ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
FACULTY OF TECHNOLOGY
DEPARTMENT OF CHEMICAL ENGINEERING

OPTIMIZATION OF ANAEROBIC CO-DIGESTION OF SEWEGE SLUDGE AND BREWERY YEAST WASTE

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

By: Tewodros Tilahun

Advisor: Dr.-Ing. Belay Woldeyes

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List of abbreviations

BOD	Biological oxygen demand
BOD_5	Five day biological oxygen demand
COD	Chemical oxygen demand
TS	Total solid
VS	Volatile solid
TN	Total concentration of nitrogen
TP	Total concentration of phosphorus
SRB	Sulfur-reducing bacteria
UASB	Up-flow anaerobic sludge blanket reactor
VFAs	Concentration of volatile fatty acids
WWTP	Wastewater treatment plant
AAWSA	Addis Ababa water and sewerage authority
FPU	Final polishing unit
EAS	Extended aeration system
WSP	Waste stabilization pond
CSA	Central statistical agency
DAP	Diammonium phosphate
ETB	Ethiopian birr
EELPA	Ethiopian electric and power authority
VIP	Ventilated improved pit latrine
EPA	Environmental protection authority
TC	Total coliform
FC	Fecal coliform

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Abstract

A batch anaerobic digestion experiment was carried out to determine the optimum methane produced from digestion of sewage sludge and brewery yeast waste in different mix, and the fertilizer potential of the sludge after digestion.

The maximum methane production from anaerobic digestion of sewage sludge and brewery yeast waste was assessed in batch tests using armfield glass made anaerobic digester in chemical engineering laboratory. The volume of biogas produced and methane composition of different mix of the feed stock were determined by water displacement and geotechnical land fill gas analyzer model GA 45, respectively. It was observed that the independent variable – mix ratio significantly affect (p-value 0.0027) the dependent variable – amount of methane produced since the p-value is less than the chosen α-level usually 0.05. The calculated volume of methane in the biogas produced per gram COD removed were 0.218L, 0.103L, and 0.075L and per gram volatile solid removed were 0.271L, 0.172L and 0.136L for sewage sludge alone, 80:20% mix, and 60:40% mix of sewage sludge to brewery yeast waste respectively. In general From the digestion of sewage sludge alone: 0.44 $m^3/d/m^3$ biogas with 57.75% methane was produced; 0.74 $m^3/d/m^3$, and 0.91 $m^3/d/m^3$ biogas with 19.84% and 19.34% methane produced from 80:20% mix and 60:40% mix of sewage sludge to brewery yeast waste, respectively. The mix ratio significantly affects the biogas production (p-value $1.65*10^{-9}$). Totally 83,850 m^3 CH_4/year can be captured and hence same amount of methane emission into the atmosphere is prevented from the sewage sludge currently managed in Addis Ababa waste water treatment plant if anaerobic digester is used.

With regard to the fertilizer potential of the digestate; heavy metal content is not a limiting factor in the use of sewage sludge managed in Addis Ababa waste water treatment as a soil conditioner and fertilizer. Moreover, the nitrogen, phosphorus and potassium content of the sludge satisfy specific plant uptake requirements in many land application systems. Sun drying on drying beds after anaerobically digested sludge is helpful in the viability of land application of treated sludge by completely inactivating the pathogen and reducing the potential risk.

Key words: Biogas, Methane, Organic fertilizer, Anaerobic digestion, Digester, Sewage sludge,
Brewery yeast waste

1. INTRODUCTION

1.1. Background

The treatment of wastewater invariably produces a residual which must be disposed of into the environment. Most often this residual is a semisolid, odiferous, unmanageable and dangerous material commonly termed sludge. Sludge, however, can also contain substantial nutrients and organics and these can be considered a replenishable natural resource.

Biogas plants are multipurpose biological processing that can be implemented for various reasons. For the purpose of energy production, biogas plants are capable of treating many different types of organic wastes, energy crops, and agricultural residues aiming to produce renewable energy (biogas) and organic fertilizer (digestate) for use in sustainable crop cultivation. In the context of wastewater treatment, biogas technology can be applied for removing persistent organic pollutants and thus secure the environment.

Addis Ababa is the capital city of Ethiopia, having 530.14 km^2 areas with an average temperature of 16 ^{0}C, diplomatic capital for Africa (OAU, ECA), regional head quarters like UNDP, UNICEF, UNHCR, and FAO. The population of the city is estimated to be 2, 738, 248 million living in 10 sub-cities and 204 kebeles divided for administrative purpose [1].

Modern sewerage service in Addis Ababa started since 1974 during which wastewater treatment plant at Kaliti is constructed and give service for sewer system; the treatment plant designed to have capacity of 7500 m^3/ d. During 1990 sludge drying bed is constructed with 250 m^3/d capacity [2].

Currently water supply for the city accounts 230,000 m^3/d; from this 30% is expected to be lost in different way and only 161,000m^3 used. 80% of the used water estimated to be wastewater [3] which is 128,800m^3. From this amount of wastewater generated in Addis Ababa 7000m^3 through sewer system, 904m^3 private and government dislodging service for Kaliti and 225 m^3 for Kotebe; totally 8, 629 m^3 collected and disposed [2].

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.

There is no wastewater treatment plant in St. George brewery. The wastewater generated released into near by river. The brewery solids mainly consist of spent grains, kieselguhr, waste yeast and (‘hot’) trub. Nitrogen and phosphorous levels are mainly depending on the handling of raw material and the amount of spent yeast present in the effluent. Fermentation tank bottom consist spent yeast and beer loss of 1 to 2% of production. 1 to 2 ton/d of yeast waste generated in the factory; it is estimated 400-800 m^3/ton of biogas yields from yeast and yeast like products [4].

1.2. Statement of the problem

The search for a systematic management of an ever increasing trend of sewage sludge generation coupled with the complex sludge characteristics is a big challenge for Addis Ababa water and sewerage authority (AAWSA) to manage such bio-solids. Accumulation of large volumes of dried sludge in treatment compound has become common. These might have immediate public health implications, which are manifested as frequent outbreak of major epidemic diseases.

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 that 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 a source of principal concern. The waste composition is characterized by high fraction of biodegradable organic material that is potentially recyclable for energy production. Currently, there are no recycling programs in place to exploit this organic fraction but instead hauled into the compound after lagoon treatment 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. Besides, disease causing bacteria and foul odor 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 not engineered so wastes are dumped; therefore, these dumpsites will not be able to accommodate increased amounts of residue or sewage sludge in the future.

The yeast waste (fermentation residue) from the St. George Brewery accounts 1-2 ton/d which is dumped in open field and near by river. Nitrogen and phosphorous levels are mainly depending on the handling of raw material and the amount of spent yeast present in the effluent; this can increase the COD of the waste water. In order to ensure that sludge reuse is carried out its composition must be determined so as to protect the environment, human and animal health.

Organic waste is responsible for pollution of soil and water bodies through leachate, and in the process of uncontrolled anaerobic digestion it may contributes to global warming from the methane produced. A possible step in mitigating these effects is enhancing resource-recovery activities of the organic waste fraction. An obvious treatment and recovery option for organic waste is the biological, treatment option for that matter anaerobic digestion (AD). Anaerobic digestion is the only process, which achieves both energy utilization and stabilization.

Human waste has been treated in anaerobic lagoons and St. George brewery waste water released in to near by river for many years, but this application is primarily a waste disposal technique, rather than an energy production and resource recovery technique. The current energy conservation policies as well as the strong demand for the reduction of atmospheric CO_2 emissions are in favor of the further development of advance AD techniques.

1.3. Objectives

1.3.1. General objective

- To determine biogas and organic fertilizer production potential of sewage sludge from municipal waste water and yeast waste from St. George brewery.
- To determine volume of waste reduction due to biogas generation and utilization as an organic fertilizer to minimize environmental pollution caused by open dumping.

1.3.2. Specific objectives

- Determine raw Sewage Sludge composition.
- Determine brewery yeast waste composition.
- Identify optimum mix ratio for highest methane production.
- Design anaerobic digester for optimum production of biogas.
- Determine potential of digestate (residue after digestion) as an organic fertilizer.

1.4 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 landfilled. In this respect, pretreatment of sewage sludge by biological process prior to open dump can be viewed as an integral part of sewage sludge management system. This concern serves as an allowable scope of action towards the recognition of a sustainable pretreatment technology before open disposal i.e., the anaerobic digestion.

The study will describe the potential value of sewage sludge and brewery yeast waste sludge as an organic fertilizer, a soil conditioner and a fuel. Since the physico-chemical nature of the sludge is unknown and the utilization of sludge will depend upon familiarity with the properties and characteristics, it also briefly discusses the composition of the sludge to identify potential scenarios for a more sustainable treatment and clean development mechanism.

2. LITERATURE REVIEW

Around the world, pollution of the air and water from municipal, industrial and agricultural operations continues to grow. The concept of the ‘four R's’, which stands for Reduce, Reuse, Recycle, and Renewable energy, has generally been accepted as a useful principle for waste handling [5].

The emission of CO_2 and other greenhouse gases (GHG) has become an important issue, particularly since Russia has ratified the Kyoto Protocol which came into force on 16 February, 2005. Governments and industries are therefore increasingly on the lookout for technologies that will allow for more efficient and cost-effective waste treatment while minimizing GHG, methane which is 23 times more potent than CO_2 is in this initiative. Anaerobic degradation can take place over a wide temperature range from 10°C to over 100°C and at a variety of moisture contents from around 50% to more than 99%. 75,000 ton/year anaerobic digestion facility can decrease GHG emissions by 1,125 metric tone carbon equivalents (MTCE) over the course of a year [6].

Energy is the core around which the development and industrialization of any nation revolve. It is a fact that any distortion in energy supply chain at any point in time results into serious economic and social hardship. The significance of energy in the provision of goods and services and in the rise of the standard of living of mankind, and the role it plays in industries for sustainability of production is a well known fact [7].

There is increasing evidence that current global energy policies, which promote the inefficient use of fossil fuels and energy, are environmentally irresponsible and unsustainable since they cause significant environmental degradation at the local, regional, and global levels. Several studies have shown that by incorporating renewable energy resources into the overall energy mix or unit of nations any of these negative environmental impacts of energy use could be avoided or minimized [7].

