter

Table 2.6. Oxygen demand and organic carbon parameters

Parameter	Description
BOD_5	Biochemical or biological oxygen demand exerted in 5 days; the oxygen consumed by a waste through bacterial action; generally about 45–55% of THOD.
COD	Chemical oxygen demand. The amount of strong chemical oxidant (chromic acid) reduced by a waste; results are expressed in terms of an equivalent amount of oxygen; generally about 80% of THOD
THOD	Theoretical oxygen demand. The amount of oxygen theoretically required to completely oxidize a compound to CO_2, H_2O, PO_4^{-3}, SO_4^{-2}, and NO^-_3.
TOC	Total organic carbon; generally about 30% of THOD.
BODu	The ultimate BOD exerted by a waste in an infinite time.
IOD	Immediate oxygen demand. The amount of oxygen consumed by a waste within 15 min (chemical oxidizers and bacteria not used)

For medium-strength domestic wastewater, about 75% of SS and 40% of FS are classified as organic. The main groups of organic substances in wastewater include proteins (40–60%), carbohydrates (25–50%), and fats and oils (10%) [1]. Urea, a constituent of urine, is also found in wastewater along with numerous synthetic organic compounds. Synthetic compounds include surfactants, organic priority pollutants, VOCs, and agricultural pesticides [5].

The U.S. Environmental Protection Agency (EPA) has identified 129 priority pollutants in wastewater; these pollutants are subject to discharge standards. Examples of priority pollutants and their health-related concerns are listed in Table 2.7.

Pathogenic organisms in wastewater can be categorized as bacteria, viruses, protozoa, and helminthes; Table 2.8 lists examples of such organisms present in raw domestic wastewater. Because of the many types of pathogenic organisms and the associated measurement difficulties, coliform organisms are frequently used as indicators of human pollution. On a daily basis, each person discharges from 100 to 400 billion coliform organisms, in addition to other kinds of bacteria [1]. In terms of the indicator concept, the

presence of coliform organisms indicates that pathogenic organisms may also be present, and their absence indicates that the water is free from disease-producing organisms. Total coliform and fecal coliform are often used as indicators of wastewater effluent disinfection.

Table 2.7. Typical waste compounds produced by commercial, industrial and agricultural activities and classified as priority pollutants

Name (Formula)	Use	Concern
Nonmetals		
Arsenic (As)	Alloying additive for metals, especially lead and copper as shot, battery grids, cable sheaths, and boiler tubes. High purity (semiconductor) grade	Carcinogen and mutagen. Long term—can cause fatigue, loss of energy and dermatitis.
Selenium (Se)	Electronics, xerographic plates, TV cameras, photocells, magnetic computer cores, solar batteries, rectifiers, relays, ceramics (colorant for glass) steel and copper, rubber accelerator, catalyst, and trace element in animal feeds	Long term—red staining of fingers, teeth, and hair; general weakness; depression; and irritation of the nose and mouth.
Metals		
Barium (Ba)	Getter alloys in vacuum tubes, deoxidizer for copper, Frary's metal, lubricant for anode rotors in	Flammable at room temperature in powder form. Long term—increased blood pressure and nerve

	X-ray tubes, and spark-plug alloys	block.
Cadmium (Cd)	Electrodeposited and dipped coatings on metals, bearing and low-melting alloys, brazing alloys, fire protection systems, nickel-cadmium storage batteries, power transmission wire, TV phosphors, basis of pigments used in ceramic glazes, machinery enamels, fungicide photography and lithography, selenium rectifiers, electrodes for cadmium-vapor lamps, and photoelectric cells	Flammable in powder form. Toxic by inhalation of dust or fume. A carcinogen. Soluble compounds of cadmium highly toxic. Long term—concentrates in the liver, kidneys, pancreas, and thyroid; hypertension suspected effect.
Chromium (Cr)	Alloying and plating element on metal and plastic substrates for corrosion resistance, chromium-containing and stainless steels, protective coating for automotive and equipment accessories, nuclear and high-temperature research and constituent of inorganic pigments	Hexavalent chromium compounds are carcinogenic and corrosive to tissue. Long term—skin sensitization and kidney damage.
Mercury (Hg)	Amalgams, catalyst electrical apparatus,	Highly toxic by skin absorption and inhalation of

	cathodes for production of chlorine and caustic soda, instruments, mercury vapor lamps, mirror coating, arc lamps, and boilers	fume or vapor. Long term—toxic to central nervous system, and can cause birth defects.
Silver (Ag)	Manufacture of silver nitrate, silver bromide, photo chemicals; lining vats and other equipment for chemical reaction vessels, water distillation, etc.; mirrors, electric conductors, silver plating electronic equipment; sterilant; water purification; surgical cements; hydration and oxidation catalyst special batteries, solar cells, reflectors for solar towers; low-temperature brazing alloys; table cutlery; jewelry; dental, medical, and scientific equipment; electrical contacts; bearing metal; magnet windings; and dental amalgams. Colloidal silver used as a nucleating agent in photography and medicine, often combined with protein	Toxic metal. Long term—permanent grey discoloration of skin, eyes, and mucus membranes.

Lead (Pb)	Storage batteries, gasoline additive, cable covering, ammunition, piping, tank linings, solder and fusible alloys, vibration damping in heavy construction, foil, babbit, and other bearing alloys	Toxic by ingestion or inhalation of dust or fumes. Long term— brain and kidney damage and birth defects.
Organic Compounds		
Benzene (C_6H_6)	Manufacturing of ethylbenzene (for styrene monomer); dodecylbenzene (for detergents); cyclohexane (for nylon); phenol; nitrobenzene (for aniline); maleic anhydride; chlorobenzene hexachloride; benzene sulfonic acid; and as a solvent	A carcinogen. Highly toxic. Flammable, and a dangerous fire risk
Ethylbenzene ($C_6H_5C_2H_5$)	Intermediate in the production of styrene and as a solvent	Toxic by ingestion, inhalation, and skin absorption; irritant to skin and eyes. Flammable and a dangerous fire risk Flammable and a dangerous fire risk. Toxic by ingestion, inhalation, and skin absorption
Toluene ($C_6HC_5H_3$)	Aviation gasoline and high-	Flammable and a dangerous

	octane blending stock; benzene, phenol, and caprolactam; solvent for paints and coatings, gums, resins, most oils, rubber, vinyl organosols; diluent and thinner in nitrocellulose lacquers; adhesive solvent in plastic toys and model airplanes; chemicals (benzoic acid, benzyl and bezoyl derivatives, saccharine, medicines, dyes, perfumes); source of toluenediisocyanates (polyurethane resins); explosives (TNT); toluene sulfonates (detergents); and scintillation counters	fire risk. Toxic by ingestion, inhalation, and skin absorption
Halogenated Compounds		
Chlorobenzene (C_6H_5Cl)	Phenol, chloronitrobenzene, aniline, solvent carrier for methylene diisocyanate, solvent, pesticide intermediate, heat transfer	Moderate fire risk. Recommend avoiding inhalation and skin contact
Chloroethene (CH_2CHCl)	Polyvinyl chloride and copolymers, organic synthesis, and adhesives for plastics	An extremely toxic and hazardous material by all avenues of exposure. A carcinogen
Dichloromethane (CH_2Cl_2)	Paint removers, solvent	Toxic. A carcinogen and a

	degreasing, plastics processing, blowing agent in foams, solvent extraction, solvent for cellulose acetate, and aerosol propellant	narcotic
Tetrachloroethene (CCl_2CCl_2)	Dry cleaning solvent, vapor-degreasing solvent, drying agent for metals and certain other solids, vermifuge, heat transfer medium, and manufacture of fluorocarbons	Irritant to eyes and skin
Pesticides, Herbicides, Insecticides		
Endrin ($C1_2H_6OCl_6$)	Insecticide and fumigant	Toxic by inhalation and skin absorption and a carcinogen
Lindane ($C_6H_6Cl_6$)	Pesticide	Toxic by inhalation, ingestion, and skin absorption
Methoxychlor ($Cl_3CCH(C_6H_4OCH_3)_2$)	Insecticide	Toxic material
Toxaphene ($C_{10}H_{10}Cl_6$)	Insecticide and fumigant	Toxic by ingestion, inhalation, and skin absorption
Silvex ($Cl_3C_6H_2OCH(CH_3)COOH$)	Herbicides and plant growth regulator	Toxic material; use restricted

Table 2.8. Infectious agents potentially present in domestic raw wastewater

Organism	Disease	Remarks
Bacteria		
Escherichia coli	Gastroenteritis	Diarrhea
Legionella pneumophila	Legionellosis	Acute respiratory illness
Leptospira (150 spp.)	Leptospirosis	Jaundice, and fever (Weil's disease)
Salmonella typhi	Typhoid fever	High fever, diarrhea, and ulceration of small intestine
Salmonella (,1700 spp.)	Salmonellosis	Food poisoning
Shigella (4 spp.)	Shigellosis	Bacillary dysentery
Vibrio cholerae	Cholera	Extremely heavy diarrhea and dehydration
Yersinia enterolitica	Yersinosis	Diarrhea
Viruses		
Adenovirus (31 types)	Respiratory disease	
Enteroviruses (67 types, e.g., polio, echo, and Coxsackie viruses)	Gastroenteritis, heart anomalies, and meningitis	
Hepatitis A	Infectious hepatitis	Jaundice and fever
Norwalk agent	Gastroenteritis	Vomiting
Protozoa		
Balantidium coli	Balantidiasis	Diarrhea and dysentery
Cryptosporidium	Cryptosporidiosis	Diarrhea
Entamoeba histolytica	Amebiasis (amoebic dysentery)	Prolonged diarrhea with bleeding and abscesses of the liver and small intestine
Giardia lamblia	Giardiasis	Mild to severe diarrhea, nausea, and indigestion
Helminths		

Ascaris lumbricoides	Ascariasis	Roundworm infestation
Enterobius vericularis	Enterobiasis	Pinworm
Fasciola hepatica	Fascioliasis	Sheep liver fluke
Hymenolepis nana	Hymenolepiasis	Dwarf tapeworm
Taenia saginata	Taeniasis	Beef tapeworm
T. solium	Taeniasis	Pork tapeworm

The quality of sewage can be checked and analyzed by studying and testing its physical, chemical and biological characteristics as explained below:

2.1.1. Physical characteristics of sewage

Physical examination of sewage is carried out in order to determine its physical characteristics. These includes: tests for determining turbidity, colour, odour, and temperature [1].

2.1.1.1. Turbidity

Sewage is normally turbid, resembling dirty dish water or wastewater from baths having other floating matter like fecal matter, pieces of paper, cigarette-ends, match sticks, greases, vegetable debris, and fruit skins, soaps etc. the degree of turbidity can be measured and tested by turbidity rods or by turbidimeter.

2.1.1.2. Colour

The colour of sewage can normally be detected by the necked eye, and it indicates the freshness of sewage. If its colour is yellowish, gray, or light brown, it indicates fresh sewage. However, if the colour is black or dark brown, it indicates stale and septic sewage. Other colours, may also be formed due to the presence of some specific industrial wastes.

2.1.1.3. Odour

Fresh sewage is practically odorless. But, however, in 3 to 4 hours, it becomes stale with all oxygen present in sewage being practically exhausted. It then starts omitting offensive

odours, specially that of hydrogen sulphide gas, which is formed due to decomposition of sewage.

2.1.1.4. Temperature

The temperature has an effect on the biological activity of bacteria present in sewage, and it also affects the solubility of gases in sewage. In addition, temperature also affects the viscosity of sewage, which, in turn, affects the sedimentation process in its treatment.

2.1.2. Chemical characteristics of sewage

Testes conducted for determining the chemical characteristics of sewage help in indicating: the stage of sewage decomposition, its strength, and extent and type of treatment required for making it safe to the point of disposal. Chemical analysis is, therefore, carried out on sewage in order to determine its chemical characteristics [9]. It includes tests for determining: total solids, suspended solids, settlable solids, chloride content, pH value, nitrogen content, presence of fats, greases, and oils, sulphides, sulphates and H_2S gases, dissolved oxygen, COD, and BOD.

2.1.2.1. Total solids, suspended solids and settlable solids

Sewage normally contains very small amount of solid in relation to the huge quantity of water. Solids present in sewage may be in any of the four forms: suspended solids, dissolved solids, colloidal solids, and settlable solids. Suspended solids are those solids which remain floating in sewage. Dissolved solids are those which remain dissolved in sewage just as salt in water. Colloidal solids are finely divided solids remaining either in solution or in suspension. Settlable solids are that portion of solid matter which settles out, if sewage is allowed to remain undisturbed for a period of two hours.

2.1.2.2. Chloride contents

Chlorides are generally found in municipal sewage, and are derived from the kitchen wastes, human faces, and urinary discharges etc. The normal chloride content of domestic sewage is 120mg/l, where as the permissible chloride content for water supplies is 250mg/l. The chloride content can be measured by titrating the wastewater with standard

silver nitrate solution, using potassium chromate as indicator, as is done for testing water supplies.

2.1.2.3. pH value

The pH value of sewage indicates the negative log of hydrogen ion concentration present in sewage. pH = -log H^+ .It is, thus, an indicator of the alkalinity of sewage. If the pH value is less than 7, the sewage is acidic, and if the pH value is greater than 7, the sewage is alkaline. The determination of pH value of sewage is important, because of the fact that efficiency of certain treatment methods depends upon the availability of a suitable pH value. The pH value can be measured quickly and automatically with the help of potentiometer, which measure the electrical potential exerted by the hydrogen ions, and thus indicating their concentration.

2.1.2.4. Nitrogen contents

The presence of nitrogen in sewage indicates the presence of organic matter, and may occur in one or more of the following forms: free ammonia, called ammonia nitrogen, albuminoid nitrogen, called organic nitrogen, nitrates and nitrites. All these different forms of nitrogen, present in sewage, can be tested and measured easily as given below: the amount of free ammonia present in sewage can be measured by simply boiling the sewage, and measuring the ammonia gas which is consequently librated. The amount of organic nitrogen can be measured by adding strong alkaline solution of potassium permanganate ($KMnO_4$) to the already boiled sewage sample and again boiling the same, when ammonia gas is librated, which is measured, so as to indicate the amount of organic nitrogen present in sewage. If however, un boiled sample is used to add $KMnO_4$ before boiling, the evolved ammonia gas will measured the sum total ammonia nitrogen as will as organic nitrogen and is known as Kjedahl nitrogen. The amount of nitrates or nitrites present in sewage sample can be developed by adding sulphonilic acid and naphathamine; whereas for nitrates, the colour is developed by adding phenol-di-sulphonic acid and potassium hydroxide [10]. The colour developed in wastewater is finally compared with the standard colours of known concentrations.

2.1.2.5. Presence of fats, oils and greases

Greases, fats and oils are derived in sewage from the discharges of animals and vegetables matter, or from the industries like garages, kitchens of hotels and restaurants, etc. The amount of greases and fats in a sewage sample is determined by making use of the facts that oils and greases are soluble in ether, and when the ether is evaporated, it leaves behind ether-soluble-matter, which represents the quantity of fats and oils. Hence, in order to estimate their amount, a sample of sewage is, first of all, evaporated. The residual solids left are then mixed with ether or hexane. The solution is then poured off and evaporated, leaving behind the fats and greases as residue, which can be easily weighted.

2.1.2.6. Sulphide, Sulphates, and Hydrogen sulphide gas

The determination of sulphides and sulphates in sewage is rarely called far, although their presence reflects aerobic, and/ or anaerobic decomposition. Sulphides and sulphates are formed due to the decomposition of various sulphur containing substances present in sewage. This decomposition also leads to evolution of hydrogen sulphide gas, H_2S, causing bad smells and odours, besides causing corrosion of concrete sewer pipes. In aerobic digestion of sewage, the aerobic and facultative bacteria, oxides the sulphur and its compounds presents in sewage to initially from sulphides, which ultimately break down to form sulphates ions (SO^{-2}_4), which is a stable and an unobjectionable product. In anaerobic digestion of sewage, however, the anaerobic and facultative bacteria reduce the sulphur and its compounds in to sulphides, with evolution of hydrogen sulphides, H_2S gas along with methane and carbon dioxide, thus causing obnoxious smells and odours [5, 6].

2.1.2.7. Dissolved oxygen (DO)

The determination of dissolved oxygen present in sewage is very important, because: while discharging the treated sewage in to river stream, it is necessary to ensure at least 4ppm of DO in it; as otherwise, fish are likely to be killed, creating nuisance near the vicinity of disposal. The DO test performed on sewage before treatment, helps in indicating the condition of sewage. It is well known by now, that only very fresh sewage contains some dissolved oxygen, which is soon depleted by aerobic decomposition. The

DO content of sewage is generally determined by Winkler's method which an oxidation-reduction process is carried out chemically to liberate iodine in amount equivalent to the quantity of DO originally present in the sewage.

2.1.2.8. Chemical oxygen demand (COD)

The organic matter present in water can be measured in a number of ways; volatile solids determination being crude measure of organic matter. Organic matter is most often assessed in terms of oxygen required to completely oxidize the organic matter to carbondioxide, water and other oxidized species. The oxygen required to oxidize the organic matter present in a given wastewater can be theoretically computed, if the organics present in wastewater are known. Thus, if the chemical formulas and the concentrations of the chemical compounds present in water are known to us, we can easily calculate the theoretical oxygen demand of these compounds by writing the balanced reaction for the compound with oxygen to produce CO_2, H_2O and oxidized inorganic components. The COD of a raw wastewater is therefore, determined by performing a laboratory test on the given wastewater with strong oxidant like dichromate solution; and the theoretical computations of COD are only performed on water solutions prepared with the known amounts of specific organic compounds in laboratory situations to compare the theoretical and test results, and to establish the limitations of the test procedures [11].

2.1.2.9. Total Organic carbon (TOC)

Another important method of expressing organic matter is in terms of its carbon content. Carbon is the primary constituent of organic matter, and hence the chemical formula of every organic compound will reflect the extent of carbon present in that compound. Known concentrations of such chemical compounds in a given wastewater will thus enable us to theoretically calculate the carbon present in that wastewater per liter of solution.

2.1.2.10. Biochemical Oxygen Demand (BOD)

The organic matter, infact, is of two types; i.e. that which is biologically oxidized (i.e. oxidized by bacteria) and is called biologically active or biologically degradable; and that which can not be oxidized biologically and is called biologically inactive. If sufficient oxygen is available in wastewater, the useful aerobic bacteria will flourish and cause the aerobic biological decomposition of wastewater, which will continue until oxidation is completed. The amount of oxygen consumed in this process is the BOD. The BOD of during 5 days at 20^{o}C is generally taken as standard demand and is written as BOD_5, or simply as BOD. It is determined in the laboratory by mixing or diluting a known volume of a sample of wastewater with a known volume of aerated pure water, and then calculating the DO of this diluted sample. The diluted water is then incubated for 5 days at 20^{o}C. In the following table (Table 2.9), characteristics of sewage sludge from different countries (Ghana, China, Japan, and Korea) are compared [5].

Table 2.9. Comparison of the characteristics of sewage sludge studied in different countries (all in mg/l except pH)

Parameters	Country			
	S.Korea[2]	Ghana[2]	China[2]	Japan[2]
pH				
BOD_5	12,600-19,200	3,800-15,000 (8,800)	15,000 - 18,000	12,900
COD	10,600-15,400	10,400-97,000 (47,600)	26,000 - 33,000	36,700
TS	32,000-44,600	-	12,000 - 30,000	31,400
VS	-	62% of TS	-	20,400
Hem. Eggs (no./l)	-	3,600 - 62,000 (29,000)	18,000 – 360,000	-

Sources: [2]Issac, 2003 [26]

2.2. Wastewater treatment Methods

The processes involved in municipal wastewater treatment plants are usually classified as being part of primary, secondary, or tertiary treatment.

2.2.1. Primary treatment

The wastewater that enters a treatment plant contains debris that might clog or damage the pumps and machinery. Such materials are removed by screens or vertical bars, and the debris is burned or buried after manual or mechanical removal. The wastewater then passes through a comminutor (grinder), where leaves and other organic materials are reduced in size for efficient treatment and removal later [9].