About 94 percent of the total energy consumption in Ethiopia is from biomass. Firewood and charcoal combined accounted for more than 79 percent and agricultural residues and dung 7.3

and 7.5 percent, respectively (Table 2.1). Petroleum and electricity play a less important role in the national energy supply systems. Their share in the total energy consumption in 1998/1999 was 6 percent. Electricity is available only to about 14 percent of the total population.

Table 2.1 Energy Supply and Consumption in Tera Joules 1991 E.C. (1998/1999 G.C.)

Sector	Fuel						Total	%
	Woody biomass	Crop Residue	Dung	Charcoal	Electricity	Petroleum		
Final Consumption	581,352	54,450	56,333	8,785	4,841	40,625	746,386	100.00
Household	542,141	52,010	53,891	8,565	1,832	7,332	665,771	89.20
Urban	34,969	2,824	3,263	5,856	1,832	4,161	52,905	7.09
Rural	507,172	49,186	50,629	2,709		3,170	612,866	82.11
Agriculture	0	0	0	0	0	1,497	1,497	0.20
Transport	0	0	0	0	0	26,743	26,743	3.58
Industry	17,101	1,409	1,396	112	1,864	4,573	26,455	3.54
Services	22,110	1,031	1,046	109	1,145	331	25,772	3.45
Percent	77.9	7.30	7.5	1.2	0.65	5.44	100	

Source: ministry of mines and energy, 2006 [8]

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%. 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 [8].

2.1. Anaerobic Digestion (AD)

Anaerobic digestion is a biological process that produces a gas principally composed of methane (CH_4) and carbon dioxide (CO_2). These gases are produced from organic wastes such as livestock and human manure, food processing waste, solid waste etc.

Anaerobic decomposition occurs naturally in: swamps, water-logged soils and rice fields, deep bodies of water, and in the digestive systems of animals. Anaerobic processes can be managed in a "digester" or a covered lagoon for waste treatment. Organic waste such as livestock and human manure, and various types of bacteria are put in an airtight container so the process could occur. The primary benefits of anaerobic digestion are biogas production, nutrient recycling, waste treatment, and odor control. Depending on the waste feedstock and the system design, biogas consist 55 to 75 percent pure methane [9].

Humans have been able to exploit this process for benefit in several contexts. Rural areas, especially in China and India, take advantage of AD extensively to process farm waste, such as manure. In North American farming communities AD is used in large farms to treat manure and control odor, at wastewater treatment plants where sewage sludge is anaerobically treated to reduce biological and chemical oxygen demands. European nations take advantage of the next logical application and employ AD to process more complicated waste streams including industrial and agricultural wastewaters and the organic fraction of municipal solid waste [6].

The earliest known use of anaerobic fermentation is 8 000–6 000 years ago with the production of ethanol, lactic and other fatty acids for different preservation techniques [10, 11]. Such system can be seen as precursors to the anaerobic waste handling systems of today.

The industrialization of AD began in 1859 with the first digestion plant in Bombay and in 1895 biogas was recovered from a sewage treatment plant in Exeter, England for fuel street lamps. From there, it continued to be widely used as a way to stabilize sewage sludge, as it is today [12]. The system was large, unheated and unmixed tanks with significant operational problems due to solid settling and scum formation. These disturbances limited the adoption of the technology until the twentieth century.

In the nineteenth century the microorganisms responsible for the anaerobic process were first described by Pasteur [10]. It was also concluded that methane forms from the biological breakdown of cellulose. For the last hundred years anaerobic digestion systems much like the ones seen today have been used for waste disposal and stabilization [13]. As of today anaerobic digestion is the most commonly applied method of treatment for sewage sludge [14, 15].

Technical improvements and increasing energy prices have led to a diversification of the waste treated and larger size AD plants. In recent times, European countries have come under pressure to explore AD market for two significant reasons: higher energy prices and increasingly stringent environmental regulations. AD facilities usually have a good record in treating a wide spectrum of waste streams such as municipal, agricultural or industrial waste. In addition to farm-scale digesters, Europe leads in large centralized AD systems [16].

The energy crises in the 1970s prompted American research into alternative energy strategies, and AD was one such option. This resulted in the first farm digester built in America in 1970 where the biogas could be used for heat and power [17].

Through government funded research and pilot demonstrations over the past 30 years, AD facilities have been dramatically improved in Europe. The academic work led to the launch of the commercialization phase where research continues today. Development has been encouraged by higher tipping fees at landfills, stricter environmental legislation, including renewable energy laws and landfill restrictions, and other tax incentives [18].

2.2. 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 the major component of the "natural" gas used in many homes for cooking and heating. 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. The theoretical amount of the gases produced can be calculated according to the Buswell equation: [19].

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

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 manure 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].

Once the raw material has been liquefied by the acid producing bacteria, methane producing bacteria convert the volatile acids into methane gas. Unlike the acid bacteria, methane bacteria reproduce slowly and are very sensitive to changes in the conditions of their environment.

2.3 Anaerobic digestion processes

2.3.1. 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;
- Removing materials which may decrease the quality of the digestate [16].

Eckenfelder et al., 1966 and Pen-Varo, 2002 describes the process of anaerobic digestion as [20, 21]:

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

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 equation above, 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 the presence of anaerobic microorganisms [6]. Anaerobic digestion process requires the combined action of a highly varied microbial population, consisting of several groups of strict and facultative bacteria strains [21, 22]. It occurs in four metabolic stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [23].

2.3.2 Hydrolysis

First process in which hydrolytic microorganisms secretes an enzyme to hydrolyse 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 [24, 25].

2.3.3 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 [21, 23]. 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 [26]. The acidogenic microorganisms prefer a slightly acidic environment (pH 4.5-5.5) and are less sensitive to changes [6].

2.3.4. 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 [21, 23].

2.3.5. Methanogenesis

The last groups of microorganisms, methanogenic, produce methane from acetic acid, hydrogen, and carbon dioxide as well as directly from other substrates [23]. 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 [27]. 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 [21]:

$$CH_3COOH \rightarrow CH_4 + CO_2$$
$$CH_3COOH + 4H_2 \rightarrow 2CH_4 + 2HO_2$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2HO_2$$

Anaerobic digestion has become popular because of the following advantages relative to aerobic methods [28, 29].

- Anaerobic digestion process requires considerably less energy and dispenses with the need for mechanical aeration, an essential requirement for aerobic processes;
- Useful energy may be recovered from methane, one of the end products;
- Relatively less sludge is produced and hence a resulting lower costs of disposal of the organic residues;
- Well-designed anaerobic processes have far greater treatment capacity than aerobic processes and therefore require a much smaller reactor volume; and
- 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 [28, 30].

Lettinga (1995) argue based on the present state of knowledge of the anaerobic digestion process [31]:

- With regard to the bacteriological complexity of the anaerobic systems, significantly more is known about the system today and gradually a better insight is being gained in the counter measures that can be taken if problems arise in the operation of the system;
- Growth rates for groups responsible for the production of methane will be optimal when the anaerobic digestion process is applied in tropical climates where the ambient temperatures are within the mesophilic range;
- The presumed low stability could be attributed to a lack of knowledge about the basic principles of the anaerobic treatment process. As a matter of fact, the anaerobic digestion process is highly stable provided the system is operated in the proper way;

- Much more is understood of the growth conditions of anaerobic organisms, and gradually large quantities of highly active anaerobic sludge from existing full-scale installations are becoming available, so that start-up of new systems can be made within a few weeks, sometimes even a few days.

2.3.6. 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. After further cleaned by screening to remove unwanted material such as small pieces of glass or plastic [32].

2.4. Environmental conditions affecting the process

Anaerobic degradation strongly influenced by chemical and physical parameters [26]. Most essential factors include the temperature, pH and buffering systems, nutrient requirement, and the presence of toxic substances in the process [33].

2.4.1. Temperature

Generally, the rate of all reactions varies with temperature. In biological systems, temperature increase is not as great as for chemical reactions. Methane production has been documented under a wide range of temperatures, but bacteria are most productive in either mesophilic conditions 25 - 40 ^{0}C, or in the thermophilic conditions, at 50 - 65 ^{0}C [6, 35]. Cecchi and Pavan et al. (1993) observed that temperature is a factor that affects the kinetics and the composition of the mixed microbial population [34].

In order to achieve reasonable methane production, the temperature should be above 20 ^{0}C, and this fact makes anaerobic treatment more attractive in tropical countries [21, 26]. Other authors have claimed success with the anaerobic digestion of waste at ambient temperature, which is known to be cost effective [35]. Temperature has a positive effect on digestion rate, resulting in higher volumetric methane production [12]; but not necessarily a limiting factor in applying anaerobic digestion rather temperature stability [36].

Most of the remedies mentioned in the literature to enhance biogas production are aimed at increasing the digester temperature to mesophilic range (i.e. optimum temperature). Some precautions taken during the installation of biogas plants and coating them with insulating materials also helps in keeping the temperature in the digester within the desired range [37].

2.4.2. pH

Each of the microbial groups in anaerobic degradation has specific pH optimum and can grow in a specific pH range [32]. A pH outside 6.0 to 8.5 pH interval can lead to imbalance. The methanogens and acetogens have pH optimum at approximately 7, while acidogens have lower pH optimum around 6. Methanogens grow very slowly at pH lower than 6.6 [22, 26]. The pH determination is really useful and is important to relate its value to other process parameters: alkalinity, VFA concentration, and biogas production and composition [22]. The amount of carbon dioxide and volatile fatty acids produced during the anaerobic process affects the pH of the digester contents. Jain and Mattiasson (1998) found that above pH 5.0, the efficiency of CH_4 production was more than 75% [38].

2.4.3. Nutrients

Organic and inorganic substances are necessary for anaerobic digestion process. Very low metal concentrations may make the anaerobic degradation process inefficient [39]; but, above a certain threshold level it can be inhibitory. An average COD/N/P ratio of 600/7/1 can be recommended for substrates to be anaerobically digested [22]. Alphernaar et al. (1993) suggested a minimum C: N: P ratio of 100:28:6 [40]. Waste material that is low in C can be combined with materials high in N to attain desired C:N ratio [41]. Presently there is no universal recommendation for nutrient concentrations that can be given because they are strongly dependent on the actual circumstances at which the AD is performed [12].

2.4.4. Toxic substances

Methanogens are considered the most sensitive to toxicity in anaerobic digestion [32]. 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.

The carbon/nitrogen (C/N) ratio is also important for process stability. A C/N ratio of 25 to 32 has been reported to have a positive effect on the methane yield. Ammonia inhibition can be neglected only at feedstock with C:N ratios above 20 [42]. At Lower C/N ratios the risk of excess nitrogen increases inhibitory and a very high C/N ratio leads to N- deficiency for biomass synthesis [32].

2.4.5. Retention time

The amount of time that feedstock stays in the digester is known as retention time or residence time; the longer a substrate is kept under proper reaction conditions, the more complete its degradation will be. The rate of the reaction, however, will decrease with increasing residence time, indicating that there is an optimal time that will achieve the benefits of digestion in a cost effective way. The appropriate time depends on the feedstock, environmental conditions and intended use of the digestate [12]. Recent research has shown that volatile suspended solids in a digester could be reduced by 64- 85% after only 10 hours, but retention times of 10 days were typical for complete digestion [43].

2.4.6. 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 [44].

2.5. Monitoring parameters and reactor stability

There are several parameters that have been used as indicators for process imbalance. An ideal indicator should be easy to measure, should detect the imbalance at an early stage and should reflect the metabolic state of the digester. Also, it is important that the relative change in the indicator should be significant compared to measurement uncertainty and background fluctuations [45]. Some of the most widely used indicators are described as follows:

2.5.1. Gas production and gas composition

The gas production will initially increase when the reactor is overloaded and then suddenly decrease after a period of time due to accumulation of inhibiting products (acids). Depending on the degree of imbalance, the gas production will decrease while the amount of CO_2 will increase because it is not consumed by H_2 utilizing methanogens. Gas production and composition cannot be solely used as indicators for process imbalance as changes can simply be a result of changes in the substrate composition. Because low biodegradability of the substrate can lead to low biogas/methane yield and does not necessarily indicate a deficient performance [45].

It is therefore important to combine gas production and composition with data for substrate composition and loading. Stenstrom (1983) observed that when overloading of the reactor occurred there was a decline in CH_4 production and consequently an increase in volatile acids concentration [46]. In situations where there have been no changes in substrate composition and loading, a change in gas production and composition can indicate process imbalance [22, 32, 45].

2.5.2. pH, VFA and alkalinity

Process imbalance in an anaerobic digester will normally lead to accumulation of volatile fatty acids (VFA) resulting in a decrease in pH. The increase in acid concentration may not register as a drop in pH immediately if the buffer capacity of the material in the reactor is high. Most organic wastes often have a high content of weak acids and bases resulting in high buffer capacity. But the organic acid level must attain a certain level before it could be detected as a drop in pH. pH is therefore difficult to use as it only reacts slowly to process imbalance [45]. pH is easy and inexpensive to measure and it is therefore an effective indicator in systems with low buffer capacity [22].

2.6. Wet digestion

Wet digestion processes are carried out at a total solids content of no more than 15% by weight, most commonly within the range of 7-12 %TS. Usually, water must be added to the feedstock at the slurring stage to dilute the waste [46].

2.7. Co-digestion

A combination of two or more substrates in anaerobic digestion is an attractive technique by which the substrates digestion process improvement is reported; the anaerobic co-digestion of various agricultural residues [47], various municipal solid wastes [48], and various other specific organic wastes [49, 50, 51], is becoming attractive for producing energy in the form of biogas. It also produces a sludge that is rich in nutrients and which is often usable as a fertilizer after composting or other treatment.

Co-digestion in the anaerobic digestion process improves nutrient balance of total organic carbon, nitrogen and phosphorus, and buffer capacity of the substrates which results in a stable and maintainable digestion process and good fertilizer quality [4, 37, 50, 52] and has economic advantages in the possibilities of utilizing digesters in sewage treatment plants, and other organic waste as co-substrates [47, 48].

2.8. Anaerobic Treatment Systems

Basically, there are two types of anaerobic treatment systems based on the rate of the digestion process [53]:

- Low rate systems**:** - in which the removal of organic matter is based on the settling of suspended organic solids with anaerobic digestion processes taking place in the accumulated sludge at the bottom such as Imhoff tank, septic tank and anaerobic ponds.

- High rate systems**:-** in which the removal of organic is based on intense contact between the influent organic matter and the large and active bacterial mass retained in the reactor such as the 'modern' anaerobic treatment systems: up-flow or down-flow anaerobic filter, sludge bed reactors, conventional contact process, up-flow anaerobic sludge blanket (UASB) and expanded granular sludge blanket (EGSB).

The high rate systems are further classified by the mechanism of sludge retention in the anaerobic reactor in practice two methods of sludge retention have found wide application:

- Systems based on immobilization of the sludge: - These are fixed film processes in which the anaerobic organisms form a thin sludge layer on a solid carried material which may be composed of granular material like sand which acts as a fluid bed or expanded bed reactors of macroscopic bodies like stones or an artificial medium forming a packed bed known as an anaerobic filter [54].
- Systems based on mobilization of the sludge: - These are suspended growth processes which employ gravity settling to retain the anaerobic material mass in the treatment system. The gravity settler may be external, as for instance in the Contact Process [55], or internal, as in the UASB [29].

2.9. Types of digesters

The simplest form of AD is the deep anaerobic lagoon. These are still used on farms in some parts of the world, but they are not very efficient and pose problems [56]. There are several basic types of digesters and the choice between these depends on the types of waste to be treated. AD can be classified into the following categories [16, 56].

- Single stage
    - Low solid process
    - High solid process
- Multistage
    - Low solid process
    - High solid process
- Batch
    - Single stage system
    - Sequential
    - UASB: biomass retained within the digester without support media

- Contact digester: essentially a stirred tank with mixing and heating systems, much of the effluent stream is separated and returned to the digester to attain a high bacterial concentration and a long bacterial retention time.
- Anaerobic filters: are retained biomass digesters with bacteria immobilized on a support to obtain high biomass concentrations and long bacterial retention times. Both upflow and downflow filters have been used in full scale plants and in both the media are fully submerged. Downflow filters usually use orientated or tubular packing and upflow filters use orientated and random packings with recycle.
- Fluidized bed digester: a combination of sludge bed and filter digester to solve the difficulties of biomass separation in the contact digester and loss of granulation or blockages in the sludge bed or filter digesters.

2.10. Digester product

Whether the primary objective of digestion is pollution control or energy production the digester will produce product which can be liquid and solid effluent and biogas [56]. Without appropriate treatment and disposal the sludge can be more harmful than the raw sewage [57]. In order to extract the maximum recovery value from these wastes the digestate should have a useful purpose. The U.S. EPA has outlined the planning steps for a sludge land application program [58]:

- Determine Sludge Characteristics; Chemical, Biological and Physical.
- Review Applicable Regulations and Guidelines for Land Application of Sludge.
- Compare Sludge Characteristics to Regulatory Requirements and Evaluate Suitability of Sludge for a Land Application Program.
- Estimate Land Area Required for Sludge Application, Availability of Land Area Necessary.
- Assess Sludge transport Modes and Their Feasibility.

Sludge was commonly applied to crops to increase yields before 1940s in U.S [57]. Commercial fertilizers began replacing sludge and, as a result, sludge was disposed of as a waste product. In

1993 the U.S. EPA publicize the 40 CFR Part 503 regulations to encourage the beneficial use of sludge and to establish standards for the safe application of biosolids due to the reintroduction of bio-solids for agriculture in the last two decade Most of the N, P, and K present in the feedstock remain in the digestate. Digestate can be applied to land as an organic fertiliser, or can be mechanically separated to produce:

- Fibre – high in organic matter and plant nutrients. Fibre can be used as a nutrient-rich soil conditioner or further processed to produce granular organic fertiliser or a combustible fuel.
- Separated liquid – contains plant nutrients and can be applied to land as an organic liquid fertiliser.

Land application of sludge is considered a beneficial alternative to land filling or incineration. Agricultural use of sludge is an effective management practice that can provide a source of revenue. In U.S. dried biosolids can have value between \$25 and \$40 per ton, depending on the quality therefore municipal sludge is processed into agricultural fertilizers and soil conditioners in most major U.S. cities [57].

Digestate quality can be asses on chemical, biological and physical aspects [22]. The chemical aspects of quality management of digestate are related to the presence of

- Heavy metals and other inorganic contaminant.
- Persistent organic contaminants.
- Nutrients (NPK).

2.11. Wastewater and Excreta

When wastewater is treated and discharged into a water body, the job is not over. Left behind are the solids, commonly called sludge; currently sludge treatment and disposal accounts over 50% of the treatment costs [5].

In conventional wastewater treatment, the objectives are accomplished by concentrating the impurities into solid and semisolid residuals and then separating them from the bulk liquid. The concentration of the solid and semisolid residuals is referred to as sludge [3]. The solid and semisolids residuals are removed from the bulk liquid after primary and/or secondary treatment. The sludge has thus undergone some measure of treatment, although it may be inadequate for its ultimate disposal.

2.11.1. Addis Ababa

In Addis Ababa conventional sewerage and treatment systems are almost absent and most disposals of human excreta is through on-site sanitation systems and not by water-flush toilets connected to centralized sewerage systems. Water and sewerage authority is under development to make connection of each house to sewerage line. These on-site sanitation facilities could be either water dependent like pour flush, water closet and aqua privies, or non-water dependent like bucket, ventilated improved pit (VIP) and vault latrines. Depending on the type of facility, its storage capacity, emptying frequency and the collection/ transportation system use, human body wastes may be stored in these on-site sanitation facilities for a day to several years.

Sewage can potentially pollute surface waters and seepage from poorly maintained sewers line, septic tanks and pit latrines contaminate groundwater [59]. Health risks from sanitation systems are mainly associated with faeces, and therefore the collection, control and treatment of faeces is important for protection of community health. One way to the solution of this problem could be recovering of safe nutrients from excreta and use them for food crop production.