2.2.1.1. Grit chamber

In the past, long and narrow channel-shaped settling tanks, known as grit chambers, were used to remove inorganic or mineral matter such as sand, silt, gravel, and cinders. These chambers were designed to permit inorganic particles 0.2 mm (0.008 in) or larger to settle at the bottom while the smaller particles and most of the organic solids that remain in suspension pass through. Today, spiral-flow aerated grit chambers with hopper bottoms, or clarifiers with mechanical scrapper arms, are most commonly used. The grit is removed and disposed of as sanitary landfill. Grit accumulation can range from 0.08 to 0.23 cu m (3 to 8 cu ft) per 3.8 million liters (about 1 million gallons) of wastewater.

2.2.1.2. Sedimentation

With grit removed, the wastewater passes into a sedimentation tank, in which organic materials settle out and are drawn off for disposal. The process of sedimentation can remove about 20 to 40 percent of the BOD_5 and 40 to 60 percent of the suspended solids. The rate of sedimentation is increased in some industrial waste-treatment stations by incorporating processes called chemical coagulation and flocculation in the sedimentation tank. Coagulation is the process of adding chemicals such as aluminum sulfate, ferric chloride, or polyelectrolytes to the wastewater; this causes the surface characteristics of the suspended solids to be altered so that they attach to one another and precipitate.

Flocculation causes the suspended solids to coalesce. Coagulation and flocculation can remove more than 80 percent of suspended solids.

2.2.1.3. Flotation

An alternative to sedimentation that is used in the treatment of some wastewaters is flotation, in which air is forced into the wastewater under pressures of 1.75 to 3.5 kg per sq cm (25 to 50 lb per sq in). The wastewater, supersaturated with air, is then discharged into an open tank; there the rising air bubbles cause the suspended solids to rise to the surface, where they are removed. Flotation can remove more than 75 percent of the suspended solids.

2.2.1.4. Digestion

Digestion is a microbiological process that converts the chemically complex organic sludge to methane, carbon dioxide, and in offensive humus like material. The reactions occur in a closed tank or digester that is anaerobic—that is, devoid of oxygen. The conversion takes place through a series of reactions. First the solid matter is made soluble by enzymes, and then the substance is fermented by a group of acid-producing bacteria, reducing it to simple organic acids such as acetic acid. The organic acids are then converted to methane and carbon dioxide by bacteria. Thickened sludge is heated and added as continuously as possible to the digester, where it remains for 10 to 30 days and is decomposed. Digestion reduces organic matter by 45 to 60 percent.

2.2.1.5. Drying

Digested sludge is placed on sand beds for air drying. Percolation into the sand and evaporation are the chief processes involved in the dewatering process. Air drying requires dry, relatively warm weather for greatest efficiency, and some plants have a greenhouse like structure to shelter the sand beds [12]. Dried sludge in most cases is used as a soil conditioner; sometimes it is used as a fertilizer because of its 2 percent nitrogen and 1 percent phosphorus content.

2.2.2. Secondary treatment

Having removed 40 to 60 percent of the suspended solids and 20 to 40 percent of the BOD_5 in primary treatment by physical means, the secondary treatment biologically reduces the organic material that remains in the liquid stream. Usually the microbial processes employed are aerobic—that is, the organisms function in the presence of dissolved oxygen. Secondary treatment actually involves harnessing and accelerating nature's process of waste disposal. Aerobic bacteria in the presence of oxygen convert organic matter to stable forms such as carbon dioxide, water, nitrates, and phosphates, as well as other organic materials. The production of new organic matter is an indirect result of biological treatment processes, and this matter must be removed before the wastewater is discharged into the receiving stream. Several alternative processes are also available in secondary treatment, including a trickling filter, activated sludge, and lagoons.

2.2.2.1. Trickling filter

In this process, a waste stream is distributed intermittently over a bed or column of some type of porous medium. A gelatinous film of microorganisms coats the medium and functions as the removal agent. The organic matter in the waste stream is absorbed by the microbial film and converted to carbon dioxide and water [9]. The trickling-filter process, when preceded by sedimentation, can remove about 85 percent of the BOD_5 entering the plant.

2.2.2.2. Activated sludge

This is an aerobic process in which gelatinous sludge particles are suspended in an aeration tank and supplied with oxygen. The activated-sludge particles, known as floc, are composed of millions of actively growing bacteria bound together by a gelatinous slime. Organic matter is absorbed by the floc and converted to aerobic products. The reduction of BOD_5 fluctuates between 60 and 85 percent. An important companion unit in any plant using activated sludge or a trickling filter is the secondary clarifier, which separates bacteria from the liquid stream before discharge.

2.2.2.3. Stabilization pond or Lagoon

Another form of biological treatment is the stabilization pond or lagoon, which requires a large land area and thus is usually located in rural areas. Facultative lagoons, or those that function in mixed conditions, are the most common, being 0.6 to 1.5 m (2 to 5 ft) in depth, with a surface area of several acres [13]. Anaerobic conditions prevail in the bottom region, where the solids are decomposed; the region near the surface is aerobic, allowing the oxidation of dissolved and colloidal organic matter. A reduction in BOD_5 of 75 to 85 percent can be attained.

2.2.3. Advanced wastewater treatment method

Growing quantities of wastewater made enlargements of treatment plants necessary. Then, trying to optimize the costs for running the plants by reducing the precipitation and minimizing the oxygen supply for the biological system in the plant sometimes leads to new problems; from the ecological and biological points of view, optimization can entail undesired side effects. If the receiving body of water requires a higher degree of treatment than the secondary process can provide, or if the final effluent is intended for reuse, advanced wastewater treatment is necessary. The term tertiary treatment is often used as a synonym for advanced treatment, but the two methods are not exactly the same. Tertiary, or third-stage, treatment is generally used to remove phosphorus, while advanced treatment might include additional steps to improve effluent quality by removing refractory pollutants. Processes are available to remove more than 99 percent of the suspended solids and BOD_5. Dissolved solids are reduced by processes such as reverse osmosis and electrodialysis. Ammonia stripping, denitrification, and phosphate precipitation can remove nutrients. If the wastewater is to be reused, disinfection by ozone treatment is considered the most reliable method other than breakpoint chlorination. Application of these and other advanced waste-treatment methods is likely to become widespread in the future in view of new efforts to conserve water through reuse [9]. However, this study focuses on the anaerobic digestion of sewage sludge. Some of the advantages of anaerobic digestion treatments are: no, or very low energy demand, production of valuable energy in the form of methane, low investment costs and low

space requirement, applicable at small as well as large scale, low production of excess sludge, which is well stabilized, low nitrogen and phosphorus requirements, high loading capacity (5-10 times that of aerobic treatment), high treatment efficiencies, suitable for camps with long term periods without discharge of wastewater, and effluents contain valuable fertilizers (ammonium salts) [10].

2.3. Experiences in anaerobic digestion of sewage sludge

Sludge treatment and disposal is becoming an important issue. Traditionally, sludge from sewage treatment plants (STPs) was applied on farmland as fertilizer and soil amendment. However, legislation concerning application of sludge on farmland is likely to be tightened, which will limit this disposal route in the future. Therefore, the interest in methods to reduce the volume and mass of biosolids is growing. Due to their high organic fraction, anaerobic digestion is one of the fundamental processes in sewage sludge treatment for reducing and stabilizing the organic solids.

Reduction of sludge solids is not the only objective of this process, but production of energy in the form of biogas, improvement of dewaterability and a high quality final product are achieved. Significant inactivation of pathogens also occurs during the anaerobic digestion, depending on the process temperature and technological layout [11].

So far, anaerobic treatment has been applied in Colombia, Brazil, and India, replacing the more costly activated sludge processes or diminishing the required pond areas. In various cities in Brazil, they show an interest in applying anaerobic treatment as a decentralized treatment system for “sub-urban”, poor, districts. The beauty of the anaerobic treatment technology is that it can be applied to a very small and very big scale. This makes it a sustainable option for a growing community.

In Sweden, many treatment plants have also been supplemented with biogas extraction where sewage sludge is digested in a biogas digester in order to recover energy from the sludge (for electricity generation and heat production), to minimize sludge volumes and facilitate the reuse of sludge as a soil improver. Re-circulation of the nutritious in sewage sludge – as an alternative to land filling – is a matter of great attention [12].

Co-digestion of sewage sludge with other organic waste is prone in Dutch in order to recover energy and phosphorus from sewage sludge. It was proved that digestion of the sewage sludge with other wastes, like livestock manures, food waste, or other industrial organic wastes. Hence, co-digestion is an efficient way for increasing the yield of biogas and further reduction of CO_2 emission [13].

Anaerobic treatment of sludge from aerobic wastewater treatment with long retention times has a very long history in some of the central European countries but has improved considerably: These anaerobic systems can be built and operated on various scales in size with a high degree of technical sophistication and automation, but sometimes are technically quite simple as well. In Central Europe, anaerobic digestion of sewage sludge is presently a routine process implemented in combination with the aerobic activated sludge process, which is the standard technology for municipal wastewater treatment here. Sewage sludge is the total solid material that results from sedimentation and bacterial activity and growth during aerobic wastewater treatment. The floating and sinking layers formed before, during and after a treatment of the wastewater are normally all fed to the sludge digester. Here, anaerobic fermentation takes place at process temperatures of 35°C (mesophilic) to 55°C (thermophilic) and biogas is generated. To generate appropriate reactor temperatures, a heating system is required. Its energy demand can partly, sometimes fully, be covered by utilizing the produced gas, which can either be burnt directly or in cogeneration units [14].

At the Littleton/Englewood Wastewater Treatment Plant (WWTP), anaerobic digestion is used to treat municipal wastewater. Here the total facility is comprised of five major components: thickened sludge loop and dedicated digester mixing and circulated sludge pumps; one floating cover, one fixed cover and two fixed submerged cover, anaerobic digesters; boilers, heat exchangers, cogeneration and a heat reservoir system to maintain a warm environment for the digestion process; digested sludge recirculation pumps for continual heating and foam suppression and mixing pumps to distribute feed sludge and toxic digestion products; and associated gas handling equipment, including a waste gas burner. Anaerobic digestion is a residual solids treatment process. Solids removed from

raw wastewater, known as primary sludge, and solids removed from the biological treatment processes, known as secondary sludge, are treated in the anaerobic digestion process. The anaerobic digestion process stabilizes the biodegradable solids concentrated from wastewater which in turn, provides the following benefits: protects public health and the environment, makes sludge relatively inert, reduces odor generation from undigested sludge, reduces bacteria and pathogenic organisms, reduces the volume and weight of sludge, and reduces the cost of sludge handling and ultimate disposal. In United States of America, anaerobic digestion of sewage sludge is used and most of them are conventional cylindrical tank shape with sloped floors and a floating cover.

In Thailand, sewage sludge production from the Bangkok metropolitan area can reaches up to 63,000 ton/y by 2010. The Beer-Thai Company, Thailand, produces beer and generates lots of sludge as waste. Sewage sludge and brewery sludge can be used to generate energy which could be saved on the fossil fuels conventionally used as a source of energy. The possibility was explored to mix brewery sludge with sewage sludge at different mixing ratios for anaerobic digestion so that the energy can be generated as biogas and at the same time, digested sewage sludge can be used as fertilizer for agricultural applications.

2.4. Mixing sewage sludge with other substrates

In order to improve the performances of anaerobic digesters, the co-digestion of waste activated sludge together with other organic wastes is a common practice adopted in wastewater treatment plants. Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates in the same unit (digester). Through co-fermentation, i.e. through the joint treatment of biogenic wastes (co-substrates) in the digesters of the wastewater treatment plant, the digester gas production can be in-creased considerably. Depending on the type and quantity of the co-substrates added, gas generation can increase so strongly that a self-sufficient energy level for the operation of the wastewater treatment plant can be realized and excess energy can be passed to the grid [15, 16]. For the joint anaerobic treatment with the raw sludge in a wastewater treatment plant a

number of biogenic wastes are suitable. Table 2.10 contains a small selection of biogenic waste usable for co-fermentation [17].

Traditionally, anaerobic digestion/AD/ was a single substrate, single purpose treatment. The use of co-substrates usually improves the biogas yields from anaerobic digester due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates [13, 18]. Some of the merits of co-digestions are:

I. Improved nutrient balance for an optimal digestion and a good fertilizer quality
II. Homogenization of particulate, floating, or settling wastes through mixing with animal manures or sewage sludge
III. Increased, steady biogas production throughout the seasons
IV. Higher income thanks to gate fees for waste treatment
V. Additional fertilizer (soil conditioner)
VI. Renewable biomass production for digestion ("Energy crop") as a potential new income of agriculture

Table 2.10 Biogenic wastes which are suitable for co-fermentation

Description of waste	**Source of waste**
Separately collected bio-wastes	Private households (bio-waste bins)
Contents of grease traps, flotation sludge	Slaughterhouses, meat processing, canteens, large-scale catering establishments, foodstuffs industry
Storage time-expired foodstuffs	Production and trade
Food scraps, kitchen waste	Canteens, large-scale catering establishments, restaurants
Starch sludge	Potato, rice and maize starch production

Dough/pastry wastes	Bread factories, pasta production
Fruit, grain and potato distillery wash	Alcohol distilleries
Market wastes	Central and weekly markets

The strength of substrate used during anaerobic process must be in some proportional ratio with the necessary nutrients which can enhance the growth of anaerobes. For a typical activated sludge process, this results in a COD: N: P requirements of 100: 5: 1 on a mass basis. Anaerobic system produce 20% or less of the amount of sludge produced in aerobic systems for the same substrate and the N and P requirements should decrease proportionally. The COD: N ratio has been observed to be as high as 700: 5. A value of 250: 5 is reasonable for highly loaded processes (0.8 – 1.2 kg COD/kg VSS/d); for processes operating at a lower loading rate the ratio can be conservatively increase from 250: 5 by multiplying it by a factor equal to the loading rate divided by 1.2 kg COD/ kg VSS/d. there are a number of trace elements required for successful anaerobic digestion. Nickel (Ni), and cobalt (Co) have been shown to promote methanogenesis [19].

2.5. The outputs of anaerobic digestion of sewage sludge

The challenge for the 21st century in terms of a sound waste management strategy is the transformation of waste into resources for the future [20]. One way of achieving this is through anaerobic digestion, providing avenues to recover energy and compost whilst reducing waste at the same time. Operating and maintaining healthy anaerobic digesters requires understanding of the substrate biodegradability, gas yields, toxicity and other anaerobic problems. The main theme of this project is to assess the enhancement of methane potential, and organic fertilizer potential and the reduction in solid wastes as the result of co-digestion of sewage sludge from Kaliti WWTP and abattoir wastes from Addis Ababa Abattoirs Enterprise.

2. 5.1. Anaerobic Digestion (AD)

Anaerobic digestion involves the breakdown of complex organics to form fermentable substrates. These substrates then undergo fermentation to biogas.

Biogas is a mixture of gasses, chiefly composed of Methane (CH_4) 50% -70% by volume, Carbon dioxide (CO_2) 30% -50% by volume and other gases, which includes Hydrogen (H_2) 0% -1% by volume and Hydrogen sulfide (H_2S) 0% - 3% by volume.

Some of conditions that must be considered when establishing an anaerobic digestion/ AD/ system includes pH 6 to 8.5, Temperature 25-40 ^{0}C (for mesophilic) and 50-60^{o}C (for thermophilic), Dry solids content 7-12%TS, Retention time (RT) 20-35 days (for mesophilic condition), Carbon to nitrogen ratio (C/N) 20:1 – 30:1.

Temperature inside the digester has a major effect on the biogas production process. There are different temperature ranges during which anaerobic fermentation can be carried out: psychrophilic (<30^{o}C), mesophilic (30–40^{o}C) and thermophilic (50–60^{o}C). However, anaerobes are most active in the mesophilic and thermophilic temperature range. [17].

Co-digestion is a reasonable way to balance the nutrients by adding other organic materials with higher nutrients than the main substrates to be used during the process.

2. 5.1.1. History of Anaerobic Digestion

Scientific interest in the manufacturing of gas produced by the natural decomposition of organic matter was first reported in the seventeenth century by Robert Boyle and Stephen Hale, who noted that flammable gas was released by disturbing the sediment of streams and lakes. In 1808, Sir Humphrey Davy determined that methane was present in the gases produced by cattle manure. The first anaerobic digester was built by a leper colony in Bombay, India in 1859. In 1895 the technology was developed in Exeter, England, where a septic tank was used to generate gas for the sewer gas destructor lamp, a type of gas lighting. In 1907, in Germany, a patent was issued for the Imhoff tank, an early form of digester [6].

Through scientific research anaerobic digestion gained academic recognition in the 1930s. This research led to the discovery of anaerobic bacteria, the microorganisms that facilitate the process. Further research was carried out to investigate the conditions under which methanogenic bacteria were able to grow and reproduce. This work was developed

during World War II where in both Germany and France there was an increase in the application of anaerobic digestion for the treatment of manure.

With the increased interest in biomass-derived energy there is a great opportunity for looking at the potential role of anaerobic digestion. In the 1970s numerous studies were carried out in which the biochemical methane potential (BMP) of crop species, wastes and other forms of biomass was reported. This biogas can be used as an energy source when its methane content exceeds 30% [18].

2. 5.1.2. Status of Anaerobic Digester in Ethiopia

Woody biomass represents the principal form of cooking and lighting fuel in Ethiopia's rural areas. An increasing fraction of the population is being confronted with the difficult choice between eating its food poorly cooked and traveling long distances to collect fuel for cooking. The scarcity of fuel wood has led to an increased utilization of dung and agri-residues for cooking, which could otherwise have been used to enhance the nutrient status and texture of the soil and contribute positively to agricultural production. Biogas offers an attractive option to replace unsustainable utilization of wood and charcoal. It complies with the principles put forward in the country's Energy Policy and Environmental Protection Strategy, and closely meets the terms of the Plan for Accelerated and Sustained Development to End Poverty (PASDEP) as well: it is a local, renewable resource that addresses the basic needs of rural households amongst which energy; it supports decentralized access to household energy; its digestate, enhances agricultural productivity and promotes organic farming, thus offering opportunities for niche markets and export. On the whole, it ensures environmental sustainability and its use as domestic fuel improves development conditions and opportunities for women and girls.

Biogas technology was introduced in Ethiopia as early as 1979, when the first batch type digester was constructed at Ambo Agricultural College with the plan of reducing the critical energy crisis of the 1970s [11]. In the last two and a half decades, around 1000 biogas plants were constructed in various parts of the country of which approximately 40 % of these plants are not operational due to a lack of effective management and follow-

up, technical problems, loss of interest, reduced animal holdings, evacuation of ownership and water problems. Other reasons for the limited success of the technology in Ethiopia include the adoption of a project-based stand-alone approach without follow-up structure in place, variations in design, and the absence of a standardized biogas technology. [12]. Currently Ethiopia has launched a five year project on biogas technology by constructing 14,000 biodigester in four regions which is carried out by National Biogas Program (NBP) with a total budget of 16.8million Euro. To promote the uptake of domestic biogas, the first phase of the programme will be implemented in selected woredas in Oromia, Amhara, SNNP and Tigray regional states. The selected woredas include: Ada'a, Dugda Bora, Hetosa, Ambo and Kuyu in Oromia; Bahir Dar Zuria, Dembia, Gondar Zuria, Fogera and Dangla in Amhara; Dale, Mareko, Meskan, Arba Minch Zuria and Derashe Special Woreda in SNNPRS and Hintalo Wajirat, Raya Azebo and Western Tigray in Tigray regional states [21].

2. 5.3. Process and Mechanism of Biomethanation

The anaerobic biological conversion of organic matter occurs in three steps. The first step involves the enzyme-mediated transformation of insoluble organic material and higher molecular mass compounds such as lipids, polysaccharides, proteins, fats, nucleic acids, etc. into soluble organic materials, i.e. to compounds suitable for the use as source of energy and cell carbon such as monosaccharide, amino acids and other simple organic compounds. This step is called the hydrolysis and is carried out by strict anaerobes such as Bactericides, Clostridia and facultative bacteria such as Streptococci, etc. In the second step, acidogenesis, another group of microorganisms ferments the break-down products to acetic acid, hydrogen, carbon dioxide and other lower weight simple volatile organic acids like propionic acid and butyric acid which are in turn converted to acetic acid. In the third step, these acetic acid, hydrogen and carbon dioxide are converted into a mixture of methane and carbon dioxide by the methanogenic bacteria (acetate utilizers like Methanosarcina spp. and Methanothrix spp. and hydrogen and formate utilizing species like Methanobacterium, Methanococcus, etc.) [6].

2. 5.4. Anaerobic Digestion Technology Description

AD promotes the bacterial decomposition of the volatile solid (VS) in organic wastes to biogas, thereby reducing lagoon loading rates and odor. The primary component of an AD system is the anaerobic digester, a waste vessel containing bacteria that digest the organic matter in waste streams under controlled conditions to produce biogas. AD yields nearly all of the liquid that is fed to the digester. This remaining fluid consists of mostly water and is allowed to evaporate from a secondary lagoon, land-applied for irrigation and fertilizer value or recycled to flush manure to the digester.

Methane is a gas that contains molecules of methane with one atom of carbon and four atoms of hydrogen (CH_4). It is odorless, colorless, and yields about 1,000 British Thermal Units (Btu) [252 kilocalories (kcal)] of heat energy per cubic foot (0.028 cubic meters) when burned [1].

The theoretical amount of the gases produced can be calculated according to the Buswell equation: [13].

$$C_nH_aO_bN_d + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3d}{4}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3d}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3d}{8}\right)CO_2 + dNH_3 \quad (2.1)$$

where: n = number of carbon atom in one mole of organic substance

a = number of hydrogen atom in one mole of organic substance

b = number of oxygen atom in one mole of organic substance

d = number of oxygen atom in one mole of organic substance

The anaerobic bacteria responsible for digestion can't survive with even the slightest trace of oxygen. So, because of the oxygen in the organic waste mixture fed to the digester, there is a long period after loading before actual digestion takes place. During this initial aerobic period, traces of oxygen are used up by oxygen loving bacteria, and large amounts of carbon dioxide are released.

When oxygen disappears, the digestion process can begin. That process involves a series of reactions by several kinds of anaerobic bacteria feeding on the raw organic matter. As different kinds of these bacteria become active, the by-products of the first kind of

bacteria provide the food for the other kind. In the first stages of digestion, organic material which is digestible (fats, proteins and most starches) are broken down by acid producing bacteria into simple compounds. The acid bacteria are capable of rapid reproduction and are not very sensitive to changes in their environment. Their role is to excrete enzymes, liquefy the raw materials and convert the complex materials into simpler substances especially volatile acids, which are low molecular weight organic acids. The most important volatile acid is acetic acid, a very common by-product of all fat, starch and protein digestion. About 70% of the methane produced during fermentation comes from acetic acid [6].

2. 5.5. Anaerobic Digestion Processes

2. 5.5.1. Pre- Treatment

A variety of pre-treatment processes are available and the selection must be done regarding to prices, feedstock and process operations. The pre-treatment process for fecal sludge is most of the time limited to grit and indigestible material removal and mixing with other organic waste. Grit which is composed of mineral matter such as sand and gravel may accumulate in the bottom of the digester and take much space.

The pre-treatment of feedstock for AD involves: removing the non-biodegradable materials not affected by digestion and take up unnecessary space, providing a uniform small particle size feedstock for efficient digestion, protecting the downstream plant form components that may cause physical damage and removing materials which may decrease the quality of the digestate. The process of anaerobic digestion is described as follows [14]:

$$C_xH_yO_z + \frac{(4x-y-2z)}{4} H_2O \rightarrow \frac{(4x-y-2z)}{8} CO_2 + \frac{(4x-y-2z}{8} CH_4 \quad (2.2)$$

where: x = number of carbon atom in one mole of organic substance

y = number of hydrogen atom in one mole of organic substance

z = number of oxygen atom in one mole of organic substance

From the above equation, there is production of CH_4, which is the most reduced organic compound and Carbon dioxide a more oxidized compound. Both gases escape from the liquid phase as biogas. Anaerobic degradation of organic fraction of waste proceeds in the absence of oxygen and in the presence of anaerobic microbes [23]. Anaerobic digestion process requires the combined action of a highly varied microbial population, consisting of several groups of strict and facultative bacteria strains as publicized in fig.1.1 [14].

2. 5.5.2. Hydrolysis

First process in which hydrolytic microorganisms secretes an enzyme to hydrolyze polymeric materials into monomers such as glucose, amino acids and fatty acids. The microorganisms producing these enzymes can be obligate or facultative anaerobes. It is commonly found that hydrolysis is the rate-limiting step in degradation when the substrate is in the particulate form [15].

2. 5.5.3. Acidogenesis

A second group of microorganisms called the fermentative acidogenic bacteria convert soluble substances including hydrolysis products in to higher volatile fatty acids, H_2 and acetic acid [14]. These organisms can be both obligate and facultative anaerobes. Acidogenesis is often the fastest step in the anaerobic conversion of complex organic matter in liquid phase digestion [15]. The acidogenic microorganisms prefer a slightly acidic environment (pH 4.5-5.5) and are less sensitive to changes [6].

2.5.5.4. Acetogenesis

The third process in which acetogenic bacteria form the products of acidogenesis into acetate, hydrogen and carbon dioxide which are substrate for the methanogens: Products from this stage vary with the type of bacteria and environmental conditions [14].

2.5.5.5. Methanogenesis

The last groups of microorganisms, methanogenic, produce methane from acetic acid, hydrogen, and carbon dioxide as well as directly from other substrates [14]. Methanogenesis is the rate-controlling portion of the process because methanogens have a much slower growth rate than acidogens. Therefore, the kinetics of the entire process can

be described by the kinetics of Methanogenesis [17]. Pen-Varo, (2002) reported the production of CH_4 from acetate or from the reduction of CO_2 in this stage according to the following reaction [14]:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2.3)$$

$$CH_3COOH + 4H_2 \rightarrow 2CH_4 + 2HO_2 \quad (2.4)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2HO_2 \quad (2.5)$$

Anaerobic digestion has become popular because of the following advantages relative to aerobic methods:

1) Anaerobic digestion process requires considerably less energy and dispenses with the need for mechanical aeration, an essential requirement for aerobic processes;
2) Useful energy may be recovered from methane, one of the end products;
3) Relatively less sludge is produced and hence a resulting lower costs of disposal of the organic residues;
4) Well-designed anaerobic processes have far greater treatment capacity than aerobic processes and therefore require a much smaller reactor volume; and
5) Many substances which are not degradable under aerobic conditions can be decomposed anaerobically.

Despite the advantages mentioned so far, the acceptance and applicability of anaerobic digestion rises within the last decade. The lack of general acceptance and applicability in the past may no longer hold due to the advances in the knowledge of anaerobic digestion process and treatment technology [17].

2.5.5.6. Post treatment

After the completion of the anaerobic digestion, the remaining biodegradable organic material, digestate or effluent, is subjected further to post treatment processes. This includes dewatering, aeration and leachate treatment. The importance of aeration process in post treatment is to remove the left over biodegradable organics by aerobically

reducing the organic compounds to valuable material which is used as soil conditioner. Further cleaning by screening to remove unwanted materials such as: small pieces of glass or plastic are among post treatment processes [23].

2.5.6. Parameters in Anaerobic Digestion

The complete process of anaerobic digestion requires a complex interaction of several varieties of bacteria that must be in equilibrium in order for the digester to remain stable. Changes in environmental conditions can disturb the equilibrium and result in the buildup of intermediaries that may inhibit the overall process or shut it down altogether. It is crucial to manage and use design control technologies to continually monitor and adjust the environment to prevent this.

Several factors within the digester effect the physical environment and therefore the rate of digestion and biogas production. The performance of biogas plant can be controlled by studying and monitoring the variation in parameters like temperature, pH, toxic substances, organic loading rate, C: N Ratio, Hydraulic retention time (HRT), percentage of solids and etc. Any drastic change in these can adversely affect the biogas production. So these parameters should be varied within a desirable range to operate the biogas plant efficiently [23]. Falling outside these ranges can cause digester failure, an expensive misstep as start-up is a slow process.

2.5.6.1. Temperature

Temperature inside the digester has a major effect on the biogas production process. There are different temperature ranges during which anaerobic fermentation can be carried out: psychrophilic (<30^{o}C), mesophilic (30–40^{o}C) and thermophilic (50–60^{o}C). However, anaerobes are most active in the mesophilic and thermophilic temperature range. The length of fermentation period is dependent on temperature. Angelidaki and Ahring (1994) observed that when the NH_3 load was high, reducing temperature below 55^{o}C resulted in an increase of biogas yield and better process stability [24].

Garba (1996) observed that methanogens were very sensitive to sudden thermal changes; therefore, any drastic change in temperature should be avoided. Nozhevnikova et

al.(1999) proposed a two step anaerobic treatment of cattle dung i.e. (I) acidogenic fermentation at high temperature (55–82^{o}C), and (II) separation of solid and liquid fractions and treating the liquid manure under low temperature conditions (5–20^{o}C).Long term adaptation of active psychrophilic microbial communities was found to be essential for efficient treatment of cattle dung at low temperature [18, 25].

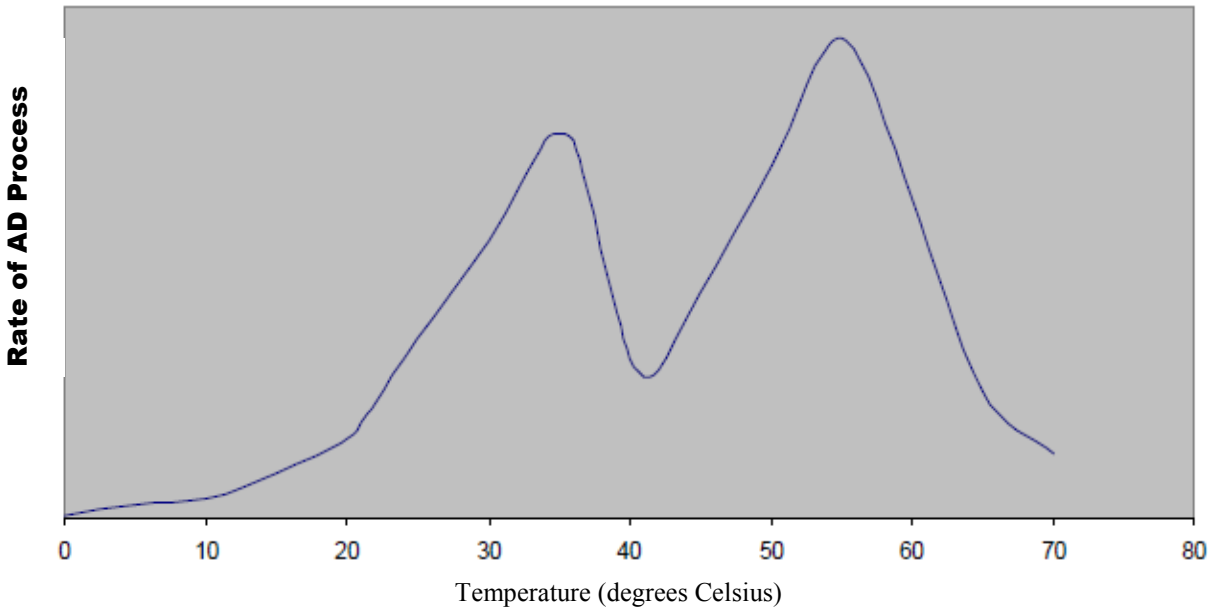

Fig. 2.1. Rate of AD Process vs Temperature (Golueke, 2002)

2.5.6.2. Toxic Substances

Methanogens are considered the most sensitive to toxicity in anaerobic digestion [15]. Inhibition can be caused by substances either entering with influent substrate or being produced by the anaerobic process itself. Products in the chain of simultaneous biochemical reactions, such as NH_3, H_2S and volatile fatty acids are pH dependent since only the non-ionized forms exhibit microbial toxicity.

2.5.6.3. pH

pH is an important parameter affecting the growth of microbes during anaerobic fermentation. pH of the digester should be kept within a desired range of 6.8–7.2 by feeding it at an optimum loading rate. The amount of carbon dioxide and volatile fatty acids (VFA) produced during the anaerobic process affects the pH of the digester

contents. For an anaerobic fermentation to precede normally concentration of volatile fatty acids acetic acid in particular should be below 2000 mg/l. Jain and Mattiasson (1998) found that above pH 5.0, the efficiency of CH_4 production was more than 75%.

The greatest potential for digester failure is a result of acid accumulation. This would occur if the amount of volatile solids loaded into the digester as fresh waste increased sharply. The acidogenic bacteria would then thrive, producing high volumes of organic acids and lowering the pH to below 5.0, a level lethal to methanogens. This creates a positive feedback loop as a declining methanogens population will in turn lead to further acid accumulation as the methogens are responsible for consuming acids. An acidic pH indicates that this process has already begun, and immediate action is required, such as by recycling more water. On the other hand, prolific methanogenesis may result in a higher concentration of ammonia, increasing the pH above 8.0, where it will impede acidogenesis (Lusk 1999). This can be opposed by adding a greater amount of fresh feedstock, which will spur acidogenesis and acid formation [24].

2. 5.6.4. Carbon to Nitrogen Ratio (C: N)

It is necessary to maintain proper composition of the feedstock for efficient plant operation so that the C: N ratio in feed remains within desired range. It is generally found that during anaerobic digestion microorganisms utilize carbon 25–30 times faster than nitrogen. Thus to meet this requirement, microbes need a 20–30:1 ratio of C to N with the largest percentage of the carbon being readily degradable (Bardiya and Gaur, 1997; Malik et al., 1987). Waste material that is low in C can be combined with materials high in N to attain desired C: N ratio of 30:1 (Barnett, 1978; Fry and Merill, 1973; Gotass, 1956; Singh, 1974).Some studies also suggested that C: N ratio varies with temperature. According to study conducted by Idnani and Laura (1971) biogas production from 0.5 kg of cow dung was almost doubled from 17.2 to 31.5 l by addition of 200 ml of urine. Use of urine soaked waste materials is particularly advantageous during winter months when gas production is otherwise low [9, 25].

A low C/N ratio, or too much nitrogen, can cause ammonia to accumulate which would lead to pH values above 8.5. Additionally, the quality of the compost is lessened with

high ammonia production. A high C/N ratio will lead to a rapid consumption of nitrogen by the methanogenic bacteria and lower gas production rates [23].

2.5.6.5. Hydraulic Retention Time (HRT)

HRT is the average time spent by the input slurry inside the digester before it comes out. The retention time is determined by the average time it takes for organic material to digest, as measured by the COD and BOD of exiting effluent. In tropical countries HRT varies from 30–50 days while in countries with colder climate it may go up to 100 days. Shorter retention time is likely to face the risk of washout of active bacterial population while longer retention time requires a large volume of the digester and hence more capital cost. Hence there is a need to reduce HRT for domestic biogas plants based on solid substrates. It is possible to carry out methanogenic fermentation at low HRT's without stressing the fermentation process at mesophilic and thermophilic temperature ranges (Zennaki et al., 1996; Singh et al., 1995; Garba, 1996).On the other hand Sanchez et al. (1992) found improvement in organic matter removal on increasing HRT while anaerobically treating cattle dung. Desai and Madamwar (1994) observed maximum gas production of 2.2 l/l/day (CH4 ¼62%) at an HRT of 10 days having a loading rate of 6 gTS/l while treating a mixture of cattle dung, poultry waste and cheese whey in the ratio of 2:1:3. Baserj a (1984) observed that at a TS concentration of 7%, the duration of digestion could be reduced to 10 days without compromising the stability of the process, but the optimum period was 16–20 days.

2.5.6.6. Organic Loading Rate

The organic loading rate (OLR) determines the volatile solids input to the digester. This parameter has a significant influence on the process performance. It is expressed as the amount of organic matter (as COD or Volatile solids) per reactor volume. If there is an excess of biodegradable matter fed to the digester, this can lead to the overproduction of volatile fatty acids then a drop in pH and a reduction in methane production will occur. Under feeding the reactor could also lead to reduction in the digester performance due to insufficient nutrients for microbial growth [26].

A higher OLR will demand more of the bacteria, which may cause the system to crash if it is not prepared. One danger of increasing the OLR would be that the acidogenic bacteria, which act early in the digestion process and reproduce quickly given enough substrate, would multiply and produce acids rapidly [17]. The methanogenic bacteria, which take longer to increase their populations, would not be able to consume the acids at the same pace. The pH of the system would then fall, killing more of the methanogenic bacteria and leading to a positive feedback loop, eventually halting digestion. An early indication of this is lowered biogas production and eventually a lower pH [23].

2.5.6.7. Percentage of Solids

Anaerobic digestion of organics will proceed best if the input material consists of roughly 8 % solids. In the case of fresh cow manure, this is the equivalent of dilution with roughly an equal quantity of water. Digestion is practiced in two broad categories of solid content: "dry digestion," with typical dry solids content of 25-30% and "wet digestion," with dry solids content of less than 15%.

A higher TS contents leads to smaller and thus less costly, reactors. This price savings may be offset, however, by the more expensive pumps needed to move denser material. Higher TS values cause excessive resistance to flow in pipes as well (Nichols 2004). Systems with lower TS tend to have much better mixing, thus increasing the degree of digestion because the bacteria can more easily access liquid substrate and because the relevant reactions require water. An additional benefit to lower solids content is that mixing is more complete when the solid content is lower. It also is more amenable to co-digestion with more dilute feed stocks, such as sewage sludge or manure.

2. 5. 6. 8. Agitation

The way in which materials flow through the digester impacts the degree of contact substrate has with resident bacteria and therefore how quickly it is digested. In the earliest systems, such as covered lagoons, the feedstock simply sits in a large bath and decomposes without mixing. Improvements on this system focused on changing the way

materials flow, such as in complete mix digesters and plug-flow digesters, or in the way materials are mixed, such as through agitation, gas injection, or recirculation.

Mixing can take place as a result of the pathway the waste must travel before it is removed. Some systems have interior walls in a cylindrical chamber that require a greater distance traveled for the waste, thereby increasing mixing [27].

The material inside any digester may be further mixed through mechanical or gas mixers that keep the solids in suspension. Often biogas is bubbled through the chamber as an inexpensive way to promote movement. Recirculating digested waste continuously through heat exchangers both improves mixing and ensures proper temperature control.

Mechanical mixers inside tanks are less common because maintenance is extremely difficult. Sealed tanks must be shut down in order to access interior machinery. Mixing can also be achieved through the recirculation of waste. After digestate is removed from the chamber at the end of its retention time, a percentage of it is fed into the stream of incoming fresh waste. This serves to inoculate the fresh waste with bacteria and increase movement in the chamber, which prevents the buildup of a scum layer. Excessive mixing, however, may disrupt microbes.

2.5.6.9. Seeding/Starter

To start up a new anaerobic process, it is critical to use inoculums of micro organisms to commence the fermentation process. The common seeding materials include digested sludge from a running biogas plant or material from well-rotted manure pit or cow manure slurry.

2.5.7. Benefits of Bio-Digester Technology

There are a number of benefits resulting from the use of anaerobic digestion (AD) technology. Well-functioning biogas systems can yield a whole range of benefits for their users, the society and the environment in general [1, 10]. In general Biogas has the following benefits:

1. Production of energy (heat, light, electricity)
2. Transformation of organic wastes into high quality fertilizer

3. Improvement of hygienic conditions through reduction of pathogens, worm eggs and flies
4. Reduction of workload, mainly for women, in fire wood collection and cooking
5. Environmental advantages through protection of forests, soil, water and air
6. Reduce global warming by reducing methane emission from waste disposal site

Thus, biogas technology can substantially contribute to conservation and development, if the concrete conditions are favorable. However, the required high investment capital and other limitations of biogas technology should be thoroughly considered.