The plant nutrients taken up in the production of food are found in excreta. If recycled can improve food security and help to eradicate famine and poverty. Human urine and faeces are products of body metabolism that are rich in plant nutrients. In most of sanitation systems nutrients are not captured for use in growing food crops. Instead, the nutrients in urine and faeces mainly end up in latrines and wastewater systems. This potentially cause groundwater and surface water pollution. The nutrients are undesirable because of their potential cause of eutrophication in receiving waters, while they are required on land for sustainable production of food and reduction of the use of chemical fertilizers which are produced by use of non-renewable resources. It is estimated that the lifetime of global economical phosphorus reserves is between 60 to 130 years [60]. Production of nitrogen-based fertilizers relies heavily on non-renewable resources. These resources are estimated to reach their global peaks [61]. Hence, for sustainable use of nutrients for food production, the nutrients in excreta should be recycled.

Fertilizing equivalent of excreta is nearly sufficient for a person to grow its own food [62]. In reality, part of this potential is lost during storage and treatment, nitrogen loss through ammonia volatilization.

2.11.2. Night-soil

The term mostly used to represent a mixture of human faeces and urine [63]; a mixture of human faeces and urine that has undergone some considerable putrefaction [64]; only faeces and urine plus small volumes of water if it is used for anal cleansing and pour-flushing [65]. It also refer to the contents from septic tanks/leaching pits which are connected to pour flush latrines [66] and for contents of cesspool and holding tanks /storage pits where it is stored for more than three months before being collected [67].

2.11.2.1. Nutrients in urine

Urine contains the largest proportion of plant nutrients found in the household waste fractions. The amount of plant nutrients excreted with urine per person per year has been reported as 2.5-4.3 kg nitrogen, 0.4-1.0 kg phosphorus and 0.9-1.0 kg potassium [68].

2.11.2.2. Nutrients in faeces

Faeces contain both water-soluble and insoluble nutrients. About 50% of the N and majority of the K in fresh faeces are water soluble, while P is primarily found as calcium phosphate particles that are slowly soluble in water [69]. Plant nutrients availability from human faeces is slower than that from urine. This is explained by the fact that a large proportion faecal N and P originate from undigested matter which has to be degraded in the soil before the nutrients become water soluble and available to plants [70].

2.11.2.3. Other constituents in urine and faeces

Human faeces and urine contain trace metals in small amount if present in excess may be harmful to man and environment. The amounts of harmful heavy metals in the urine are low since biological uptake and their excretion being small. Uptake of heavy metals occurs by ingestion and inhalation. The percentage uptake is higher for inhaled metals than for ingested metals [71, 72].

2.11.2.4. Storage

Storage of faeces for a specific time results in a reduction in pathogenic microorganisms due to natural die-off [72]. The degree of reduction depends on the storage conditions and type of microorganisms present. Ambient temperature, pH, moisture and biological competition all affect inactivation.

Table 2.2 Fertilizing value of human excreta

Nutrient	In urine 500 L/yr.	In feces 50 L/ yr.	Total	Required for 250kg cereal
N	4	5	4.5	5.6
P	0.4	0.2	0.6	0.7
K	0.9	0.3	1.2	1.2

Source: Drangert, 1998 [61]

2.11.3. Septage

Some of the on-site sanitation facilities at homes, offices, commercial houses and institutions are water dependent. In the water dependent on-site sanitation facilities, the human excreta flushed out using water. The resulting wastewater (mixture of flush water, faeces and urine) is discharged into septic tanks, the combination of the sludge produced in the septic tank as a result of the anaerobic digestion of the settled solids, scum and liquid pumped from septic tank is known as septage. The actual quantities and constituents of septage vary widely, the greatest variation being found in communities that do not regulate the collection and disposal of septage [3].

Table 2.3 Typical characteristics of septage

Constituent	Concentration, mg/L			
	Metcalf & Eddy, Inc. (1991)		Strauss and Heinss (1995) (Accra, Ghana)	
TS	5,000 - 100,000	40,000	3,000 - 114,000	14,000
TSS	4,000 - 100,000	15,000	700 - 34,000	7,000
VSS	1,200 - 14,000	7,000	490 - 23,800	4,900
BOD_5	2,000 - 30,000	6,000	360 - 1,300	630
COD	5,000 - 80,000	30,000	820 - 52,000	8,500
TKN as N	100 - 1,600	700	-	-
NH_3 as N	100 - 800	400	-	-
TP as P	50 - 800	250	-	-
Heavy metals	100 - 1,000	300	-	-
Helminth eggs, (no./L)	-	-	200 - 13,000	4,300

Source: Isaac, 2003 [53]

Table 2.4 heavy metal concentrations in septage and EU standards for admissible levels in sludge used in agriculture

Heavy metal (g/kg TS)	Bangkok	Manila	US	EU Standard
Cd	2.5	5.3	18	20-24
Pb	6.8	84	215	750-1200
Cu	289	64	165	1000-1750
Zn	2085	1937	1260	2500-4000
Cr	20	16	28	1000-1500

Source: Martin Strauss, 2000 [73]

It is important to consider chemical constituents when faecal sludge or wastewater is being used for soil amendment to add soil fertility. This can limit heavy metal accumulation in soil and crops through repeated use of sludge [74].

The collection and transportation of night-soil and septage from their various sources to the final treatment/disposal sites is done by vacuum trucks. Most often, the contents of the trucks are mixtures of both toilet sludge and septage and hence difficult to distinguish between the wastes that arrive at the treatment/disposal sites [53]. It is thus appropriate to have a term that would include all types of faecal wastes coming from the on-site sanitation systems that have undergone some measure of digestion. The term sewage sludge is used in this study because Sewage is mainly liquid waste containing some solids produced by humans which typically consists of washing water, feces, urine, laundry waste and other material which goes down drains and toilets from households and industry [75].

Characterization of the physical, chemical and biological composition of sewage sludge is a major step in understanding their nature and essential in the design treatment and disposal facilities. However, compared with wastewater and sludge generated in the western and industrialized countries, very little has been done to date to characterize sewage sludge from on-site sanitation systems in developing countries.

The characteristics of collected sewage sludge vary greatly. It depends on the season, type of the on-site sanitation system, the emptying frequency, the extent of storm-water or groundwater infiltration into the sanitation facility, and on user habits [76].

The main characteristics of night-soil and toilet sludge from the literature are [53]:

- High organic concentration with a considerable portion being biodegradable (COD > 20,000);
- pH values slightly above the neutral value;
- The ammonium-nitrogen concentrations ranging from 2,000 - 5,000 mg/L; and
- High solids concentration with considerable volatile portions.

Anaerobic processes are specially suited to the treatment of heavily contaminated organic wastes with COD greater than 5000 mg/L [77]. Thus with the characteristics of night-soil and toilet sludge being within or close to the ranges optimal for the anaerobic digestion conversion process, it should be possible to stabilize night-soil and toilet sludge by anaerobic treatment process as evidenced by the use of the process technology throughout the available literature.

3. METHODOLOGY

The followings are the methodology used in the study to accomplish the objective of the study:

3.1. Materials

Analytical reagents were used for the analysis of sludge and brewery yeast waste composition and analysis were conducted for samples from Addis Ababa waste water treatment plant and St. George Brewery.

The materials were analysed for TS, VS, TN, TK, TP, heavy metal, Coliform and parasite ova, and biogas production using equipment and apparatus such as cylindrical glass made anaerobic digester, rubber hose, incubator, drying oven, furnace, Spectrophotometer, test tube, microscope, measuring cylinder and weighing scale through out the experiment. The most important equipment and apparatus used in the analysis procedure are described in the annex.

3.2. Methods

The methods used in this study are described hereunder:

3.2.1. Study variables

- Amount of biogas and methane composition.
- Physical, chemical and biological characteristics of sewage sludge and yeast waste before and after digestion:
  pH, TS, moisture content, VS, Total Nitrogen, Total Phosphorus, Total Potassium, Heavy metal (Cd, Cr, Cu, Pb, Ni, Zn) and pathogen (fecal coliform, total coliform, parasite ova).

3.2.2. Study design

A single factor experimental design with 3 level of mix in 2 replication of each level; having a hypothesis of the response variable, quantity of biogas, varies with the variation of mix ratio of the feed stocks.

3.2.3. Sample analysis

A batch anaerobic reactor under mesophilic condition (35 ± 1 ^{0}c) for a digestion period of 20 days was used in the Environmental Engineering, Chemical Engineering Department laboratory.

- Volume of biogas production was determined by water displacement.
- Methane and carbon dioxide in biogas measured by geotechnical instrument land fill gas analyzer model GA 45 in EPA laboratory and the gas was sampled using Tedlar gas sampling bag item number Z27909-9 and Z27908-0 PVF gas sampling bag.
- Total solid was estimated from weight loss up on evaporation at 105 ^{0}c for 24 hours (standard method procedure 2540 B) [78].
- Total volatile solid content was estimated from weight loss upon ignition at 550 ^{0}c for 2 hours (standard method procedure 2540 E) [78].
- pH using Jenway model 3510 digital pH meter.
- Total nitrogen (Hach method 10072 TNT per-sulfate digestion).
- Total Phosphorus (Hach method 8190 molybdovanadate with acid per-sulfate digestion).
- Total heavy metals determination (standard method procedure3030E and 3111B) [78].
    - Sample was predigested with HNO_3 in order to destroy organic matter and stabilize the metal to be determined.
    - An atomic absorption spectrophotometer model NOVAA 400, analytikjena campany, Germany was used to determine heavy metals concentration.
- Total coliform and fecal coliform (using standard method procedure 9221B and 9221E respectively) [78].
- Parasite through microscope observation in Yekatit 12 hospital.

3.2.4. Statistical analysis

After the determination of the amount of biogas in each level or treatment ANOVA and multiple comparisons were performed.

3.3. Experimental set up

Experiments were carried out in two 5 liters laboratory scale cylindrical anaerobic digester W8 issue 3 armfield model with temperature control (Fig. 3.1) to determine biogas production from sewage sludge and brewery yeast waste co-digestion.

Figure 3.1: Anaerobic digester used during the test run

The temperature of each reactor is controlled by an electric heating mat wrapped around the external wall. Reactor temperatures may be separately set at any desired value in the range ambient to 55 ^{O}C.