2.5.7.1. Economic Benefits

a) Considering the whole life-cycle, it is more cost-effective than other treatment options
b) Savings on kerosene, diesel fuel and, possibly, wood or charcoal
c) An additional energy supply for commercial activities
d) Energy independence(calorific value of biogas is about 6kWh/m^3)-this correspondent to half a liter of diesel oil
e) Generates high quality renewable fuel
f) Enhanced soil productivity because of the use of bio-slurry
g) Savings on chemical fertilizers and/or additional income from higher agricultural yields
h) Effective workload reduction on women in searching for fire wood.

2.5.7.2. Waste Treatment Benefits

a) Natural waste treatment process
b) Requires less land than aerobic composting
c) Reduces disposed waste volume and weight to be land filled

2.5.7.3. Health Benefits

Reduction in smoke borne diseases [12,17]:

i. eye-irritation
ii. Lung problem

iii. Asthma
iv. Dizziness/ head ache
v. Respiratory tract infection etc.

The followings are among the principal organisms killed in biogas plats such as:

i. Typhoid
ii. Paratyphoid
iii. Cholera and dysentery bacteria (in one or two weeks)
iv. Hook worm and bilharzias (in three weeks)
v. Tapeworm and roundworm die completely when the fermented slurry is dried in the sun

In addition to these, biogas improves household sanitation when latrines are attached to bio-digesters and also easier, cleaner cooking and create better hygiene.

2.5.7.4. Environmental Benefits

Biogas technology has immense benefits in regulating ecosystems. The followings are few to mention:

i. Significantly reduces greenhouse gas (GHG) emissions
ii. Eliminates odours
iii. Produces a sanitized compost and nutrient-rich liquid fertilizer
iv. Maximizes recycling benefits
v. Prevention of land fertility degradation due to the excessive use of chemical fertilizers – researches shows that organic fertilizers which comes from biogas plant contains three times more nitrogen than the best compost made through open or air digestion.
vi. Lessen local deforestation
vii. Enhance climate change monitoring strategy

2.5.8. Types of Biogas Plant

There are different designs of bio-digesters in use today. They can be classified based on feeding type and plant types.

2.5.8.1. Based on Methods of Feeding

In AD process technology, two general models are used: the batch process and the continuous process.

I. Continuous Feeding

Continuous plants are filled and emptied regularly —normally daily. Each design is suitable for continuous operation, but the feed material must be flowable and uniform. In this process, fresh material continuously enters the tank and an equal amount of digested material is removed. Continuous plants are more suitable for rural households. The necessary work fits better into the daily round. Gas production is constant, and somewhat higher than in batch plants. The disadvantage of the continuous process is the removed effluent is a combination of completely digested and partially digested material. To minimize the removal of partially digested material, some designs dictate the path of the digestate inside the chamber, for example through the use of interior walls [22, 23].

II. Batch Feeding

In the batch process, the substrate is put in the reactor at the beginning of the degradation period and sealed for the complete retention time, after which it is opened and the effluent removed. The disadvantage of this type of system is the large tank volume required due to the long retention time, the low organic loading rate and the formation of a scum layer [24]. Only about 1/3 of the tank volume is used for active digestion, making this a poor option in crowded urban settings.

2.5.8.2. Based on Physical Appearance of Biogas Plant

I. Balloon Plants
II. Fixed-Dome Plants
III. Floating-Drum Plants

Three main types of simple biogas plants can be distinguished (see Fig. 2.2) [18]:

a) Balloon plants,

b) Fixed-dome plants, and

c) Floating-drum plants.

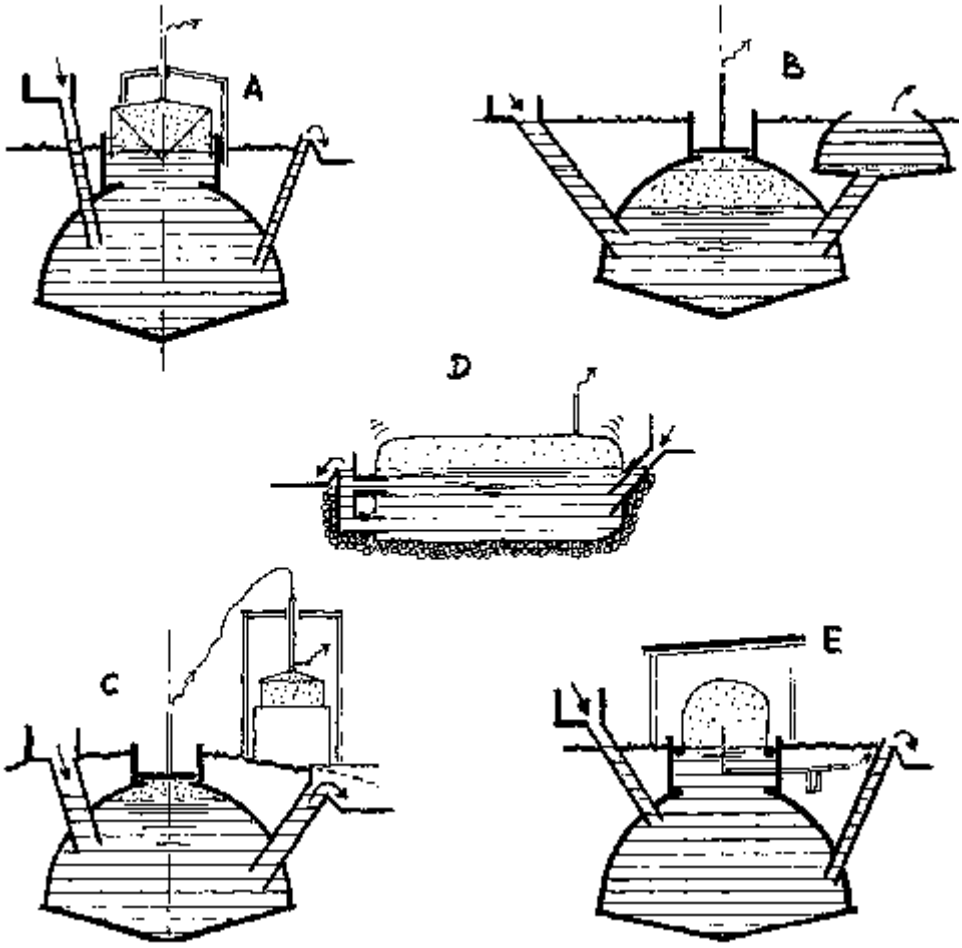

Fig. 2.2. Simple biogas plants

A) Floating-drum plant, B**)** Fixed-dome plant, C**)** Fixed-dome plant with separate gasholder. The gas pressure is kept constant by the floating gasholder. The unit can be operated as a continuous overflow-type plant with no compensating tank. The use of an agitator is recommended. **D)** Balloon plant, **E)** Channel-type digester with folia and sunshade.

I. Balloon Plants

A balloon plant consists of a plastic or rubber digester bag, in the upper part of which the gas is stored. The inlet and outlet are attached direct to the skin of the balloon. When the gas space is full, the plant works like a fixed-dome plant - i.e., the balloon is not inflated; it is not very elastic.

The fermentation slurry is agitated slightly by the movement of the balloon skin. This is favourable to the digestion process. Even difficult feed materials, such as water hyacinths, can be used in a balloon plant. The balloon material must be UV-resistant. Materials which have been used successfully include RMP (red mud plastic), Trevira and butyl.

Advantages:

Low cost, ease of transportation, low construction (important if the water table is high), high digester temperatures, uncomplicated cleaning, emptying and maintenance [18].

Disadvantages:

Short life (about five years), easily damaged, and does not create employment locally, little scope for self-help. Balloon plants can be recommended wherever the balloon skin is not likely to be damaged and where the temperature is even and high. One variant of the balloon plant is the channel-type digester with folia and sunshade.

II. Fixed-Dome Plants

A fixed-dome plant (Fig.2.3) consists of an enclosed digester with a fixed, non-movable gas space. The gas is stored in the upper part of the digester. When gas production commences, the slurry is displaced into the compensating tank [18]. Gas pressure increases with the volume of gas stored; therefore the volume of the digester should not exceed 20 m^3. If there is little gas in the holder, the gas pressure is low.

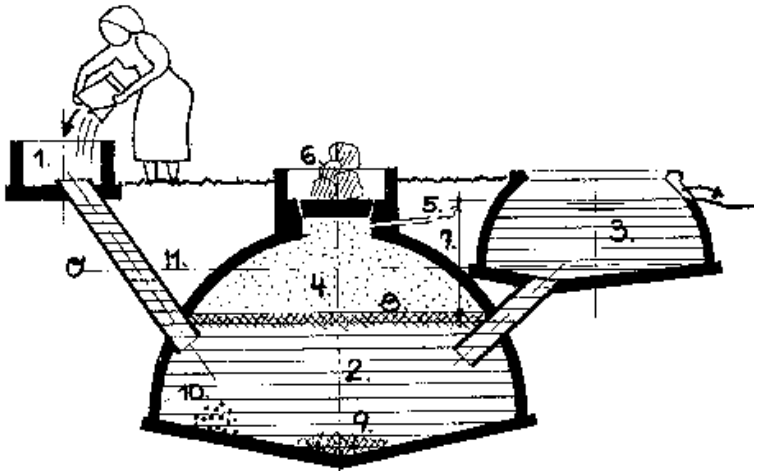

Fig.2.3. Fixed-dome plant

1. Mixing tank with inlet pipe. **2**. Digester. **3**. Compensating and removal tank. **4**. Gasholder. **5**. Gas pipe. **6**. Entry hatch, with gaslight seal and weighted. **7**. Difference in level = gas pressure in cm WC. **8**. Supernatant scum; broken up by varying level. **9**. Accumulation of thick sludge. **10**. Accumulation of grit and stones. **11**. Zero line: filling height without gas pressure.

If the gas is required at constant pressure (e.g., for engines), a gas pressure regulator or a floating gasholder is required. Engines require a great deal of gas, and hence large gasholders. The gas pressure then becomes too high if there is no floating gasholder [18].

Advantages:

Low construction cost, no moving parts, no rusting steel parts, hence long life (20 years or more), underground construction, affording protection from winter cold and saving space, creates employment locally.

Disadvantages:

Plants often not gaslight (porosity and cracks), gas pressure fluctuates substantially and is often very high, low digester temperatures. Fixed-dome plants can be recommended only where construction can be supervised by experienced biogas technicians.

III. Floating-Drum Plants

Floating-drum plants (Fig.2.4) consist of a digester and a moving gasholder. The gasholder floats either direct on the fermentation slurry or in a water jacket of its own. The gas collects in the gas drum, which thereby rises. If gas is drawn off, it falls again. The gas drum is prevented from tilting by a guide frame.

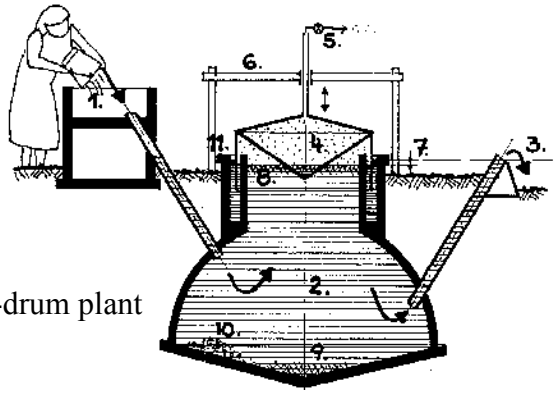

Fig.2.4. Floating-drum plant

1. Mixing tank with inlet pipe. **2**. Digester. **3**. Overflow on outlet pipe. **4**. Gasholder with braces for breaking up surface scum. **5**. Gas outlet with main cock. **6**. Gas drums guide structure. **7**. Difference in level = gas pressure in cm WC. **8**. Floating scum in the case of fibrous feed material. **9**. Accumulation of thick sludge. **10**. Accumulation of grit and stones. **11**. Water jacket with oil film.

Advantages:

Simple, easily understood operation, constant gas pressure, volume of stored gas visible directly, few mistakes in construction.

Disadvantages:

High construction cost of floating-drum, many steel parts liable to corrosion, resulting in short life (up to 15 years; in tropical coastal regions about five years for the drum), and regular and maintenance costs due to painting.

In spite of these disadvantages, floating-drum plants are always to be recommended in cases of doubt. Water-jacket plants are universally applicable and especially easy to maintain. The drum won't stick, even if the substrate has high solids content [18].

Floating-drums made of glass-fiber reinforced plastic and high density polyethylene have been used successfully, but the construction cost is higher than with steel. Floating-drums made of wire-mesh-reinforced concrete are liable to hairline cracking and are intrinsically porous. They require a gaslight, elastic internal coating. PVC drums are unsuitable because not resistant to UV.

The floating gas drum can be replaced by a balloon above the digester. This reduces construction costs (channel type digester with folia), but in practice problems always arise with the attachment of the balloon at the edge. Such plants are still being tested under practical conditions.

2.5.9. Fertilizer Potential of digestate

During the digestion process, gaseous nitrogen (N) is converted to ammonia (NH_3). In this water-soluble form the nitrogen is available to the plants as a nutrient. A particularly nutrient-rich fertilizer is obtained if co-digestion is used.

Compared with solid sludge from fermented feeds, most of the time the liquid slurry is rich in nitrogen and potassium. The solid fermentation sludge, on the other hand, is relatively richer in phosphorus. A mixture of solid and liquid fermented material gives the best yields. The nutrient ratio is then approximately N: P_2O_5: K_2O= 1:0.5:1. Fermented slurry with a lower C/N ratio has better fertilizing characteristics. Compared with fresh wastes like manure, increases in yield of 5 - 15 % are possible. Particularly good harvests are obtained from the combined use of compost and fermentation slurry.

The fertilization effect depends on the type of crop and on the soil. Information given in specialized literature is seldom applicable directly. Tests of one's own are always better. Reliable information is possible only after three to five years.

When fermentation slurry is used as fertilizer for years, the soil structure is improved. The proportion of organic materials in the soil is increased, enabling the soil to store more water. If fermentation slurry is to be stored before spreading on the field, it should be covered with earth in layers. This reduces evaporative nitrogen losses even further [12].

Nitrogen is mostly found under organic form in sludge, and to a lesser extent under ammoniac form. Other mineral forms of nitrogen are only found as traces. As plants can assimilate only mineral nitrogen, the agricultural value of the sludge is also determined by the aptitude of its organic N to be mineralized. The nitrogen availability depends on the type of sludge. Nutrients such as Nitrogen and phosphorus are essential elements for the growth of microorganisms, plants and animals. Nitrogen is the building block in the synthesis of protein and hence the quantity in wastewater is essential to be known to determine if the wastewater is treatable.

Phosphorus is used by the plant for its growth, the rigidity of its cell walls, and for the development of its root system. Sludge-borne phosphorus is of particular interest as phosphorus is a limited natural resource. Phosphorus in sludge is mostly present under mineral form.

Potassium (K), sometimes known as potash, is important for general health of plants. It is key in the formation of chlorophyll and other plant compounds. Potassium is also known to help with disease resistance. Potassium deficiency is hard to symptomize, but plants are generally sickly, with small fruit, yellowing from the older leaves upwards, and sickly blooms. Sources of organic potassium include sul-po-mag (sulfate of potash magnesia, quick release), greensand, and liquid fertilizers such as Earth Juice's Meta-K [20].

Potassium (K) is required by all plant and animal life. Plants require potassium for photosynthesis, osmotic regulation and the activation of enzyme systems. Potassium deficiency in cereal crops results in reduced growth, delayed maturity, lodging caused by weak straw, and low bushel weight [12].

3. Materials and Methods

3.1. Materials

Glass bottle, filter papers (DP-70, 47mm), N840.3FT.18 type vacuum filter, crucibles, folks, Jenway model 3510 digital pH meter, Beschickung-Loading model 100-800 type oven, dissector, armfield W8 Anaerobic Digester, magnetic stirrer, rubber hose, incubator, muffle furnace, measuring cylinder, sterile plastic Petri dish, hand lens, lids, GA-45 gas analyzer, Lovibond oxidirect TS 606/4-I type, HI 839800 COD Hanna Reactor, Tedlar gas sampling bag, model NOV AA 400 AAS and JD 210-4 mode3l No. weighing scale were used through out the experiment.

Physiochemical and biological characteristics of sewage sludge and abattoir waste and their mixture before and after digestion were analyzed for the parameters mentioned below at laboratories found in different institutions. Analytical reagents was used for the analysis of sewage sludge and abattoir waste composition and analysis were conducted for samples from Addis Ababa waste water treatment plant Kaliti site and Addis Ababa Abattoirs Enterprise.

The parameters such as total solids (TS), volatile solids (VS), biochemical oxygen demand, (BOD_5), and pH were analyzed in Environmental Engineering laboratory of Chemical Engineering Department. In addition to these, analyses for the following parameters were done at the laboratory of Addis Ababa Environmental Protection Authority: Chemical oxygen demand (COD), Heavy metal (Cd, Cr, Cu, Pb, Ni, and Zn), Total Nitrogen (TKN), Total Phosphorus, and Total Potassium. Determination of pathogen (total and fecal Coliform) was done at the laboratory of Environmental Science Program.

3..2. Methods

3.2.1. Study Variables

Amount of biogas produced from only sewage sludge (100% SS), and co-digestion of 80%:20%, and 60%:40% (the first percentage is for sewage sludge and the second one is for abattoir effluents) were determined through water displacement and the gases were collected using Tedlar gas sampling bag and the collected gases were analyzed using GA-45 (Geotechnical Instrument) at the laboratory of Addis Ababa Environmental Protection Authority.

Physical, chemical and biological characteristics (pH, TS, VS, BOD_5, COD, heavy metals mentioned above, TKN, total phosphorus, total potassium, pathogens) of sewage sludge and different mixtures of sewage sludge and abattoirs wastes (80%:20)%, 60%:40%) before and after digestion were analyzed.

Total solid was estimated from weight loss up on evaporation at 105^{o}C for 24 hours (standard method procedure 2540 B).

Total volatile solid content was estimated from weight loss upon ignition at 550^{o}C for 2 hours in muffle furnace (standard method procedure 2540 E). pH using Jenway model 3510 digital pH meter.

3.2.2. Experimental design

A single factor experimental design with three level of mix in three replication of each level was used with the response variable; quantity of biogas varies with the variation of mix ratio.

3.2.3. Sample Analysis

A batch anaerobic reactor under mesophilic condition (35^{o}C) for a digestion period of 20 days was used in the laboratory for each set up.

Biogas production was determined by water displacement, methane and carbon dioxide in biogas measured by GA-45 at Addis Ababa EPA. Organic matter (OM) content was

estimated from weight loss upon ignition at 550^{o}c for 3 hours in the furnace at Chemical Engineering Department of Addis Ababa University. pH was measured using Jenway model 3510 pH meter at Environmental Engineering laboratory of Chemical Engineering Department of Addis Ababa University.

3.2.4. Experimental Procedure

Digester, necessary fittings, and different measuring device were prepared prior to collect the samples from each site (samples from Kaliti WWT plant and AAAE). Enough amount samples from each site were placed in Chemical Engineering Department Laboratory using refrigerator till feed stock preparation.

Sample preparation such as testing for different parameter and recording (pH, BOD_5, TS, VS, COD), Preparation of different mix and homogenizing (80%:20%, 60%:40%) digester feeding incubation were done and finally experimental results collected.

3.2.4.1. Biological Oxygen Demand (BOD_5)

Biochemical oxygen demand (BOD) – this is the amount of oxygen required for the oxidation of a wastewater by bacteria. It is therefore a measure of the concentration of organic matter in a waste that can be oxidized by bacteria ('bio-oxidized' or 'biodegraded'). Or BOD is the number of milligrams of O_2 required to carryout the oxidation of organic carbon in one liter of water. BOD is usually expressed on a 5-day, 20°C basis – that is as the amount of oxygen consumed during oxidation of the wastewater for 5 days at 20°C. This is because the 5-day BOD (usually written 'BOD_5') is more easily measured than is the ultimate BOD (BODu), which is the oxygen required for the complete bio-oxidation of the waste.

Microorganisms such as bacteria are responsible for decomposing organic waste. When organic matter such as dead plants, leaves, grass clippings, manure, sewage, or even food waste is present in a water supply, the bacteria will begin the process of breaking down this waste. When this happens, much of the available dissolved oxygen (DO) is consumed by aerobic bacteria, robbing other aquatic organisms of the oxygen they need to live.

The most widely used parameter of organic pollution applied to both wastewater and surface water is the 5-day BOD (BOD_5). Results of the BOD tests are used to determine the approximate quantity of oxygen that will be required to biologically stabilize the organic matter present in wastewater, the size of waste treatment facilities, the efficiency of some treatment process and compliance with wastewater discharge permits.

Method

Lovibond BOD_5 system oxidirect was used to analyze the BOD_5 of the samples and their different mix ratios before and after digestion processes.

Preparation of the sample, estimation the measurement reagent and selection of the volume for the sample were carried out. The sample volume is related to the expected BOD_5 value. The oxidirect is designed to operate with the following ranges and samples volume allowing BOD_5 measurement up to 0-4000 mg/l with out any dilution, for 0-2000 mg/l expected value 56 ml sample volume with 3 drop ATH to avoid nitrification and 3-4 drop KOH, for 0-4000 mg/l expected value 21.2 ml sample volume with 1 drop ATH to avoid nitrification and 3-4 drop KOH.

Necessary pre treatments such as adjusting the pH (the optimum pH value for BOD_5 is between 6.5 and 7.5 and if higher or lower adjust by HCl or H_2SO_4 and NaOH, mixing well) were carried out.

Fig.3.1. Preparation of solution for BOD_5 measurement

Required reagent

KOH to absorb CO_2 and ATH to avoid nitrification were used.

Materials used

BOD bottle, BOD sensor, BOD bottle rack, Incubator and measuring cylinder were used.

Fig. 3.2. BOD_5 under analysis

Measurement procedure

1) measure the sample precisely using appropriate over flow and if necessary add nitrification inhibitor (ATH)
2) insert magnetic stirring rod
3) place 3-4 drop of KOH solution into the seal gasket and insert gasket in the neck of the bottle
4) screw the BOD sensors to the sample bottle
5) place the bottle in the bottle rack
6) start the measurement
7) incubate the sample in accordance with the instructions BOD_5 for 5 days at 20 ^{0}C

3.2.4.2. Chemical oxygen demand (COD) – this is obtained by oxidizing the wastewater with a boiling acid dichromate solution. This process oxidizes almost all organic compounds to carbon dioxide and water, the reaction usually proceeding to more than 95 per cent completion. The advantage of COD measurements is that they are obtained very quickly (within 3 hours), but they have the disadvantages that they do not give any information on the proportion of the wastewater that can be oxidized by bacteria, nor on the rate at which bio-oxidation occurs.

There is no general relationship between these various oxygen demands (BOD_5 and COD). However, for untreated domestic wastewater a large number of measurements have indicated the following approximate ratios:

$$BOD_5/COD = 0.5 \qquad (3.1)$$

These oxygen demands can also show us the strength of wastewater. The higher the concentration of organic matter in a wastewater, the 'stronger' it is said to be. Wastewater strength is often judged by its BOD_5 or COD (Table 2.1).

3.2.4.3. Total Solids and Volatile Solids (TS and VS)

I) Total Solids (TS)

Total solids are a measure of the suspended and dissolved solids in water. Matter suspended or dissolved in water or wastewater is considered as solids. A high amount of solids in water generally makes it not desirable for consumption. Solid analyses are important in the control of biological and physical wastewater treatment processes and for assessing compliance with regulatory agency wastewater effluent limitations. A limit of 500 mg dissolved solids/l is set by EPA as secondary standard for drinking water.

Fig.3.3. Sample in the oven for TS analysis

II) Volatile Solids (VS)

Volatile solids are those solids lost on ignition (heating to 550^{o}C.) They are useful to approximate the amount of organic matter present in the solid fraction of wastewater, activated sludge and industrial wastes.

Method

APHA, procedure 2540B and 2540E method was used to determine volatile solids.

Apparatus used

Evaporating dishes, desiccator, provided with a desiccant containing a color indicator of moisture, drying oven operating at 103-105^{o}C, Analytical balance, Graduated cylinder, Beaker, and Muffle furnace operating at 550^{o}C were used.

Measuring procedure

Preparation of evaporating dish:

a) Ignite clean evaporating dish at 550^{o}C for 1h in a muffle furnace for VS
b) Heat clean dish to 103 to 105^{o}C for 1h
c) Store and cool dish in desiccator until needed (usually to room temperature)
d) Weigh immediately before use

Analysis of the Sample

a) Pipet a measured volume of well mixed sample to a pre weighed dish
b) Evaporate to dryness on drying oven for 24hrs
c) If necessary add successive sample portions to the same dish after evaporation
d) Cool dish in desiccator to balance temperature, and weigh it immediately
e) Ignite the residue produced by method 2540B in a muffle furnace for 3hrs
f) Transfer to a desiccator for final cooling in a dry atmosphere

Fig.3.4. VS analysis in Muffle furnace

Calculation

The amounts of TS and VS in the sample can be computed using equation 3.2 and 3.3 respectively.

$$mg\ total\ solid\ /\ l = \frac{(A-B)}{Sample\ volume, ml} X100 \qquad (3.2)$$

where: A = weight of dried residue + dish, mg, and B = weight of dish, mg.

$$mg\ volatile\ solid\ /\ l = \frac{(X-Y)}{Sample\ volume, ml} X100 \qquad (3.3)$$

where: X = weight of dried residue + dish before ignition, mg, Y = weight of residue + dish after ignition, mg.

3.3. Experimental set up

Experiments were carried out in 5 liters laboratory scale cylindrical anaerobic digester W8 issue 3 arm field model with temperature control (Fig.3.4) to determine biogas production from co-digestion of sewage sludge and abattoir waste.

Fig. 3.5. Anaerobic digester used in the laboratory

The temperature of reactor was controlled by an electric heating mat wrapped around the external wall. The gas off-take from the reactor was taken to a volumetrically calibrated collector vessel operating by water displacement. A constant head, liquid seal device ensures that the gas pressure in the reactor is maintained at a constant value throughout the test run. The collected gas can be exhausted from the vessel and the volume re-filled with water during a run without breaking the liquid seal.

Liquid and gas sampling points are located at all strategic points around the reactors. Non-return valves and liquid seal syphon breaks were included in the process pipe work to ensure each reactor operates at a constant volume without the entrance of air or the danger of accidental symphonic action. The equipment was mounted on a vacuum formed plastic base with an integral drain channel to cope with spillages and wash down.

4. Results and Discussion

Physico-chemical, evaluations were carried out to see the potential of co-digestion of sewage sludge and abattoir waste for energy recovery after anaerobic digestion.

4.1. Experimental Results

4.1.1. Determination of raw sewage sludge composition

The physiochemical characteristics of the sewage sludge used in the study has been determined and the experimental results are displayed in Table 4.1. The total solid of the sewage sludge was 39,831 ± 3,987.6 mg/l and the volatile solid of the sewage sludge was 27043 ± 4956. The mean value of COD of the sewage sludge was 32,872 ± 2,600.5 mg/l.

Table 4.1 Composition of sewage sludge before digestion (mean value ± SD)

Parameters	Unit	Sewage sludge (Kaliti waste water treatment)
pH		7.47 ± 0.35
TS	mg/l	39,831 ± 3,987.6
VS	mg/l	27,043 ± 4,956
COD	mg/l	32,872 ± 2,600.5
BOD_5	mg/l	12,600 ± 3,567
TN	mg/l	49.6 ± 8.3
TP	mg/l	78.8 ± 9.4
TK	mg/l	231.7 ± 13.25
Cu	mg/l	0.172 ± 0.0741
Ni	mg/l	0.1417 ± 0.0572
Cr	mg/l	0.00519 ± 0.0032
Pb	mg/l	<0.0001
Cd	mg/l	Nil
Zn	mg/l	0.3241 ± 0.082
TC	MPN/100ml	20×10^6
FC	MPN/100ml	12×10^6
Parasite		
Ascaris	No./l	18,000-39,000
Hook worm	No./l	0 – 3,800

MPN = most probable number

4.1.2. Determination of raw Abattoir waste composition

The physiochemical characteristics of abattoir waste used in the study were determined and the experimental results are displayed in Table 4.2. The total solid of the abattoir

waste was 10,823± 5,656.85 mg/l and its volatile solid was 2,529.32 ± 638. The mean value of COD of the abattoir waste was 6,950 ± 636.40mg/l.

Table 4.2 Composition of raw abattoir waste (mean value ± standard deviation)

Parameters	Unit	Abattoir waste (AAAE)
pH		6.62 ± 0.47
TS	mg/l	10,823± 5,656.85
VS	mg/l	2,529.32 ± 638
COD	mg/l	6,950 ± 636.40
BOD_5	mg/l	3,975±775
TN	mg/l	171.5 ± 26.16
TP	mg/l	69.5 ± 21.72

The characteristics of sewage sludge as main substrate and the abattoir waste as co-substrate mixed in different mix ratio were analyzed and the results are tabulated in table 4.3 below. When the mixed wastes were characterized; the mean value of the total solid of 80%:20% mix by volume was 35,397 ± 3,145.7mg/l and that of 60%:40% mix of sewage sludge to abattoir waste was 31,148 ± 2,517mg/l, the volatile solid of the two mixes were 23,199 ± 2,053mg/l and 19, 327±1,678.4mg/l respectively. When considering the COD of the mixes 28,203 ± 1,609.7mg/l for 80%:20% mix and 25,607 ± 2,345mg/l for 60:40% mix of sewage sludge to abattoir waste (SS: AW). From table 4.1, the C/N of sewage sludge before digestion is about 660:1 which shows the deficiency of nutrients for efficient anaerobic digestion. From table 4.2, the C/N ratio of abattoir waste is 35:1, which is more than the nutrient values needed for anaerobes to carryout AD. Hence, mixing the both wastes (SS and AW) can enhance the digestion processes of sewage sludge.

Table 4.3 Characteristics of sewage sludge and abattoir waste mixtures at different mix ratio before digestion (mean ± standard deviation)

Parasite	Unit	SS alone (100%:0)	SS:AW (80%: 20%)	SS: AW (60%: 40%)
pH		7.47 ± 0.35	7.62 ± 0.23	6.78 ± 0.102
TS	mg/l	39,831 ± 3,987.6	35,397± 3,145.7	31,148 ± 2,517
VS	mg/l	27,043 ± 4,956	23,199±2,053	19, 327±1,678.4
COD	mg/l	32,872 ± 2,600.5	28,203 + 1,609.7	25,607 ± 2,345
BOD_5	mg/l	12,600 ± 3,567	11,222.9 ± 735.6	9,895±1,507.2
TN	mg/l	49.6± 8.3	84.5 ± 11.3	91.1 ± 3.3
TP	mg/l	78.8 ± 9.4	67.61 ± 4.1	83.02 ± 7.4
TK	mg/l	231.7 ± 13.25	107.13 ± 21.08	99.87 ± 15.16
Parasite ova				
Ascaris	No./l	18,000-39,000	14,000 - 32,000	10,000 - 32,000
Hook worm	No./l	0 – 3,800	0 – 3,800	Nil

4.1.3. Determination of Feedstock Characteristics after Digestion

The results of the experiment carried out with digestion and co-digestion of sewage sludge and abattoir waste to find out maximum biogas production with maximum methane yield were pointed out in table 4.4.

The total solid after digestion of sewage sludge alone, 80%:20% mix and 60%:40% mixes of sewage sludge to abattoir waste were 24,695 ±1,025mg/l, 21,592.2± 451.7mg/l and 18,880.6 ±123.5mg/l respectively. The mean value of volatile solid of the feed after digestions were 18,389.2 ± 1,614.27 for sewage sludge alone, 14,594.6 ± 1,307 mg/l for 80%:20% mix of sewage sludge to abattoir waste, and 11,460.9 ± 605.32mg/l for 60%:40% mix of sewage sludge to abattoir waste. The C/N ratio of mixtures of sewage sludge and abattoir wastes has improved as the mix ratio increases (table 4.3).

Table 4.4 Characteristics of feedstock after digestion (mean value ± standard deviation)

Parameters	Unit	SS alone (100%:0)	SS:AW (80%: 20%)	SS: AW (60%: 40%)
pH		7.93±0.106	7.67 ± 0.230	7.4 ± 0.004
TS	mg/l	25,965 ±1,025	21,592.2± 451.7	18,880.6 ±123.5
VS	mg/l	18,389.2 ± 1,614.27	14,594.6 ± 1,307	11,460.9 ± 605.32
COD	mg/l	10,891.6± 674.16	8,172.9 ± 827.13	7,228.1 ± 214.6
BOD_5	mg/l	2,898± 234.34	2,581.26 ± 267	2,275.8 ± 513.26
TN	mg/l	46.6 ± 6.82	62.6 ± 0.062	65.87 ± 0.023
TP	mg/l	68.6 ± 4.65	63.8 ± 0.042	76.349 ± 0.082
TK	mg/l	111.4 ± 8.67	69.2 ± 0.026	68.1 ± 0.034
Cu	mg/l	0.1602 ± 0.068	<0.0001	<0.0001
Ni	mg/l	0.0786 ± 0.084	0.0920 ± 0.018	0.1863 ± 0.048
Cr	mg/l	0.0139 ± 0.023	<0.0001	<0.0001
Pb	mg/l	0.0892 ± 0.056	0.0356 ± 0.023	<0.0001
Cd	mg/l	<0.0001	<0.0001	<0.0001
Zn	mg/L	0.748 ± 0.067	0.6627 + 0.030	0.5777 + 0.031
TC	MPN[1]/ 100ml	32 x 10^4	12 x 10^4	6 x 10^4
FC	MPN[1]/ 100ml	14 x10^4	7 x10^4	2 x10^4
Parasite ova				
Ascaris	No./l	18,000-39,000	14,000 - 32,000	10,000 - 32,000
Hook worm	No./l	0 – 3,800	0 – 3,800	Nil

[1]MPN = Most Probable Number

4.1.4. Determination of maximum mix ratio for highest methane yield

For the determination of maximum methane in the study from digestion and co-digestion of sewage sludge and abattoir waste: 100%, 80%:20% and 60%:40% mixes of sewage sludge to abattoir waste were used. The cumulative biogases produced during the experimental period for the digestion of the feed stocks were offered in table 4.5. From the digestion of sewage sludge alone: 0.51 $m^3/d/m^3$ biogas with 33.8% methane was produced; 0.85 $m^3/d/m^3$ and 0.93 $m^3/d/m^3$ (see annex-I for calculation of the above figures) biogas with 48.3% and 56.9% methane produced from 80%:20% mix and 60%:40% mix of sewage sludge to abattoir waste, respectively.

Table 4.5 Cumulative biogas production and composition during the experiment

Feed stock	Biogas (l/20 days)	Methane (%)	CO_2 (%)	Others (%)
Digestion of Sewage sludge alone	40.61	33.8	62. 9	3.3
Digestion of 80%:20% mix of SS to AW	68.12	48.3	42.36	9.34
Digestion of 60%:40% mix of SS to AW	74.28	56.9	30.89	12.21

4.1.5. Organic fertilizer potential of the Slurry (digestate)

The term complete fertilizer often refers to any mixture containing all three important elements; such fertilizers are described by a set of three numbers. They are usually sold in packages, on which the percentage by weight of the macronutrients nitrogen (N), phosphorus (P), and potassium (K) are listed on the label—always in the order N-P-K. For example, a fertilizer that is labeled 10-5-3 is 10 percent nitrogen, 5 percent phosphorus, and 3 percent potassium. For the determination of potential of organic fertilizer, the nitrogen, phosphorus and potassium content of the slurry (digestate) was measured and the mean value was displayed in table 4.6 below.

Table 4.6 Fertilizer value of feedstock after digestion

Parameters	Unit	SS alone	80%SS:20% AW mix	60%SS:40%AW mix
Nitrogen	mg/l	64.6 ± 6.82	62.6 ± 0.062	60 ± 0.023
Phosphorus	mg/l	68.6 ± 4.65	63.8 ± 0.042	54.4 ± 0.082
Potassium	mg/l	111.4 ± 8.67	69.2 ± 0.026	68.1 ± 0.034

4.2. Discussion

The quantity and quality of biogas produced with different mix ratio of sewage sludge and abattoir wastes (100%, 80%:20% and 60%:40%) are shown in table 4.5. The mix ratio (60% by volume of sewage sludge to 40 % by volume of abattoir wastes) was observed to produce the highest quantity of biogas in this study. This might be because of the replacement of nutrients lost from sewage sludge from abattoir wastes and however, further investigation is needed to know the reason behind the increments of biogas productivity as the mix ratio increases.

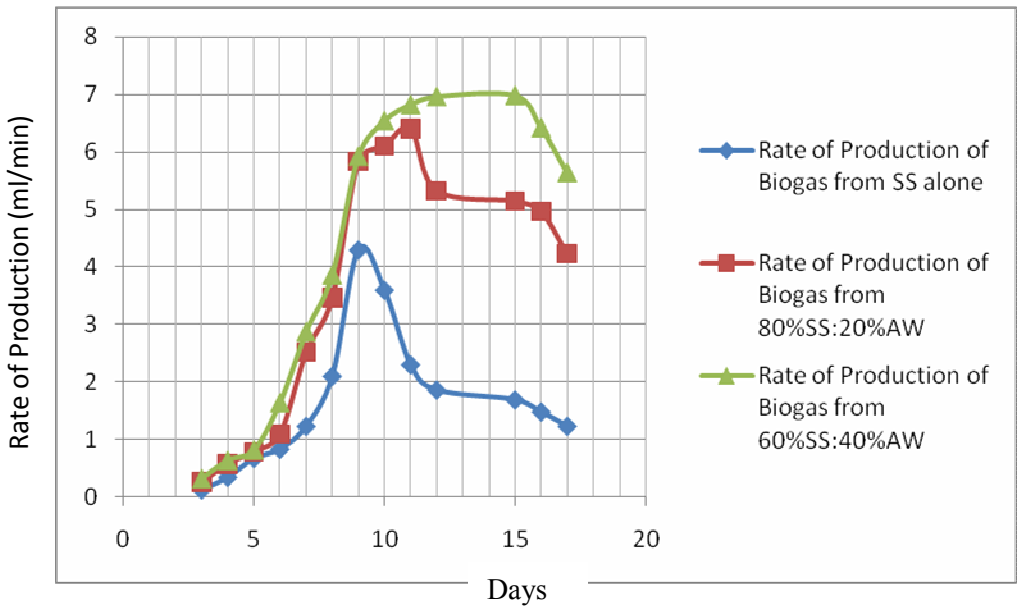

Fig. 4.1.Rate of production of Biogas from SS alone and from different mix ratio of SS to AW

4.2.1. Characteristics of Sewage Sludge and Abattoir Waste before Digestion

As presented in the Table 4.1, the physiochemical characteristics of sewage sludge exhibit extreme variations. These variations have also been observed in a number of prior studies and are attributed to several factors such as origin of the sludge, type of on-site sanitation system, amount of ageing that has taken place, extent of storm water and groundwater infiltration, and user habit [25].

Table 4.7 Comparison of parameters in the study with parameters compiled from literature

Parameter	Sewage sludge[1] (Kaliti)	Literature[2]
pH	7.47 ± 0.35	7.2 – 8.8
BOD_5 (mg/l)	12,600 ± 3,567	8,000 – 23,000
COD (mg/l)	32,872±2,600.5	10,000 – 97,000
COD/BOD_5	2:1 – 3.4:1	1.5:1 – 5:1
TS (mg/l)	39,831±3,987.6	12,000 – 45,100
VS (mg/l)	27,043 ± 4,956	≥ 50%TS
Helminthes eggs (no./l) Ascaris Hookworm	 18,000-39,000 0 – 3,800	-

Source: [1]values from under study; [2]Issac, 2003[26].

The number of helminthes eggs observed in this experimental study suggests that there is a great problem to ward sanitation based disease here in Addis Ababa. 1999 E.C health report of the city shows helmintic disease is in the 7th order with 3% prevalence among the ten top diseases. More over, the finding indicates the unsafe nature of untreated sewage sludge for land application.