The gas off-take from each reactor is 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 are included in the process pipework to ensure each reactor operates at a constant volume without the entrance of air or the danger of accidental syphonic action.

The equipment is 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, microbiological and parasitological evaluations were carried out to see the potential of co-digestion of sewage sludge and brewery yeast waste for energy recovery and land application after anaerobic digestion.

4.1 Experimental results

Chemical oxygen demand (COD), biological oxygen demand (BOD), volatile solid (VS), total solid (TS) and pH were determined at Environmental Engineering laboratory, Chemical Engineering Department; heavy metal, total coliform (TC) and fecal coliform (FC), total phosphorus (TP), total nitrogen (TN) and total potassium ((TK) were determined at Addis Ababa environmental protection authority laboratory using standard methods for water and waste water examination [78]; Yekatit 12 hospital laboratory for parasite determination was used.

4.1.1 Determination of raw sewage sludge composition

The physical and chemical characteristics of the sewage sludge used in the study were determined and the observed results are displayed in Table 4.1. The total solid of the sewage was 39,531 ± 4,817.5 mg/L and the volatile solid of the sewage sludge accounts 67.3% of the total solid. When considering the COD of the sewage sludge, the mean value was 33,000 ± 2,549.5 mg/L.

Figure 4.1 Test tubes after test, COD and BOD measuring instrument used in the study.

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

Parameters	Unit	Sewage sludge (Kaliti waste water treatment)
pH		7.68 ± 0.18
TS	mg/L	39531 ± 4817.5
VS	mg/L	26843 ± 5258
COD	mg/L	33000 ± 2549.5
BOD_5	mg/L	12800 ± 2258
TN	mg/L	55.9 ± 5.9
TP	mg/L	82.8 ± 15.6
TK	mg/L	225.8 ± 88.7
Cu	mg/L	0.151 ± 0.0642
Ni	mg/L	0.1509 ± 0.0642
Cr	mg/L	0.00315 ± 0.001
Pb	mg/L	Nil
Cd	mg/L	Nil
Zn	mg/L	0.2475 ± 0.054
TC	MPN/100ml	$22*10^6$
FC	MPN/100ml	$12*10^6$
Parasite		
o Ascaris	No./ L	15,000-45,000
o Hook worm	No./ L	0 – 5,000

MPN = most probable number

4.1.2 Determination of brewery yeast waste composition

The physical and chemical characteristics of brewery yeast waste used in the study were determined and the observed results are displayed in Table 4.2. The total solid of the brewery yeast waste was 124,445 ± 2,061.8 mg/L and the volatile solid of the sewage sludge accounts 91.7% of the total solid. When considering the COD of the sewage sludge, the mean value was 182,000 ± 707 mg/L.

Table 4.2 Composition of brewery yeast waste before digestion (mean value ± standard deviation)

Parameters	Unit	Yeast waste (St. George beer)
pH		5.65 ± 0.2
TS	mg/L	124445 ± 2061.8
VS	mg/L	114106 ± 2379
COD	mg/L	182000 ± 707
BOD_5	mg/L	120500 ± 1118
TN	mg/L	41.85 ± 7.85
TP	mg/L	65.15 ± 9.05
TK	mg/L	263.5 ± 0.2972
Cu	mg/L	0.0815 ± 0.0149
Ni	mg/L	0.04655 ± 0.02735
Cr	mg/L	0.02075 ± 0.00705
Pb	mg/L	Nil
Cd	mg/L	Nil
Zn	mg/L	0.2086 ± 0.0886

The characteristics of sewage sludge as main substrate and the yeast waste as co-substrate mixed in different mix ratio were determined and the results are shown in Table 4.3 below. When the wastes mixed and characterized; the mean value of the total solid of 80:20% mix by volume was 56193 ± 3062.5 mg/L and that of 60:40% mix of sewage sludge to yeast waste was 74195 ± 1195 mg/L, the volatile solid of the two mixes were 73.3% and 85.5% of the total solid respectively. When considering the COD of the mixes 45333 ± 1699.7 mg/L for 80:20% mix and 77500 ± 1500 mg/L for 60:40% mix of sewage sludge to brewery yeast waste (ss:yw).

Table 4.3 Characteristics of sewage sludge and brewery yeast waste mixture at different mix ratio before digestion (mean + standard deviation)

Parasite	Unit	Sewage sludge alone (100%:0)	Sewage sludge to yeast waste (80%: 20%)	Sewage sludge to yeast waste (60%: 40%)
pH		7.68 + 0.18	7.03 + 0.16	6.69 + 0.001
TS	mg/L	39531 + 4817.5	56193 + 3062.5	74195 + 1195
VS	mg/L	26843 + 5258	41316.7 + 4329	63439.5 + 1893.5
COD	mg/L	33000 + 2549.5	45333 + 1699.7	77500 + 1500
BOD_5	mg/L	12800 + 2258	16466.7 + 910	39700 + 1300
Parasite ova				
o Ascaris	No./L	15,000 - 45,000	14,000 - 40,000	10,000 - 40,000
o Hook worm	No./L	0 - 5,000	0 – 5,000	-

4.1.3 Determination of feed stock characteristics after digestion

The results of the experiment carried out with digestion and co-digestion of sewage sludge and brewery yeast waste to determine maximum biogas production with good methane quality were indicated in Table 4.4.

The total solid after digestion of sewage sludge alone, 80:20% mix and 60:40% mix of sewage sludge to brewery yeast waste were 24,563 + 1,495 mg/L; 39,058 + 909.7 mg/L and 50,705 + 334.5 mg/L respectively. The mean value of volatile solid of the feed after digestion were 8133 + 891.800 for sewage sludge alone, 24212 + 1902 mg/L for 80:20% mix of sewage sludge to yeast waste, and 37589 + 1675.5 mg/L for 60:40% mix of sewage sludge to brewery yeast waste.

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

Parameters	Unit	Sewage sludge alone (100%:0)	Sewage sludge to yeast waste (80%: 20%)	Sewage sludge to yeast waste (60%: 40%)
pH		7.87 ± 0.110	7.2 ± 0.009	7.1 ± 0.007
TS	mg/L	24563 ± 1495	39058 ± 909.7	50705 ± 334.5
VS	mg/L	8133 ± 891.800	24212 ± 1902	37589 ± 1675.5
COD	mg/L	9667 ± 471.400	16667 ± 1247	30500 ± 1500
BOD_5	mg/L	2967 ± 124.700	6067 ± 309	16300 ± 1100
TN	mg/L	65.9 ± 8.500	63.2 ± 0.040	44.9 ± 0.038
TP	mg/L	76.35 ± 5.750	68.1 ± 0.015	72.9 ± 0.035
TK	mg/L	113.8 ± 53.375	50.5 ± 0.018	35.8 ± 0.033
Cu	mg/L	0.1882 ± 0.033	0.0156 ± 0.007	0.0855 ± 0.025
Ni	mg/L	0.0865 ± 0.041	0.0154 ± 0.022	0.1732 ± 0.012
Cr	mg/L	0.0143 ± 0.001	0.0193 ± 0.02	0.0248 ± 0.009
Pb	mg/L	Nil	Nil	Nil
Cd	mg/L	Nil	Nil	Nil
Zn	mg/L	0.754 ± 0.0997	0.6627 ± 0.030	0.5777 ± 0.031
TC	MPN/100ml	$35*10^4$	$11*10^4$	$7*10^4$
FC	MPN/100ml	$17*10^4$	$9*10^4$	$3*10^4$
Parasite ova				
o Ascaris	No./ L	15,000 - 45,000	14,000-40,000	10,000-40,000
o Hook worm	No./ L	0 - 5000	0 – 5,000	-

MPN = Most probable number

4.1.4 Identification of maximum mix ratio for highest methane production

For the determination of maximum methane in the study from digestion and co-digestion of sewage and brewery yeast waste:100%, 80:20%, and 60:40% mix of sewage sludge to brewery yeast waste were used. The cumulative biogases produced during the experimental period for the digestion of the feed stocks were presented in Table 4.5. From the digestion of sewage sludge alone: 0.44 $m^3/d/m^3$ biogas with 57.75% methane was produced; 0.74 $m^3/d/m^3$, and 0.91 $m^3/d/m^3$ biogas with 19.84% and 19.34% methane produced from 80:20% mix and 60:40% mix of sewage sludge to brewery yeast 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	35.20	57.80	35.20	7.00
Digestion of 80:20% mix of sewage to yeast waste	59.30	19.84	63.50	16.66
Digestion of 60:40% mix of sewage to yeast waste	72.70	19.34	65.40	15.26

4.1.5 Determination of potential of sludge after digestion as an organic fertilizer

For the determination of fertilizing potential the nitrogen, phosphorus and potassium content of the sludge after digestion was measured and the mean value displayed in Table 4.6 below.

Table 4.6 Fertilizer value of sludge after digestion

Parameter	Unit	Sewage sludge alone	80:20% mix	60:40% mix
Nitrogen	mg/L	65.9 $\pm$ 8.500	63.2 $\pm$ 0.040	44.9 $\pm$ 0.038
Phosphorus	mg/L	76.35 $\pm$ 5.750	68.1 $\pm$ 0.015	72.9 $\pm$ 0.035
Potassium	mg/L	113.8 $\pm$ 53.375	50.5 $\pm$ 0.018	35.8 $\pm$ 0.033

Microscopic observation of digested sludge after Sun drying for one month confirm the complete absence of the parasite ova which is a good indication of parasite die off when digested sludge exposed to direct sun light for considerable time.

4.2 Discussion

4.2.1 Characteristics of sewage sludge and brewery yeast waste before digestion

As shown in the Table 4.1, the physical and chemical characteristics of sewage sludge exhibit extreme variations. These variations have also been observed in a number of earlier studies [76] and have been attributed to several factors which included:

- Origin of the sludge;
- Type of on-site sanitation system;
- Amount of ageing that has taken place;
- Extent of storm water and groundwater infiltration;
- User habit.