As indicated in Table 4.7 all the mean values of parameters considered in this study are in harmony with the values from literature. The methane potential of a waste is related to the concentration of organics, chemical oxygen demand (COD) in it and the efficiency of

treatment. The COD to BOD_5 ratio ranges from 2:1 – 3.4:1 which indicates that, the sewage sludge under study has high organic content in which a considerable portion can be biodegradable. Consequently, anaerobic digestion processes can be another option for sewage sludge treatment with recovery of valuable energy and soil conditioner besides reduction of the volume of total and volatile solids. As observed from table 4.4, abattoir effluents are also rich in organic contents and nutrients which can enhance methane yield and serve as nutrients for anaerobes.

4.2.2. Characteristics of feedstock after digestion

Of the physiochemical properties after digestion of feedstock analyzed in this study, total solids, volatile solids, chemical oxygen demand and biological oxygen demands are discussed in detail as follows:

4.2.2.1. Total solids (TS)

Reduction of total solids by 38%, 39% and 39.4% of the feed stock for sewage sludge alone, 80%:20% and 60%: 40% mix of sewage sludge to abattoir waste, were observed respectively. This shows that there is a slightly increase in the removal efficiency of total solids as the mix ratio of sewage sludge and abattoir waste increases.

4.2.2.2. Volatile solids (VS)

As seen from table 4.4, reductions in volatile solids are also observed with the following percentages: 32%, 37.1% and 40.7% for sewage sludge alone, 80%:20% and 60%:40% mix of sewage sludge and abattoir waste respectively. From the reduction percentage of total solids and volatile solids, it can be concluded that co-digestion can reduce the area which is covered by dry cake in the dumpsite, Kaliti.

4.2.2.3. Chemical Oxygen Demand (COD)

Considerable removal efficiencies of COD were generally observed on sewage sludge and abattoir waste digestion with the average efficiency of 70%, 71%, and 71.8% for sewage sludge, 80%:20% mix of sewage sludge and abattoir waste and 60%:40% mix of sewage sludge and abattoir waste respectively. The COD removal efficiencies over the duration of the experiment were comparable to those reported in the literature ranging

from 60-75%. On the whole, the high removal efficiencies for COD are a good indication of the fact that the anaerobic digestion under proper operating conditions could be used for the pre-treatment of sewage sludge before the conventional sewage treatment plant.

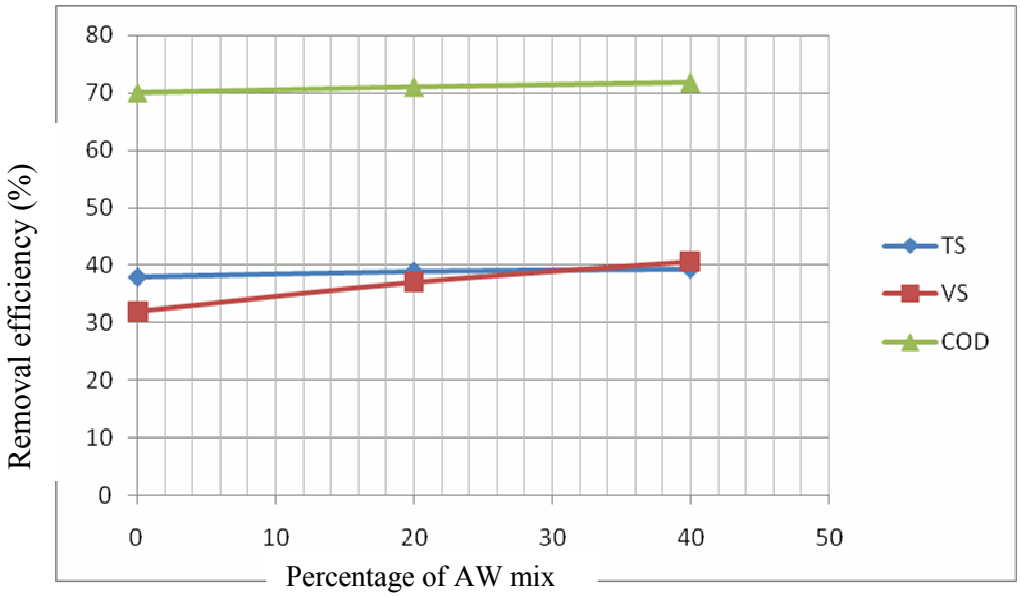

Fig. 4.2. Percent removal of TS, VS, and COD with respect to co-substrate mix (AW)

4.2.3. Identification of maximum mix ratio for the highest methane yield

The rate of production of biogas was measured by water displacement and the volumes of the biogas collected were recorded during the experiment period. The production of biogas was used mainly as an indication of the progress of the digestion process. The mean cumulative biogas produced for the digestion of sewage sludge and its co-digestion(AW) was indicated in Table 4.5 and is elaborated in Fig.4.3 below. As can be observed from Table 4.5 and Fig.4.3, biogas production from mixed digestion is better than digestion of sewage sludge alone and there is a trend of increase in biogas production with highest methane whenever co-substrate mix volume increase.

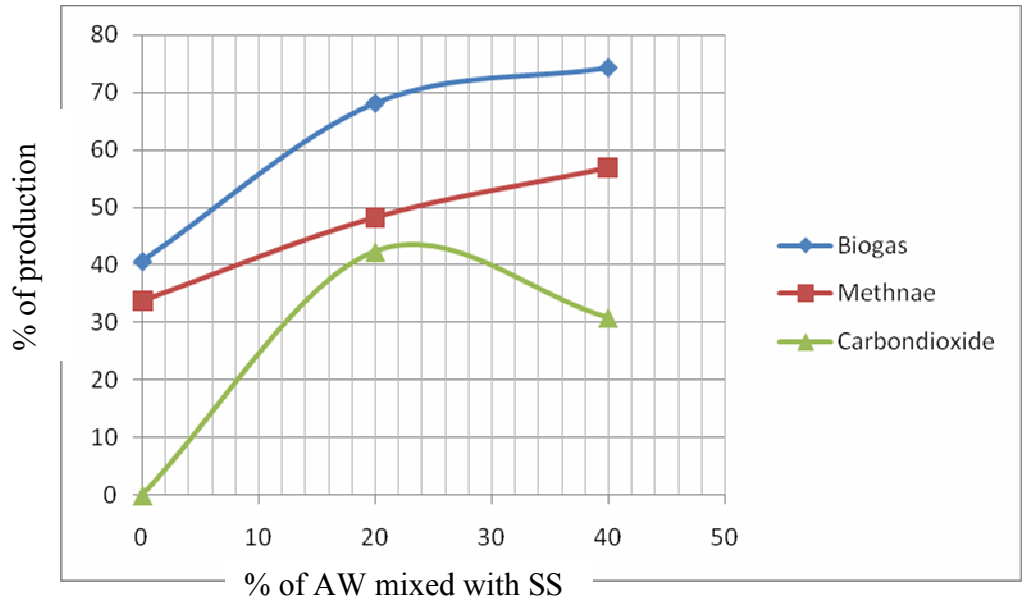

Fig.4.3. cummulative Biogas production vs percentage of co-substrate (AW)

4.2.4. Potential of sludge after digestion as an organic fertilizer

Due to the decomposition and breakdown of parts of its organic content, digested sludge provides fast-acting nutrients that easily enter into the soil solution, thus becoming immediately available to the plants. Hence, its soil conditioning value is enhanced. Nevertheless, the presence of pathogens and heavy metals must meet the requirements set by a country.

4.2.4.1. Heavy metal

From an agricultural point of view, the use of sewage sludge as fertilizer has restricted applications based on heavy metal content. Such limitations were published in the European Directive 86/278/EEC and in pollution control standard in Ethiopia [27, 28]. None of the heavy metals measured was over the maximum established limits as shown in Table 4.4. Increment in micronutrient after digestion is observed in this experimental study, such situation is observed by Ilangovan and Noyola [29] in using UASB reactor treating molasses stillage containing high concentration of potassium since potassium is one of the best extractants for metals bound to the exchangeable sites in sludge.

4.2.4.2. Pathogens

The digestion significantly reduce the coliform bacteria: 98.6 % for fecal coliform and 98.4 % for total coliform; but not the helminthes eggs, indicate that the digested sludge can not be directly used for agricultural application with out further treatment like sun drying which is less expensive than pasteurization to completely inactivate the remaining bacteria and helminthes eggs. It was observed complete removal of helminthes eggs after drying the digested sludge on direct sun light exposure for one month in this study. Ludwing [31] report the same situation of complete removal of parasite when the fermented slurry is dried in the sun.

4.2.4.3. Macronutrient

The agricultural value of sludge mainly derives from its nutrient content. Sludge, like other organic fertilizers, has long-term beneficial effects on the soil: organic matter contained in sewage sludge improves the physical properties of soil such as aggregate stability, water retention and infiltration, and reduce soil compatibility [31]. It was observed that this sludge had enough content of organic matter, nitrogen, phosphorus and potassium with a near to neutral pH (Table 4.4).Therefore, the sludge after digestion has fertilizing potential, especially if the entire process, such as the anaerobically digested sludge after being sun-dried on drying beds has been considered for completely inactivation of the pathogen.

5. Design of Anaerobic Digester

The design of anaerobic digester is a function of sludge production, digestion period, degree of digestion required, loss of moisture, and conversion of organic matter. If the progress of sludge digestion is assumed to be linear, than the capacity of the digestion tank (digester) is given as [23]:

$$V = (V_1 + V_2)/2 \times t \qquad (5.1)$$

where V = volume of the digester in m^3

V_1 = Raw sludge added per day, m^3/d

$V_2 = V_1/3$, Equivalent digested sludge produced per day on completion of digestion, m^3/d

t = digestion period, d.

When the daily digested sludge couldn't be removed (even though digestion gets completed) due to the factors, such as monsoon season, winter season, etc.; then separate capacity for its storage should be provided in the tank. This capacity eventually amounts to $V_2 \times T$, where T is the number of days for which the digested sludge is stored. The total digestor volume is then given as:

$$V = (V_1 + V_2)/2 \times t + V_2 \times T, \text{ for monsoon storage} \qquad (5.2)$$

However, when the change during digestion is assumed to be parabolic rather than linear, the average volume of digesting sludge will be $[V_1 - 2/3(V_1 - V_2)]$ and the required capacity will be given by:

$$V = \{V_1 - 2/3(V_1 - V_2)\} \times t \qquad (5.3)$$

$$V = \{V_1 - 2/3(V_1 - V_2)\} \times t + V_2 \times T, \text{ for monsoon storage} \qquad (5.4)$$

The capacity of the sludge digestion tank calculated above may also be modified for the following additional factors: amount of sludge withdrawn and its interval, provision of adequate free-board at the top, storage for winter or monsoon season, type of pre-treatment given to fresh sludge and collection of gas; etc.

5. 1. Design Criteria

As outlined above, the design of anaerobic digester is mainly depend on the loading rates (Hydraulic loading rate or Organic loading rate) of the system. Hydraulic loading rate is used in the design when the wastewater is relatively low strength such as domestic sewage. The maximum hydraulic loading rate is limited by the constraint that the Upflow velocity in the reactor must not cause excessive sludge wash-out. This Upflow velocity usually should not exceed 1m/h in the UASB reactor and is calculated as follows:

$$v_i = \frac{Q_i}{A} = \frac{V_i}{A(HRT)} = \frac{H}{(HRT)} \qquad (5.5)$$

where: v_i = liquid upward velocity (m/h);

Qi = average wastewater flow (m^3/h);

A = surface area of the UASB reactor (m^2);

Vr = volume of the reactor (m^3);

(HRT) = hydraulic retention time (h); and

H = height of the UASB reactor (m).

Van Haandel et al. [32] state that from available experimental results, an average retention time of six hours is sufficient in tropical and subtropical regions (T > 18^{o}C) to achieve satisfactory treatment efficiency in one compartment UASB reactors.

For concentrated wastewaters, the organic load rather than the hydraulic load becomes the determining factor in the design of the reactor. The organic load is defined as the mass of influent organic material per unit time and the specific organic load is the mass of influent organic materials per unit time and per unit of reactor volume. The specific organic load is expressed as kilograms COD applied per unit reactor volume and per unit time. The specific organic load is calculated as follows:

$$l_0 = \frac{L_0}{V_r} = \frac{Q_i S_{ti}}{V_r} = \frac{S_{ti}}{(HRT)} \qquad (5.6)$$

where: l_o = applied specific COD load (kg COD m^{-3} d^{-1})

L_o = organic (COD) load (kg COD d^{-1})

Vr = volume of the reactor (m^3);

Qi = average wastewater flow (m^3/d);

Sti = influent organic material (COD) concentration (kg/m^3);

(HRT) = hydraulic retention time (d).

The maximum design organic load of organic material may be 20 kg COD/m^3/d for wastes containing a high concentration of dissolved organic material of vegetable origin to be digested at or near the optimal temperature for mesophilic digestion [33].

Yet another criterion to be considered in design of reactor is its physical feature. They can be either circular or rectangular in shape. Circular reactors have the advantage of higher structural stability but are more difficult to construct than a rectangular or square unit. For this reason large reactors are generally constructed in rectangular or square cross sections and small reactors are generally constructed in cylindrical shape [34]. Furthermore, when more than one reactor unit is constructed, the rectangular shape is advantageous because sidewalls can be shared by different units.

5.2 Design of UASB reactor for sewage sludge treatment at Kaliti

For the design of Upflow Anaerobic Sludge Blanket (UASB) reactor for sites under study, Kaliti waste water treatment site, the following design assumptions will be used:

Table 5.1 Design Assumptions and Requirements

Population	3.3million
Current sewage managed at Kaliti	844 m^3/d
COD	32,872mg/l
Total Solids	39,831 mg/l
Volatile solid	27,043 mg/l
Mean temperature	16 ºC

Since the feedstock has high organic content, equation (5.2) is used for design of UASB.

Volumetric Load

Total volume of sewage sludge currently collected by government and non-government vehicles and managed at Kaliti dump site is 844 m^3 /d. Assuming dilution ratio of 1:5;

Volumetric load, V_{load} = 844m^3/d x 5 = 220m^3/d (5.7)

COD Load

Total COD_{load} = COD conc. x volume of daily dumped

= 32,872mg/l x 844m^3/d = 32,872 x 1000mg/m^3 x 844m^3/d

= 27,743,968 x 1000 mg/d = <u>27,744kg/d</u>

Influent COD concentration = [27,744 kg COD/d] /4,220 m^3/d

≈ <u>6.57 kg COD/m^3</u>

Assume applied specific COD load (lo) = 17 kg COD/m^3.d

Volume of reactor, Vr, = L_o / l_o, from equation (8.6)

$= [27{,}744 \text{ kg COD/d}] / 17 \text{ kg COD/m}^3\text{.d}$

$= 1{,}632 \text{ m}^3$; assuming 85% effective volume and the total reactor volume including free space are equal to $1{,}920 \text{ m}^3$.

From this total volume of reactor needed to undergo anaerobic digestion, it can be understood that one reactor can't handle the daily sewage sludge dumped at Kaliti site. Hence, more than one reactor has to be constructed to handle the daily dumped sewage sludge effectively. Using a reactor of dimensions (LWH), 10m x 8m x 6m, four compartments digester with volume of 480m^3each and a total volume of 1920m^3 can accommodate the waste to be digested.

Daily flow to each compartment = $V_{load}/4 = 4{,}220\text{m}^3\text{d}^{-1} /4 = 1{,}055\text{m}^3\text{/d}$

Organic load to each reactor = $6.57 \text{ kg/m}^3 \times 1{,}055 \text{ m}^3\text{/d} = 6{,}931.35 \text{ kg COD/d}$

Applied specific COD load $l_o = [6{,}931.35 \text{ kg COD/d}] / 480 \text{ m}^3 = 14.44 \text{ kg COD/m}^3\text{.d}$ which is $< 20 \text{ kg COD/m}^3\text{.d}$.

Total cross-sectional area of 4 compartment reactor = $4 \times 10\text{m} \times 8\text{m} = 320 \text{ m}^2$

Hydraulic retention time, $HRT = S_{ti} / l_o = [6.57 \text{ kg/m}^3] / [17 \text{ kg COD/m}^3\text{.d}]$

$= 0.3865\text{d} = 9.28\text{h}$

Upflow velocity, V_i (m/h) = H / (HRT) = 6m /9.28h = 0.65 m/h, which is < 1 m/h**.**

Table 5.2 Assumptions of Treatment Performance for UASB Reactor [26]

Parameter	Treatment Performance
COD removal	70%
TS removal	60%
VS removal	75%
Volume of methane per g COD removal	5.5 ml
Volume of methane per g VS removal	9.6 ml

Influent Characteristics after dilution

COD = 6.57kg/m^3

Total Solids = TS concentration x volumetric load

= 39,831mg/l x 844 m^3/d = 39.831 kg/m^3 x 844 m^3/d = 33,617.4 kg TS/d

TS concentration = [33,617.4 kg TS/d] /[4,220 m^3/d]

≈ 7.97 kg TS/m^3, i.e. ≈ 7,970 g/m^3 or mg/l

Volatile Solids load = VS concentration x volumetric load

= 27,043mg/l x 844 m^3/d

= 27.043 kg/m^3 x 844 m^3/d = 22,824.3kg VS/d

VS concentration = [22,824.3kg VS/d] / [4,220 m^3/d]

≈ 5.41 kg VS/m^3, i.e. ≈ 5,410 g/m^3 or mg/l

From assumed values of parameters given in Table 5.2, the effluent characteristics from the UASB reactor will be:

Effluent COD = 0.3 x 6,570 g/m^3 = 1,971 g/m^3

Effluent BOD (assuming COD/BOD is 3.4:1) = 579.7 g/m^3

Effluent TS = 0.4 x 7,970 g/m^3 = 3,188 g/m^3

Effluent VS = 0.25 x 5,410 g/m^3 = 1,352.50 g/m^3

Methane Production

Using the total volatile solids, the volume of methane produced can be computed as follows:

VS removed = 22,824.3kg VS/d x 0.75

= 17,118.23 kg VS/d = 17,118,230 g VS/d

Volume of methane = 9.6 ml/g VS x 17,118,230 g VS/d

= 164,435,008ml/d

= 174,435 l/d ≈ 174.4 m^3/d methane can be produce.

About 52,320m^3 methane can be produced annually (for the system operating 300 days per year) if UASB reactor is constructed at this dump site. This brings an electric energy equivalent of 406,946.23 kWh and income of 150,570.10 Birr/year with the current price of around 37cents per kWh.

6. Mass and Energy Balance

Material and energy balances are fundamental to many engineering disciplines and have a major role in decisions related to sustainability of the engineering ventures. Material quantities, as they pass through processing operations, can be described by material balances. Such balances are statements on the conservation of mass. Similarly, energy quantities can be described by energy balances, which are statements on the conservation of energy. If there is no accumulation, what goes into a process must come out. This is true for batch operation. It is equally true for continuous operation over any chosen time interval.

6.1. Mass Balance

A mass balance (also called a material balance) is an application of conservation of mass to the analysis of physical systems. By accounting for material entering and leaving a system, mass flows can be identified which might have been unknown, or difficult to measure without this technique. The exact conservation law used in the analysis of the system depends on the context of the problem but all revolve around mass conservation, i.e. that matter cannot disappear or be created spontaneously. Therefore, mass balances are used widely in engineering and environmental analyses. In anaerobic digestion, the material balance is a typical flow of materials for an anaerobic digestion system. An overall mass balance can be constructed to examine the products from the anaerobic digestion of solid wastes.

Solid wastes entering the digester consist of organic material, inorganic constituents and water. During digestion a fraction of the volatile solids are converted into biogas. The biogas consists primarily of methane and carbon dioxide. Other compounds that are present in the biogas such as hydrogen sulfide are practically important but due to their low fraction will not be considered in the framework when calculating the volumetric weight of the biogas. Also leaving the digester are the digested residue, waste water and non-recyclables. The digested residue consists of the volatile solids that were not converted into gas, any microbial biomass formed and the fraction of the total solids that was not digestible. The amount of waste water that comes out of the digester will change depending on the technology used.