The variation is highlighted in Table 4.7 where characteristics of toilet sludge from Accra, Ghana, Kumasi, China, Japan, and Korea compared to those obtained in this study. In Accra, the minimum five day biological oxygen demand (BOD_5) was 3, 800 mg/L while the minimum in this study was 9200 mg/L which is a little bit higher than the mean value of Accra and lower than the minimum values reported in Korea, Kumasi, and China. With regard to chemical oxygen demand (COD), the minimum in this study was 29000 mg/L which is near to that of the minimum reported in China and almost half of the mean value of Accra. One major factor that could account for this extreme variation of the values in this study to that reported elsewhere is the amount of water used at the on-site sanitation facility which may cause dilution in measured parameter and leads to less or more in concentration as well as the amount of aging that taken place on the onsite sanitation before collection for further treatment.

Table 4.7 Comparison of the characteristics of sewage sludge in this study to other reported elsewhere (all in mg/L except pH)

Country Parameter	Kaliti sewage sludge[1]	Korea[2]	Ghana[2]	China[2]	Kumasi, Ghana[2]	Japan[2]
pH	7.68 ± 0.18	7.2-7.9	-	-	8.1 - 8.5	-
BOD_5	12800 ± 2258	12600-19200	3,800 - 15,000 (8,800)	15,000 - 18,000	14,200 - 52,000	12900
COD	33000 ± 2549.5	10600-15400	10,400 - 97,000 (47,600)	26,000 - 33,000	36,600 - 175,000	36700
TS	39531 ± 4817.5	32000-44600	-	12,000 - 30,000	31,300 – 87,000 (55,700)	31400
TVS	26843 ± 5258	-	62% of TS	-	48 – 76 (71)	20400
Hem. Eggs (no./L)	15,000-45,000 0 – 5,000		3,600 - 62,000 (29,000)	18,000 - 360,000		

Sources: 1 -present study; 2 -Issac, 2003 [53]

The characteristics of the sewage sludge from this study compare quite satisfactorily with the characteristics compiled from the literature (Table 4.8). In general, the values were not higher than those reported in the literature. The physico-chemical characteristics indicate that the sewage sludge managed in Kaliti waste water treatment plant contains high concentrations of organic matter. Total volatile solids, expressed as a percentage of total solids, range from 57 to 73.2% and had a mean of 67.3%. The high percentage of organic material in the sewage sludge, coupled with the wide fluctuations of the physico-chemical characteristics make the anaerobic digestion process a preferred option for sewage sludge treatment. The COD to BOD_5 ratios range from 2:1 – 3.4:1 thus of the organic content a considerable portion is biodegradable.

Table 4.8 Comparison of data in this study with data compiled from literature

Parameter	Sewage sludge[1]	Literature[2]
pH	7.68 ± 0.18	7.2 – 8.8
BOD_5 (mg/L)	12800 ± 2258	8,000 – 23,000
COD (mg/L)	33000 ± 2549.5	10,000 – 97,000
COD/BOD_5	2:1 – 3.4:1	1.5:1 – 5:1
TS (mg/L)	39531 ± 4817.5	12,000 – 45,100
TVS (mg/L)	26843 ± 5258	≥ 50%
Helminthes eggs (no./L)		-
❖ Ascaris	15,000-45,000	
❖ Hookworm	0 - 5,000	

Source: 1 -present study; 2- Issac, 2003[53].

The number of helminth eggs observed in this experimental study suggests 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 indicate the unsafe nature of untreated sewage sludge for land application.

The brewery yeast waste was slightly acidic with good smell; it is probably due to the presence of fermentation alcohol and beer in the spent yeast, mean VS value of 114,106 mg/L and was rich in nutrients such as nitrogen, phosphorus and potassium. The nitrogen and phosphorous content of the brewery waste water depend on the amount of spent yeast present in the sewer line. In agreement with others [79], this study also confirms brewery yeast waste is one of the potential largest COD discharging processes in brewery. The mean COD value in this study is 182,000 mg/L; which is near to the minimum value reported [79] i.e. 180,000 – 220,000 mg/L. When the physico-chemical characteristics of yeast waste compared with the sewage sludge in this study, the variation of the values with time (Fig. 4.2) is minimal and may be tolerable. The mean total solid content of the yeast waste is 124,445 mg/L. An agreement in total solid content of brewery yeast waste report elsewhere with this study is observed, i.e. 12 to 15 % [79].

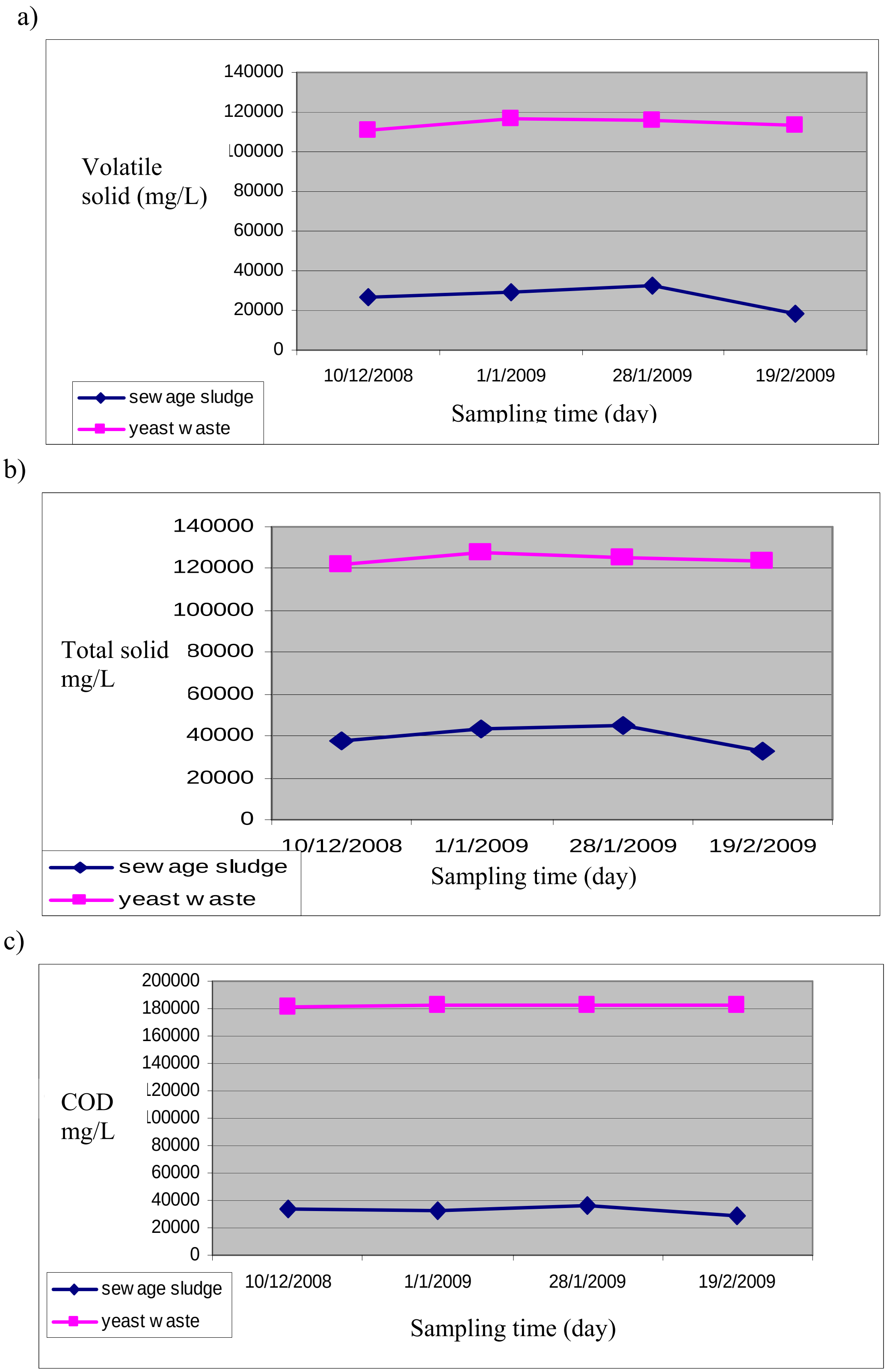


Figure 4.2 Values for volatile solid, total solid and COD of sewage sludge and brewery yeast waste in different sampling time.

As shown in Table 4.3 and Fig. 4.3 when the sewage sludge mix with the brewery yeast waste, as co-substrate, there is significant change in composition and the variation with time decreases relatively when the co-substrate volume increases. The mean value of total solid in the sewage sludge is 39,531 mg/L in high variation with time but in 20% co-substrate mix, it becomes 56,193 mg/L and in 40% co-substrate mix 74,195 mg/L; relatively the variation goes in decreasing and the solid content of the feed approach to the recommended value for anaerobic digestion [44, 46]; however, the COD value increase significantly and become far away from the recommended value for anaerobic digestion [3].

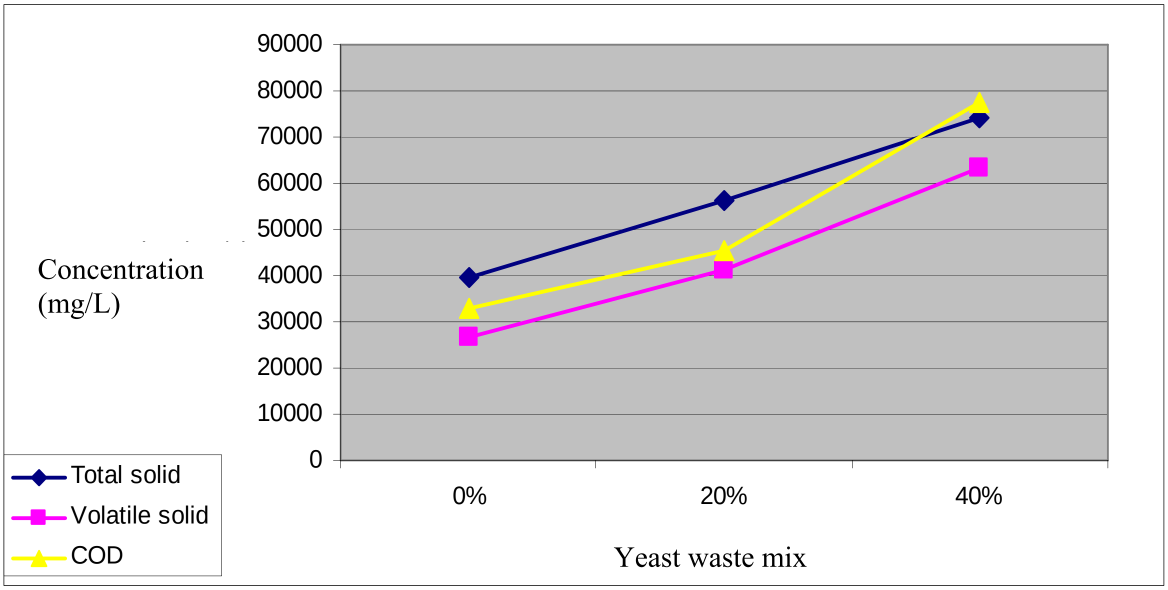


Figure 4.3 Concentrations of VS, COD, and TS with respect to co-substrate mix.