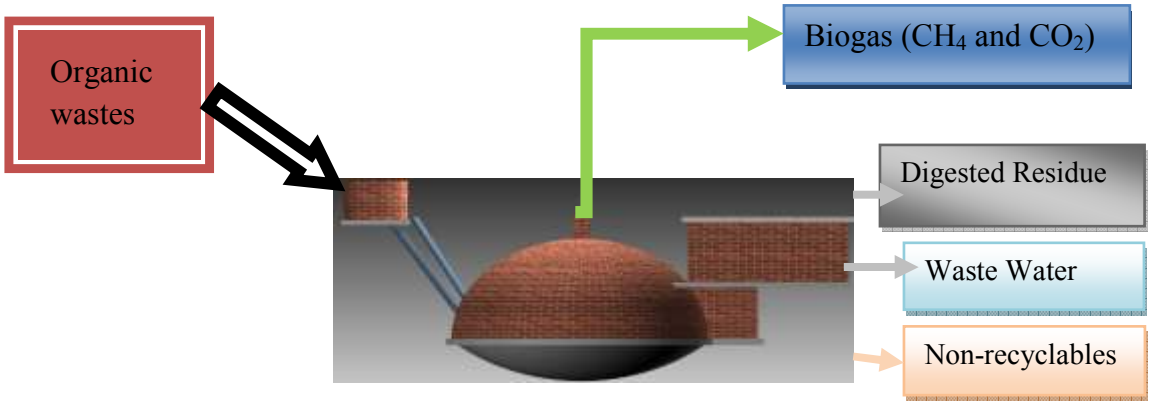

Fig.6.1. Mass Balance of Anaerobic Digestion

The first step in mass balance in anaerobic digestion is to determine the composition and characteristics of the feedstock which are already done. Mass balance with in the UASB reactor for any given constituent takes the form:

Accumulation = Input – Output + Generation and each term in the mass balance equation have the units of mass/time. Assuming all the wasted organic solids in the effluent stream and taking solid residence time 20 days and the treatment efficiency of UASB, the following mass balance can be computed:

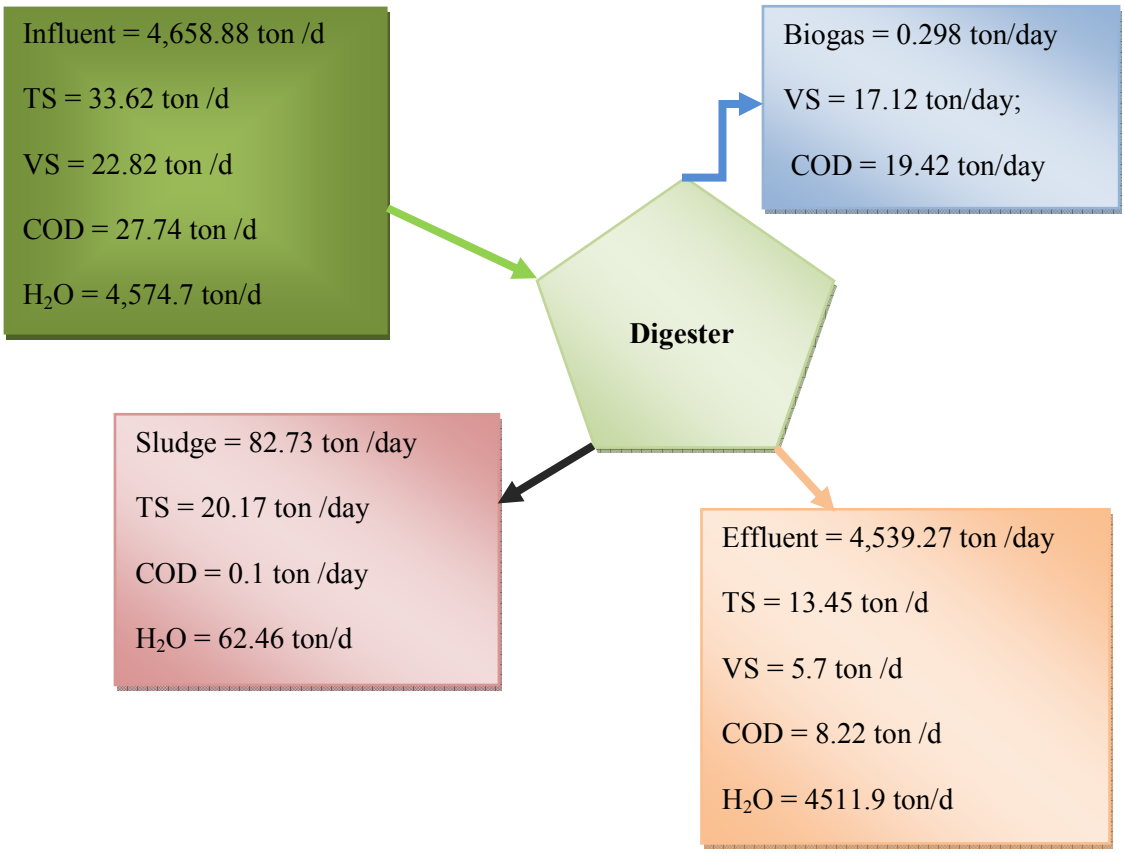

Fig.6.2. Complete mass balance of anaerobic digestion

6.2. Energy Balance

Energy balance of an anaerobic digester involves fuel value of biogas, conversion of biogas to useful energy and digester heat input.

Energy balance in UASB is balance between energy produced from biogas and energy required to maintain mesophilic temperatures. Other energy requirements of anaerobic digester are stirring, pumping, etc. Energy produced depends on OMR, so for feed stocks with lower ODM, energy produced will be lower.

Digester Heat Loss/Input

There are two parts of digester heat inputs: heat lost from digester tank and heat required to raise temperature of feedstock.

To calculate heat lost from tank, we need to know surface area, conductivity and thickness of insulation and temperature difference. To calculate heat required to raise temp of feed, we need to know mass of feedstock and temperature difference.

From assumptions based on Metcalf and Eddy [1] and present study; specific heat capacity of sludge = 4,200 J/kg. ^{0}C**, c**oncrete digester with dimension 10m x 8m x 6m, daily flow to the reactor 4,220 m^3, sludge temperature 13 ^{0}C, heat transfer coefficient (U), plain concrete wall above ground, 300 mm thick not insulated = 4.7-5.1 W/$m^2.^0$C, Plain concrete floor, 300 mm thick in contact with dry earth = 1.7 W/$m^2.^0$C, and fixed concrete cover, 100 mm thick and covered with built up roofing = 4-5 W/$m^2.^0$C, have been considered. To calculate the heat requirement for the sludge, the following equation has been used:

$$Q_s = m_s C_p \Delta T \qquad (6.1)$$

$$= (4{,}220\ m^3/d)\ (1020\ kg/\ m^3)\ (4{,}200\ J/kg.\ ^0c)\ (35\ ^0c - 13\ ^0c)$$

$$= 3977 \times 10^8\ J/d = 4603.5\ kW$$

Computation of area of wall, floor and roof:

Wall = $2[(10 \times 6) + (8 \times 6)]\ m^2 = 312\ m^2$

Floor = $2 \times (10 \times 8)\ m^2 = 160\ m^2$

Roof = $2 \times (10 \times 8)\ m^2 = 160\ m^2$

Heat loss by conduction is calculated using the basic equation:

$$Q = UA\Delta T \qquad (6.2)$$

Wall = $2\{(5\ W/m^2.^0c)\ (312\ m^2)\ (35\ ^0c - 16\ ^0c)\ (86400\ sec/d)\} = 51.22 \times 10^8\ J/d$

Floor= $2\{(1.7\ W/m^2.^0c)\ (160\ m^2)\ (35\ ^0c - 16\ ^0c)\ (86400\ sec/d)\} = 8.93 \times 10^8\ J/d$

Roof = $2\{(5\ W/m^2.^0c)\ (160\ m^2)\ (35\ ^0c - 16\ ^0c)\ (86400\ sec/d)\} = 26.27 \times 10^8\ J/d$

Total loss = (51.22 x 10^8 + 8.93 + 26.27 x 10^8) J/d = 86.42 x 10^8 J/d = 99.72kW

Calculate the heat exchanger capacity required for the system:

Qs = heat required for sludge and heat required for digester

Qs = 3977 x10^8 J/d + 86.42 x 10^8 J/d

Qs = 4063.42 x10^8 J/d = 4703.21 kW

Still there is mass flow heat through hot water and this can be computed as follows:

Mass flow of hot water, assuming change in temperature 19^{o}C

$Q_w = m_w C_p \Delta T$; $m_w = Q_w / C_p \Delta T$, from equation (6.1)

= (4063.42 x10^8 J/d) / (4,200 J/kg. ^{0}C x 19 ^{o}C) = 6 x 10^6 kg/d = 6,000 m^3/d

,(ρ_{H2O} = 1000kgm^{-3})

7. Economic Analysis of the Project

Anaerobic digestion systems provide an opportunity to produce renewable energy from sewage sludge. These systems are typically quite capital intensive and require a thorough economic analysis to assess economic feasibility [34, 35]. Economic fundamentals such as rising energy prices continue to improve the economic potential of these systems.

To determine the cost-benefit and feasibility of implementing an AD facility at Kaliti waste water treatment site, several factors must be considered. First, the source of the waste must be determined (wastes from toilet and septic tanks) as well as the means to separate and collect it. Next, an appropriate technology must be chosen, that best suits the characteristics of the city's waste and limitation capacity to manage all wastes. Finally, the markets for the products, both solid and gas, must be established. If all these criteria are met, the interest and enthusiasm of the governing authorities or investor must be present before a plant can be sited [36].

The cost to construct the digester must be known in order to study the feasibility of this project. Assuming the dimensions of the digester as earlier, 10m x 8m x 6m, for length, width and height respectively, and assuming the thickness of the wall is 0.2 at the top and 0.5 at the bottom, the cross sectional area of the wall of the digester will be:

Cross sectional area of the wall = 0.5x (0.2 + 0.5) x 6 = 2.1 m^2

Volume of reinforced concrete for wall = 2 x (8 + 10) m x 2.1m^2 = 75.6 m^3 and

[(2x10) +8] m x 2.1m^2 = 58.8 m^3 for the other compartment

Let the depth of foundation slab be 0.5m

Volume of reinforced concrete for the slab = 0.5m x 8m x 10m = 40 m^3

Let depth of top slab be 0.1m,

Volume of reinforced concrete for the slab = 0.1m x 8m x 10m = 8m^3

The current market price of unit rate for the reinforced concrete including rebar and labour is ≈ 6,860.00 Birr.

Over all reinforced concrete cost = 6,860.00x (75.6 m^3+ 40 m^3+ 8m^3) = 847,896.00 Birr and 6,860.00 x (58.8 m^3 + 40 m^3 + 8m^3) = 732,648 Birr for the other compartment

Area of framework for wall = 2 x 2 x (8m + 10m) x 6m = 432m^2 and

[(2x10) +8] m x 6m = 168m^2

Area of framework for top slab = 8m x 10m = 80m^2

The current market price for unit rate of framework including labour cost, Birr 572.00

Overall framework cost = 572 x (432 m^2+ 80m^2) = 292,864.00 Birr and

572 x (168 m^2 + 80m^2) = 141,856.00 Birr is needed for the additional compartment attached to one side of the digester.

Total construction cost for a digester = 847,896.00 + 292,864.00 = 1,140,760.00 Birr

Hence, total construction cost for other 3 compartments attached to one side of digester wall is 3x (847,896.00 + 292,864.00) = 3,422,280 Birr

For the four compartment digester, (1,140,760 + 3,422,280) Birr = 4,563,040 Birr

Cost estimate of storage / flow equalizer tank all in Birr

Let the Width, length and height of the storage tank are 8m, 12m, and 3m respectively and let the thickness of the wall be 0.2m at the top and 0.5 at the bottom;
Cross sectional area of the wall = 0.5x (0.2 + 0.5) m x 3m = 1.05 m^2

Volume of reinforced concrete for wall = 2x (8m + 12m) x 1.05m^2 = 42 m^3 and [(2 x 12m) + 8m] x1.05m^2 = 33.6 m^3

Let the depth of foundation slab be 0.5m

Volume of reinforced concrete for the slab = 0.5m x 8m x 12m = 48 m^3

Let depth of top slab be 0.1m

Volume of reinforced concrete for slab = 0.1m x 8m x 12m = 9.6 m^3

Current market price for the unit rate of reinforced concrete including rebar and labour is 6,860.00 Birr.

Over all reinforced concrete cost = 6,860.00 x (42 m^3 + 48 m^3 + 9.6 m^3) = 683,256.00 and 6,860.00 x (33.6 m^3+48 m^3 + 9.6 m^3) = 625,632.00 Birr

Area of framework for wall = 2 x 2 x (8m + 12m) x 3m = 240m^2 and

[(2x12m) +8m)] x 3m = 96m^2

Area of formwork for top slab = 8m x 12m = 96 m^2

The current market price for the unit rate of framework including labour cost is 572.00 Birr.

Overall framework cost = 572.00 x (240 m^2 + 96 m^2) = 192,192.00 Birr and

572.00 x (96m^2 + 96 m^2) = 109,824.00 Birr

Total construction cost for a storage tank = 683,256.00 + 192,192.00 = 875,448.00Birr

Total construction of other 7 compartment =7x (625,632 +109,824) Birr = 5,148,192.00 Birr is required.

For the 8 compartment storage tanks = (875,448.00 + 5,148,192.00) Birr = 6,023,640.00 Birr is needed.

The cost of heat exchanger has to also be considered in construction of anaerobic tank. Exchanger type: shell/tube, floating head large area 3,444 ft^2, carbon steel, internal pressure 150 psi rating cost 91,900USD in 2007 [35]; with the 13.74 Birr per US dollar current exchange to 1,262,706.00 Birr.

Solar water heater

Heat required is 4703.21 kW, assuming radiation of 5.62 kWh /m^2.day and the power collected per square meter is (5.62 kWh /m^2.day) x (day/24 hours) = 487.5 W/m^2). Heliostat area required is therefore; (4703.21 kW) / 487.5 W/m^2 = 9,648 m^2, let say 9,600 m^2. The area of a unit heliostat is 120m^2 and its cost is 48.00 USD. Number of heliostat required for such activity is: 9,600 m^2/ 120 m^2 = 80. The total cost is 80 x 48.00 USD = 3840.00 USD which is equal to 52,761.60Birr with the current exchange rate of 13.74Birr per US dollar.

Cost estimate for hot water pump

Centrifugal pump, vertical turbine one stage discharge pipe diameter 4 inch made from cast iron and APi-610 with seal type packing 3,700 USD [35] which is equal to 50,838.00Birr is needed.

Cost estimate for propeller top entering with 3hp working in atmospheric pressure mixing chamber agitator 4,900 USD [35] which is equal to 67,326.00Birr. For eight mixers 538,608.00Birr is required.

Direct cost or total physical cost of the plant

Civil and mechanical cost (all in Birr):

Total construction cost for digester = 4,563,040.00 Birr

Total construction cost for storage tank = 6,023,640.00 Birr

Process equipment cost can be computed as follows (all in Birr**):**

Total purchase cost of major equipments (PCE)

Shell and tube heat exchanger =1,262,706.00

Agitator = 538,608.00Birr, Pump = 50,838.00Birr, Heliostat = 52,761.60Birr

Total = 1,904,913.60 Birr

Estimation of fixed capital cost, reference table 6.1 in Coulson [36]

The major direct costs to be added to PCE are listed below; PCE = 1,904,913.60 Birr

Equipment erection (f_1) = 0.4; Piping (f_2) = 0.7; Instrumentation (f_3) = 0.2;

Electrical (f_4) = 0.2

Therefore, the total physical plant cost (PPC) or direct cost is:

PPC = PCE ($1 + f_1 + f_2 + f_3 + f_4$) = 1,904,913.60 Birr x (1+0.4+0.7+0.2+0.2)

= 4,762,284.00 Birr

The major indirect cost: design and engineering (f_{10}) = 0.3; contingencies (f_{12}) = 0.1

Fixed capital cost (FC) = PPC ($1 + f_{10} + f_{12}$) = 4,762,284.00 Birr x (1+0.3+0.1)

= 6,667,197.60 Birr

Total investment cost required for the project = FC = 6,667,197.60 Birr, and including the civil and mechanical cost = 17,253,877.60 Birr.

Annual operating cost, reference table 6.6 from Coulson [36]

Assuming operating time 300 days in a year, and there are two basic costs in this category:

I. Fixed cost *(*Birr*)*

Maintenance cost 10% of fixed capital cost = 441,947.10 Birr

Operating labour one extra man a day 1000 birr per month = 12,000 Birr per year

Plant overheads = 50% of operating labour and maintenance cost = 226,973.55 Birr

Laboratory 30% of operating labour = 3,600

Insurance 1% of fixed capital = 44,194.71 Birr

Fixed cost = 728,715.36 Birr

II. Variable costs *(*Birr*)*

Raw materials = 0

Cost to transport AW = 1,823,040.00 Birr

Miscellaneous materials, 10% of maintenance cost = 44,194.71 Birr

Utility - Electric power = 0.37 birr/kWh x 43.2 kW x 8hour/day x 300 day /year = 38,361.60 Birr

Shipping and packaging = not applicable

Variable cost = 1,905,596.31 Birr

Direct production cost (DPC) = variable cost + fixed cost = 2,634,311.67 Birr

Sales expense, General overheads and research and development = not applicable

Total production cost or annual operating cost = 811,271.67 Birr

Estimation of benefits of total income

The major benefits of anaerobic digestion are: methane, fertilizer, and environmental, health and social benefit.

I. Methane

Annually, 52,320 m^3methane is produced. Assuming the heating value of methane 650 Btu/ft^3 [38, 39], the energy equivalent is 24,143,790.00 J/m^3 which is equal to 352,096.91 kWh /year. Assuming the utilization of electric energy to be more efficient than methane utilization by 5%, then the electrical energy equivalent of such amount of energy is 334,492.03 kWh /year. The current rate of electrical energy utilization price by Ethiopian electric and power authority was 37 cents per kWh and considering 15% tax, the price of the produced energy from methane is 142,326.35 Birr.

II. Fertilizer

The term complete fertilizer often refers to any mixture containing all three important elements listed as N (nitrogen), P_2O_5 (phosphate equivalent) and K_2O (potash equivalent). Fertilizer grade is the percent weigh of N, P_2O_5 and K_2O given to fertilizer and figured on a full ton basis. Urea is 46% N and grade as (46-0-0) and its current price is $275.60 per ton. Diammonium phosphate (DAP) grade as (18-46-0), it has 18% nitrogen and 46% P_2O_5 [37]. Its current price is $324.22, cost of 18% nitrogen and that of 46% phosphate as P_2O_5. Potash grade is (0-0-60) and its price is $203.10.

Nitrogen fertilizer

Equivalent urea for nitrogen content in sewage sludge after digestion is given by:

Mass of urea = (mass of nitrogen) / 0.46 [37, 40].

Mass of nitrogen in the sewage sludge = concentration x rate of flow = 65.9 mg/l x 82.08 m^3/d. Assuming 300 days in a year, the mass of nitrogen is 1,622.722 kg/year. Mass of urea is therefore divide the value by 0.46 and equals 3.53 ton/year. This cost $972.87. With the current exchange rate of USD and Birr, i.e. 13.72birr, the price is 13,347.75 Birr will be obtained from urea produced during the process.

Phosphorus fertilizer as P_2O_5

Equivalents DAP for phosphorus as P_2O_5 content in sewage sludge after digestion is given by: Mass of DAP = (mass of phosphorus as P_2O_5) / 0.46 [37].