4.2.2 Determination of feed stock characteristics after digestion

The characteristics of sewage sludge and brewery yeast waste after digestion at different mix ratios are shown in Table 4.4 and the major characteristics discussed hereunder.

4.2.2.1 Total solid

The total solids were reduced to about 35%, 30.3% and 31.7% of the feed stock: sewage sludge alone, 80:20% and 60: 40% mix of sewage sludge to brewery yeast waste, respectively. A better removal was observed in sewage sludge digestion and almost equal and less removal when yeast waste mix during the digestion. Generally there may be a trend in decreasing of removal efficiency when the co-substrate mix volume increase (Fig. 4.4).

4.2.2.2 Volatile solid

It was observed a significance variation in removal of volatile solid in the digestion of sewage sludge alone and the addition of co-substrate, brewery yeast waste (Fig. 4.4). The mean removal efficiency of 69.7% is observed for digestion of sewage sludge alone and 41.2% for 80:20% mix, and 40.7% for 60:40% mix of sewage sludge to brewery yeast waste. It is a very good indication of high uptake rate for the organic fraction of the total solids. The high VS removal efficiencies in sewage sludge digestion indicate the effectiveness of the anaerobic reactor in digesting sewage sludge under anaerobic digestion during proper operating conditions. The removal efficiency by the addition of co-substrate has made almost no difference.

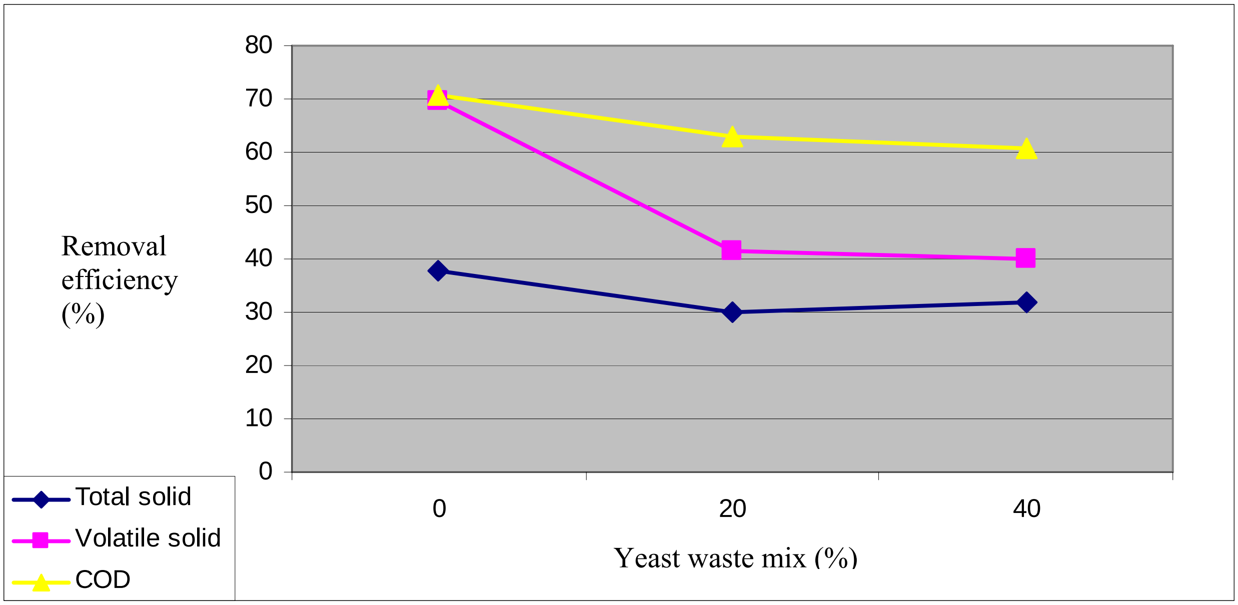


Figure 4.4 Percent removal for TS, VS, and COD with respect to co-substrate mix.

Comparison of the volatile and total solid before and after digestion gives an indication of the utilization of the organic content in the reactor. Before digestion TVS/TS ratio of sewage sludge alone with an average value of 67.9% while after digestion it was 33.1%, a mean drop of 34.8% from before digestion TVS/TS ratio. As indicated in the fig. 4.5, the ratio before digestion was always higher than the ratio after digestion, an indication of the utilization of the organic fraction during the anaerobic digestion; this is true for all the feed used in this study.

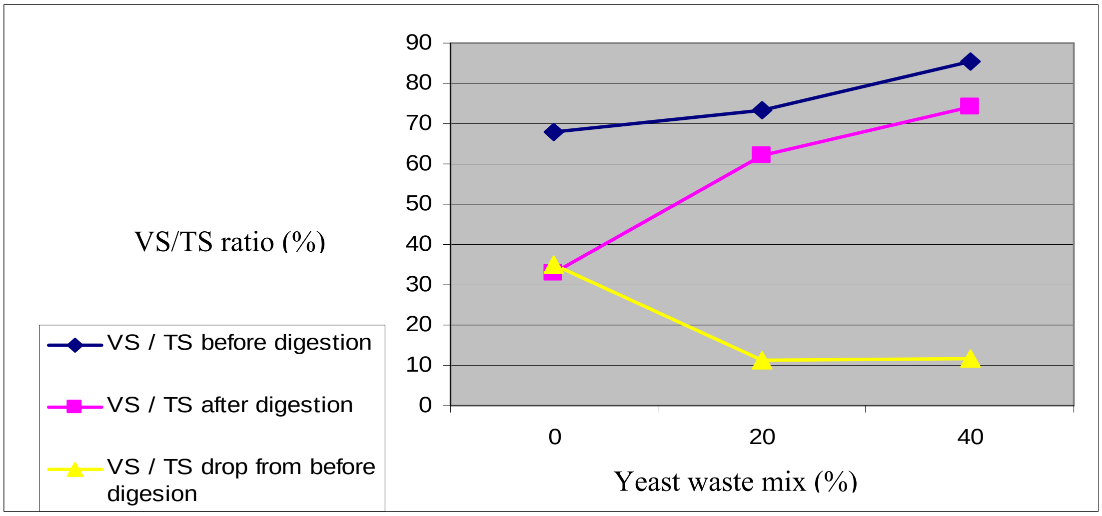


Figure 4.5 Volatile solid to total solid ratio with respect to co-substrate mix ratio.

4.2.2.3 COD

Considerable removal efficiencies of COD were generally observed on sewage sludge and brewery yeast waste digestion with the average efficiency of 70.7%, 63.2%, and 60.6% for sewage sludge, 80:20% mix of ss:yw and 60:40% mix of ss:yw, 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.

4.2.3 Determination of potential of sludge after digestion as an organic fertilizer

The important parameter of the sludge fertilizing potential observed in this study discussed hereunder:

4.2.3.1 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 [80, 81]. None of the heavy metals measured was over the maximum established limits as shown in Table 4.9. Increment in micronutrient after digestion is observed in this experimental study, such situation is observed by Ilangovan and Noyola [82] 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.

4.2.3.2 Pathogen

The digestion significantly reduce the coliform bacteria: 98.6 % for fecal coliform and 98.4 % for total coliform; but not the helminth 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 helminth eggs. It was observed complete removal of helminth eggs after drying the digested sludge on direct sun light exposure for one month in this study. Ludwing [83] report the same situation of complete removal of parasite when the fermented slurry is dried in the sun.

4.2.3.3 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 compactibility [73]. 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 inactivate the pathogen.

Table 4.9 Comparison of values after digestion with recommended maximum concentration of trace elements in irrigation water and standards of discharge to land in Ethiopia (all in mg/L)

Element	A[1]	B[1]	C[1]	D[2]	E[3]	Remarks
Cd	Nil	Nil	Nil	1	0.01	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solution. Conservative limits recommended because of its potential for accumulation in plants and soils to concentrations that may be harmful to humans
Cr	0.01	0.02	0.02	2	0.1	Not generally recognized as an essential growth element. Conservative limits recommended because of lack of knowledge on toxicity to plants
Cu	0.19	0.02	0.09	2	0.2	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solution
Ni	0.09	0.02	0.17	3	0.2	Toxic to a number of crops at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH
Pb	Nil	Nil	Nil	0.5	5.0	Can inhibit plant cell growth at very high concentration
Zn	0.75	0.66	0.58	5	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH >6.0 and in fine-textured or organic soils

Source: 1- present study; 2 - Pollution control standard in Ethiopia [80]; 3 - Metcalf and Eddy [3]

A – Sewage sludge alone

B – 80 : 20 % mix of sewage sludge to yeast waste

C – 60 : 40 % mix of sewage sludge to yeast waste

D – Controlled pollution standard of discharge to land in Ethiopia

E – Recommended maximum concentration of trace element in irrigation water

4.2.4 Identification of maximum mix ratio for highest methane production

The production of biogas was observed and volumes of the biogas collected were recorded during the experiment period and the production of biogas was used mainly as an indication of the progress of the digestion process.