Mass of phosphorus in the sewage sludge = 76.35 mg/l x 82.02m^3/d x 300day/year = 1.88 ton/year. Mass of P_2O_5 in the sludge after digestion is given by using conversion factor 0.748 which is equal to 1.41 ton/year; then mass of equivalent DAP is 3.065 ton/year and the price is $824.49 which is equal to 11,312.00 Birr using the current 13.74 birr per USD. Mass of nitrogen in the DAP is 0.5517ton/year which is $126.34 = 1,733.40 Birr; therefore, the price of phosphorus fertilizer as P_2O_5 is 11,312.00 Birr - 1,733.40 Birr = 9,578.60 Birr.

Potash fertilizer

Potash fertilizers are quantified by their K_2O equivalent. Mass of potassium in the sewage sludge after digestion as K_2O using the conversion factor 1.21 from potassium to K_2O [37,41] =111.4 mg/l x1.21x 82.08 m^3/d x 300 days/year = 3.32 ton/year. The K_2O equivalent of the mass of potash fertilizer is 5.53 ton/year and its price $934.57 which is equal to 12,822.30 Birr.

III. Environmental, health and social benefit

It is difficult to valuate exactly such benefits prior of making assessments on the environmental, health and social added values the communities can obtain on implementation of this project. However, to estimate such issue, let us take the cost of safe disposal individual pays for vacuum truck for service they got; which is on average 14.70 Birr per cubic meter. The total waste collected annually 253,200 cubic meter which cost = 3,722,040.00 Birr. Assuming 25% of such safe disposal cost for environmental, health and social benefits in using anaerobic digester which costs 930,510.00 Birr, the total cost of safe disposal and benefit = 4,652,550.00 Birr.

Economic evaluation

Net cash flow (NCF):

Gross profit (GP) = sales income – total production cost

= 4,830,625.00 – 2,634,311.67= 2,196,313.30 Birr

Depreciation cost (DC): assuming zero salvage value, 10 year service life and straight line method

DC = (depreciable FCI –salvage value) / service life

= 17,253,877.60ETB/10 year = 1,725,387.75 Birr

Neglecting tax, scrap value and time value of money, the net profit (NP) is given by:

NP = GP – DC = 2,196,313.30 Birr - 1,725,387.75 Birr = 470,925.55 Birr /year

Pay back period (PBP) = DC / NP = (1,725,387.75) / (470,925.55)

= 3.66years

Rate of return on investment (ROR) = GP / (total investment)

= (2,196,313.30 / 17,253,877.60) x100 = 12.7%.

8. Conclusions and Recommendations

8.1. Conclusions

Sewage sludge wastes are loaded by organic portion which contains the most valuable elements, carbon, for the formation of methane where as abattoir effluents contain excess valuable nutrients for anaerobes which lead the co-digestion of the two wastes to high degree of methanization process.

As shown in Table 4.5 and Fig.4.3, the mix ratio (60% by volume of sewage sludge to 40 % by volume of abattoir wastes) was observed to produce the maximum quantity of biogas with the maximum percentage of methane. This shows that co-digestion of sewage sludge and abattoir wastes enhance the quality and quantities of methane yield.

From Fig.4.2, the average percentage removal of TS, VS, and COD increase with the mix ratio of the sewage sludge and its co-substrate (abattoir wastes). From the average percentage reduction of those parameters, it can be concluded that there is a reduction in

the volume of the waste if anaerobic digester is executed at the dump site of Kaliti waste water treatment plant.

The experimental results showed that, using anaerobic digestion of sewage sludge considerable amount of methane can be captured from being emitted into atmosphere so as to prevent greenhouse effect. Into the bargain, valuable energy and high quality organic fertilizers can also be obtained from AD of sewage sludge and abattoir effluents.

8.2. Recommendations

From the findings of this research study, anaerobic digestion technology is recommended for the efficient handlings of ever increasing sewage sludge at the Kaliti dump site. Abattoir wastes are suggested to be used as co-substrate for the efficient digestion of sewage sludge. However, yet better appropriate co-substrate should be searched and tested to increase the feasibility of the biogas production from sewage sludge. Pilot biogas plant is recommended to be constructed onsite with the same operating scheme done at laboratory scale and its effectiveness under different conditions and seasons should be tested before the execution of this project; in contrast to batch process used in this study, further study is recommended to be done and its effectiveness has to be checked by using continuous process. Repeatedly researches are also recommended to be carriedout in order to assure the feasibility of the process.

8.3. Further Investigations

As seen from this study, biogas generation rate was increase with the mix ratio of abattoir wastes with sewage sludge. This can be as results of increase in dilution of the mixture, which can facilitate sympathetic environment for anaerobes or because of the addition of nutrients to the sewage sludge. Hence, therefore, further study is need in order to justify the reason behinds the increments of biogas generation with mix ratio of abattoir wastes with sewage sludge.

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Appendices-I: Calculations of amount of biogas in $m^3/d/m^3$

From table…, 40.61 L/20d biogas was produced from 4L (5 L- 1 L) SS feed only. Five liter sample was feed into the digester out of which one liter is starter (inoculums).

$40.61 \times 10^{-3} m^3/20d/4 \times 10^{-3} m^3 = 0.51 m^3/d/m^3$ biogas was produced. ($1m^3 = 10^3$ L)

$68.12 \times 10^{-3} m^3/20d/4 \times 10^{-3} m^3 = 0.85 m^3/d/m^3$ biogas was produced.

$74.28 \times 10^{-3} m^3/20d/4 \times 10^{-3} m^3 = 0.93 m^3/d/m^3$ biogas was produced.

Appendices -II: Laboratory procedures

1.1. COD

Method

1) Adaptation of the USEPA 410.4 approved method for the COD determination on surface waters and wastewater
2) Oxidizable organic compounds reduce the dichromate ion (orange) to the chromic ion (green)
3) The amount of remaining dichromate is determined

Required reagent

1) Reagent vial
2) Deionized water

Materials used

1) C9800 Hanna reactor
2) HI 740216 test tube cooling rack

Measurement procedure

Reagent blank correction

a) This method needs a reagent blank correction
b) A single vial may be used more than once
c) The blank vial is stable for several months (room temperature)
d) For most accurate measurement, run a blank for each set of measurements and always use the same lot of reagents for blank and sample

Choose a homogeneous sample

Samples containing settle able solids need to be homogenized with a blender

1) Preheat the Hanna reactor C9800 to 150 ^{0}c (32^{o}F)
2) Remove the cap from two reagent vials
3) Add exactly 0.2 ml of sample to one vial (sample vial)
4) Add exactly 0.2ml of deionized water to the other (blank vial)
    a) Keep the vial at 45 degree angle while adding the water and the sample
    b) Replace the cap tightly and mix by inverting each vial a couple of times
    c) Insert the vials into the reactor and heat them for 2 hours at 150^{o}c
    d) At the end of digestion period switch of the reactor and wait for 20 minute to allow the vials to cool to about 120^{o}c
    e) Invert each vials several times while still warm, then place them in the test tube rack
    f) Leave the vials in the tube rack to cool to room temperature

    Do not shake or invert any more otherwise the sample may become turbid

    1) Select the program number corresponding to oxygen demand, chemical HR (COD) on the secondary LCD by pressing program increase or decrease symbol
    2) Place the blank vial into the holder and push it completely down
    3) Press zero and ‘sip’ will blink on the display
    4) Wait for a few seconds and the display will show ‘-0.0-‘ now the meter is zeroed and ready for measurement
    5) Remove the blank vial
    6) Place the sample vial into the holder and push it completely down
    7) Press read direct and ‘sip’ will blink during measurement
    8) Instrument directly displays concentration in mg/l of oxygen demand on the crystal display
    9) multiply the reading on the liquid crystal display by 10 to obtain the concentration in mg/l of oxygen demand
    10) Interference
        a) Chloride above 20000 mg/l

b) Samples with higher chloride concentration should be diluted

BOD_5

Method

Lovibond BOD system oxidirect

1) preparing the sample
2) estimate the measurement reagent and select the volume for the sample
3) The sample volume is related to the expected BOD value. The oxidirect is designed to operate with the following ranges and samples volume allowing BOD measurement up to 0-4000 mg/l with out any dilution
4) for 0-2000 mg/l expected value 56 ml sample volume with 3 drop ATH to avoid nitrification and 3-4 drop KOH
5) for 0-4000 mg/l expected value 21.2 ml sample volume with 1 drop ATH to avoid nitrification and 3-4 drop KOH
6) carry out the necessary pre treatment of the sample (setting pH value 6.5 to 7.5, filtering)
   a) the optimum pH value for BOD is between 6.5 and 7.5
   b) if higher or lower adjust by HCL or H_2SO_4 and NaOH
   c) mix well and advisable to settle or filter

Required reagent

a) KOH to absorb CO_2
b) ATH to avoid nitrification

Materials used

a) BOD bottle
b) BOD sensor
c) BOD bottle rack
d) Incubator
e) Measuring cylinder

Measurement procedure

1) measure the sample precisely using appropriate over flow and if necessary add nitrification inhibitor (ATH)
2) insert magnetic stirring rod
3) place 3-4 drop of KOH solution into the seal gasket and insert gasket in the neck of the bottle
4) screw the BOD sensors to the sample bottle
5) place the bottle in the bottle rack
6) start the measurement
7) incubate the sample in accordance with the instructions BOD_5 for 5 days at 20 ^{0}C

TS and VS

Method

APHA, procedure 2540B and 2540E

Apparatus used

a) Evaporating dishes
b) Desiccator, provided with a desiccant containing a color indicator of moisture
c) Drying oven operating at 103-105 ^{0}C
d) Analytical balance
e) Graduated cylinder
f) Beaker
g) Muffle furnace for operating at 550 ^{0}C

Measuring procedure

Preparation of evaporating dish

a) Ignite clean evaporating dish at 550 ^{0}C for 1h in a muffle furnace for VS
b) Heat clean dish to 103 to 105 ^{0}C for 1h
c) Store and cool dish in desiccator until needed
d) Weigh immediately before use

Sample analysis

a) Pipet a measured volume of well mixed sample to a pre-weighed dish
b) Evaporate to dryness on drying oven
c) If necessary add successive sample portions to the same dish after evaporation

d) Cool dish in desiccator to balance temperature, and weigh

e) Ignite the residue produced by method 2540B in a muffle furnace

f) Transfer to a desiccator for final cooling in a dry atmosphere

Calculation

$$mg\ total\ solid\ /\ L = \frac{(A-B)}{Sample\ volume, ml} X100$$

where: A = weight of dried residue + dish, mg, and B = weight of dish, mg.

$$mg\ volatile\ solid\ /\ L = \frac{(A-B)}{Sample\ volume, ml} X100$$

where: A = weight of dried residue + dish before ignition, mg and

B = weight of residue + dish after ignition, mg.

Total coliform and fecal coliform

Method

APHA, procedure 9221B and 9221E

Materials used

Volumetric flask, Durham tube, spatula, loop, test tube rack, incubator, autoclave, sewage, and culture media

Presumptive phase

a) Reagent and culture medium – lactose peptone broth

b) Procedure

c) Prepare growth media

   a. 70 gm in 1 ml distilled water

   b. Sterilize at 121 ^{0}C for 15 min

1) Arrange fermentation tubes in rows of five or ten tubes

2) Add 10 ml growth media in each tube

3) Inoculate each tube in a set of five with replicate sample volumes

4) Mix test portions in the medium by gentle agitation

5) Incubate inoculated tubes or bottles at 37 ^{0}C. After 24 $\pm$ 2h swirl each tube or bottle gently and examine it for growth, gas and acidic reaction (shades of yellow color). If no gas or acidic reaction is evident, reincubate and reexamine at the end of 48 $\pm$ 3h. Record presence or absence of growth, gas, and acid production. Growth with acidity signifies a positive presumptive reaction
6) Interpretation- production of an acidic reaction or gas in the tubes or bottles within 48 $\pm$ 3h constitutes a positive presumptive reaction. Submit tubes with a positive presumptive reaction to the confirmed phase

Confirmed phase

a) Culture medium- brilliant green lactose bile broth
b) Procedure

Prepare growth media

a) 40 gm in 1 ml distilled water
b) Sterilize at 121 ^{0}C for 15 min

1) Submit all presumptive tubes or bottles showing growth, any amount of gas, or acidic reaction with in 24 $\pm$ 2h of incubation to the confirmed phase
2) Gently shake or rotate presumptive tubes or bottles showing gas or acidic growth to resuspend the organisms.
3) With a sterile loop 3 to 3.5 mm diameter, transfer one or more loopfuls of culture to a fermentation tube containing brilliant green lactose bile broth
4) Incubate the inoculated brilliant green lactose bile broth tube at 37^{0}C for total coliform and 44 ^{0}C for fecal coliform. Formation of gas in any amount in the inverted vial of the brilliant green lactose bile broth fermentation tube at any time with in 48 $\pm$ 3h constitutes a positive confirmed phase

For the combination of positive tubes calculate bacterial density according to the following formula:

$$MPN/100ml = MPN\ value\ (from\ table)\ X\ \frac{10}{largest\ volume\ tested\ in\ dilution\ series\ used\ for\ MPN\ determination}$$

Heavy metal

1. Method

APHA, procedure 3030E-nitric acid digestion

2. Apparatus used
    a) Hot plate
    b) Conical (Erlenmeyer) flasks,
    c) Volumetric flasks
    d) Watch glasses
    e) Boiling chips
    f) Pipette
    g) AAS (flame system) model NOV AA 400, analytikjena company, Germany
3. Reagent

Nitric acid concentration analytical or trace metal grade

4. Procedure
    a) Transfer a measured volume (100 ml recommended) of well-mixed, acid-preserved sample appropriate for the expected metals concentrations to a flask or beaker.
    b) In a hood, add 5 ml concentrated HNO_3
    c) If a beaker is used, cover with a ribbed watch glass to minimize contamination. Boiling chips, glass beads, or Hengar granules may be added to aid boiling and minimize spatter when high concentration levels (>10 mg/l) are being determined.
    d) Bring to a slow boil and evaporate on a hot plate to the lowest volume possible (about 10 to 20 ml) before precipitation occurs.
    e) Continue heating and adding conc. HNO_3 as necessary until digestion is complete as shown by a light-colored, clear solution. Do not let sample dry during digestion.
    f) Wash down flask or beaker walls and watch glass cover (if used) with metal-free water and then filter if necessary. Transfer filtrate to a 100-ml volumetric

flask with two 5-mL portions of water, adding these rinsings to the volumetric flask. Cool, dilute to mark, and mix thoroughly.

g) Take portions of this solution for required metal determinations.

Phosphorus

Method

1) Hach method 8190: Molybdovanadate with acid per-sulfate digestion
2) Adaptation of the standard method for examination of water and waste water 20^{th} ed. 4500-P C, vanadomolybdophosphoric acid method. A persulfate digestion converts organic and condensed inorganic forms of phosphates to orthophosphate then the reaction between orthophosphate and the reagent cause a yellow tint in the sample

Required reagent

1) Potassium per-sulfate powder pillows
2) 1.54 N NaOH solution
3) Molybdovanadate reagent
4) Deionized water

Materials used

1) Hach reactor
2) Hach spectrophotometer model DR / 2010
3) Measuring cylinder
4) Pipette

Measurement procedure

Reagent blank correction

a) This method needs a reagent blank correction
b) A single vial may be used more than once
c) The blank vial is stable up to one day (room temperature)
d) For most accurate measurement, run a blank for each set of measurements and always use the same lot of reagents for blank and sample

1) Choose a homogeneous sample

2) Preheat the Hach reactor to 150 ^{0}C
3) Remove the cap from two reagent vials
4) Add exactly 5ml of sample to one vial (sample vial)
5) Add exactly 5 ml of deionized water to the other (blank vial)

Replace the cap tightly and mix by inverting each vial a couple of times

1) Add the content of one potassium per-sulfate reagent powder pillows for phosphorus analysis to each vials
2) Replace the cap tightly and shake gently the vials until all the powder is completely dissolved
3) Insert the vials into the reactor and heat them for 30 minute at 150 ^{0}C
4) At the end of digestion period switch of the reactor and place the vials carefully in the test tube rack and allow to cool to room temperature
5) Select the program number corresponding to total phosphorus on the secondary LCD by pressing program increase or decrease symbol
6) Remove the cap from the vials and add exactly 2ml of sodium hydroxide solution (1.54 N) to each vial while keeping the vial at 45 degree
7) Replace the cap tightly and mix by inverting the vial a couple of time
8) Remove the cap from the vial and add exactly 0.5 ml of molybdovanadate reagent to each vial while keeping the vial at 45 degree
9) Replace the cap tightly and mix by inverting the vial a couple of time
10) Place the blank vial into the holder and push it completely down
11) Press timer and the display show the countdown prior to the measurement, alternatively, wait for 7 minute and pres zero in both case 'sip' will blink on the display
12) The display will show '-0.0-' now the meter is zeroed and ready for measurement
13) Remove the blank vial
14) Place the sample vial into the holder and push it completely down
15) Press read direct and 'sip' will blink during measurement

16) Instrument directly displays concentration in mg/l of total phosphorus on the liquid crystal display
17) To convert the reading to mg/l of P_2O_5, multiply by a factor of 0.748
18) To convert the reading to mg/l of phosphorus concentration, multiply by a factor of 0.326

Nitrogen

Method

a) Hach method 10072: TNT per-sulfate digestion
b) Chromotropic acid method, a persulfate digestion converts all forms of nitrogen to nitrate. Then the reaction between nitrate and the reagents causes a yellow tint in the sample

Required reagent

a) Reagent vial-total nitrogen hydroxide reagent
b) Total nitrogen per-sulfate powder pillows
c) Total nitrogen reagent A powder pillows
d) Total nitrogen reagent B powder pillows
e) Deionized water

Materials used

a) Hach reactor
b) Hach spectrophotometer model DR / 2010
c) Measuring cylinder
d) Pipette

Measurement procedure

Reagent blank correction

1) This method needs a reagent blank correction
2) A single vial may be used more than once
3) The blank vial is stable up to one week (room temperature)
4) For most accurate measurement, run a blank for each set of measurements and always use the same lot of reagents for blank and sample

a) Choose a homogeneous sample

b) Preheat the Hach reactor to 105 ^{0}C
c) Remove the cap from two digestion vials
d) Add the content of one packet of total nitrogen per-sulfate reagent powder pillows
e) Add exactly 0.5 ml of sample to one vial (sample vial)
f) Add exactly 0.5 ml of deionized water to the other (blank vial)

Replace the cap tightly and shake vigourously the vials for about 30 seconds until all the powder is completely dissolved

1) Insert the vials into the reactor and heat them for 30 minute at 105 ^{0}C
2) At the end of digestion period switch of the reactor and place the vial in test tube rack after digestion to cool at room temperature
3) Select the program number corresponding to total nitrogen on the secondary LCD by pressing program increase or decrease symbol
4) Remove the cap from the vials and add the content of one packet of total nitrogen reagent powder pillow to each vial. Replace the cap tightly and shake gently the vials for 15 seconds
5) Wait for 3 minute with out shaking the vials to allow the reaction to complete
6) Remove the cap from the vials and add the content of one packet of total nitrogen reagent B powder pillows to each vial. Replace the cap tightly and shake gently the vials for 15 seconds
7) Wit for 2 minute with out shaking to allow the reaction to complete
8) Remove the cap from two other reagent vials
9) Add exactly 2 ml of digested sample from the digested sample vial to one reagent vial (sample vial), and 2 ml of digested blank to other reagent vial (blank vial) while keeping the vial at 45 degree angle
10) Replace the cap tightly and invert the vials 10 times
11) Place the blank vial into the holder and push it completely down
12) Press timer and the display show the countdown prior to the measurement, alternatively, wait for 5 minute and pres zero in both case 'sip' will blink on the display

13) The display will show '-0.0-' now the meter is zeroed and ready for measurement
14) Remove the blank vial
15) Place the sample vial into the holder and push it completely down
16) Press read direct and 'sip' will blink during measurement
17) Instrument directly displays concentration in mg/l of total nitrogen on the liquid crystal display
18) To convert the reading to NH_3, multiply by 1.22
19) To convert the reading to NO_3, multiply by 4.43
20) Interference
    a) Bromide above 240 mg/l
    b) Chloride above 3000 mg/l

Appendices-III. Feeding the Sample to the digester