The mean cumulative biogas production for the digestion of sewage sludge and its co-digestion tests is shown in Fig. 4.6. In biogas production mixed digestion is better than digestion of sewage sludge alone; it was observed in this experiment there is a trend of increase in biogas production when ever co-substrate mix volume increase. As shown in the analysis of variance (annex 2.1) the independent variable- mix ratio significantly affects (p-value $1.65 * 10^{-9}$) the dependent variable-amount of biogas produced. When the p-value of a coefficient is less than the chosen α-level (usually 0.05), there is evidence of a significant relationship between the predictor or factor level and the response variable.

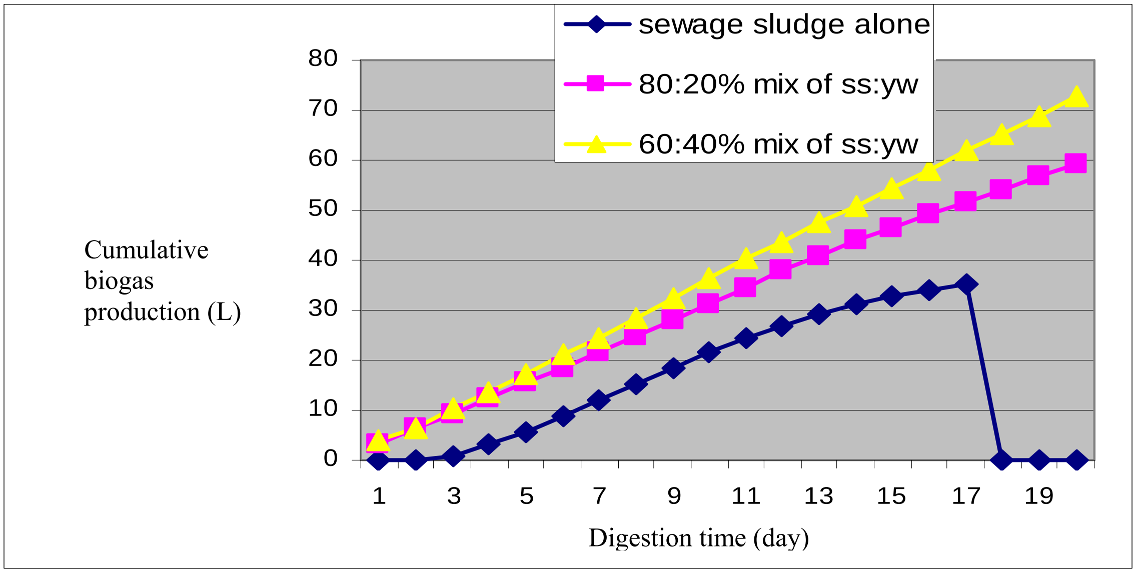


Figure 4.6 Cumulative biogas productions during anaerobic co-digestion of sewage sludge and brewery yeast waste.

The sewage sludge and brewery yeast waste co-digestion gave the maximum overall biogas yield compared with digestion of sewage sludge alone, most probably because the wastes had the highest TS content and high biodegradability by AD since TS is one factor influence biogas production in anaerobic digestion [44, 46].

Methane concentrations measured during the digestion period and mean values in different mix ratio are shown in Figs. 4.7 and 4.8, respectively. A better methane composition with an average of 57.8% was observed when sewage sludge digested with out brewery yeast waste mix. When the brewery yeast waste mix the percentage composition of methane decreases significantly and gradually increase with an average 19.84% and 19.34% for 80:20% and 60:40% mix of sewage sludge to yeast waste. As shown in the analysis of variance (annex 2.2) the independent variable-mix ratio significantly affects (p-value 0.0027) the dependent variable-amount of methane produced. When the p-value of a coefficient is less than the chosen α-level (usually 0.05), there is evidence of a significant relationship between the predictor or factor level and the response variable.

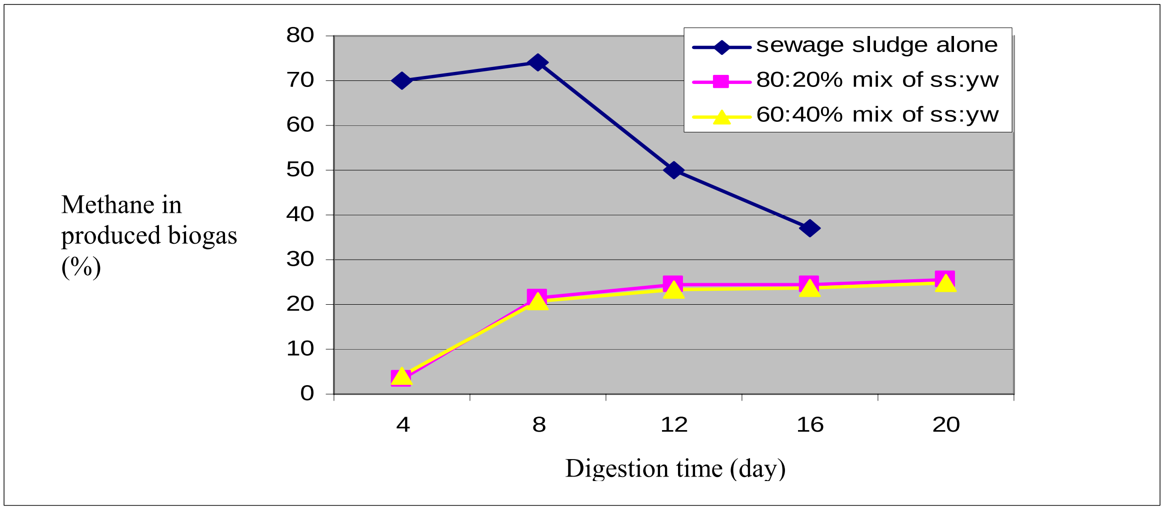


Figure 4.7 Methane compositions during the digestion period.

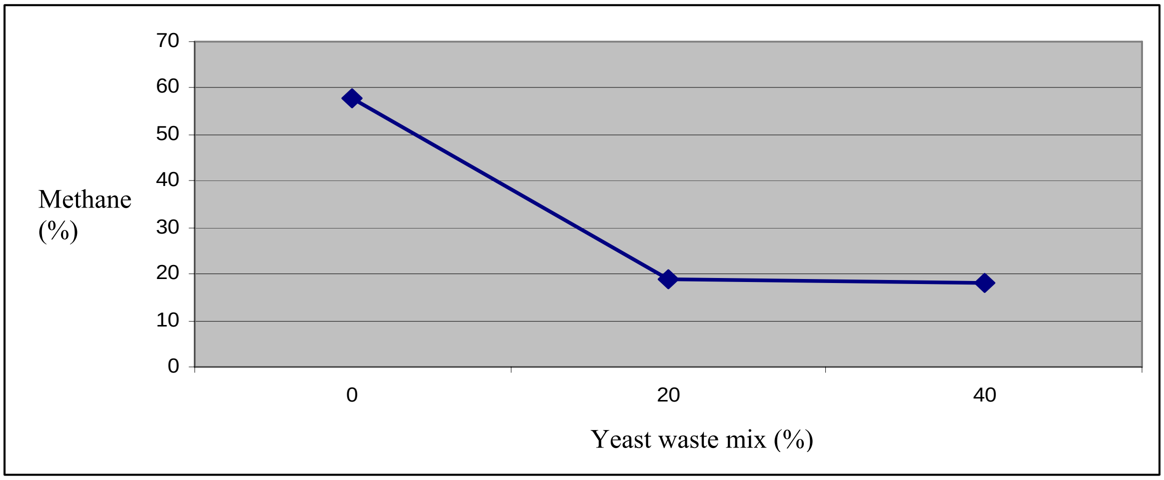


Figure 4.8 Methane compositions with respect to different mix ratio.

Carbon dioxide concentrations for sewage sludge alone detected were low when compared to mixed digestion and remained fairly constant (Fig. 4.9); on average, 35.2%, but for mixed digestion were high compared to digestion of sewage sludge alone, on average 63.5% for 80:20% mix and 65.4% for 60:40% mix digestion. This also show how much the methanogen bacteria were dominated by others in the digester when yeast waste mix with sewage sludge.

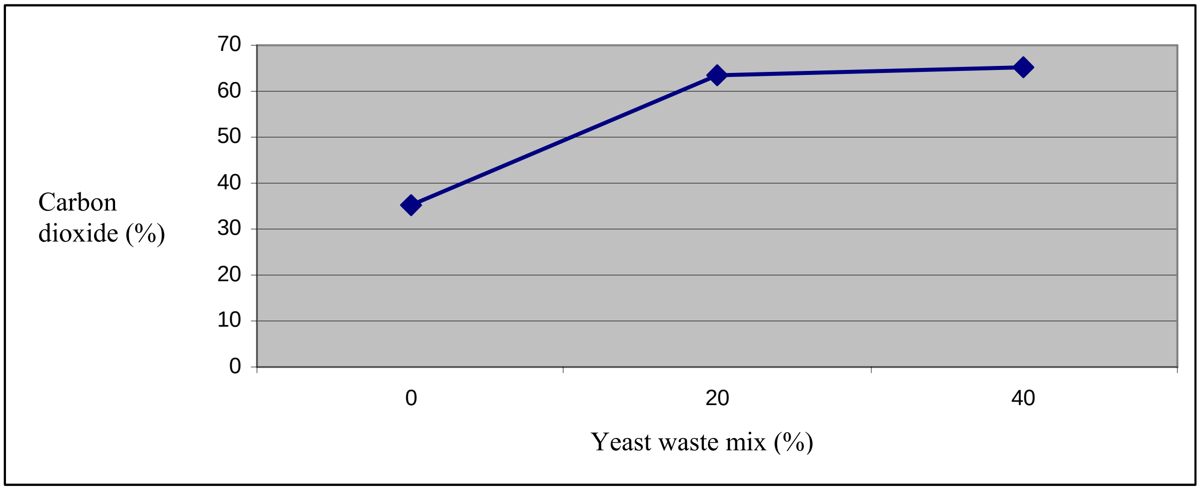


Figure 4.9 Carbon dioxide compositions in different co-substrate mix.

The calculated volume of methane per gram of VS removed (Fig. 4.10) was always higher than that for the COD in all digestion feed stocks. The calculated volume of methane in the biogas produced per g COD removed were 0.218L , 0.103L, and 0.075L; with regard to VS, 0.271L, 0.172L, and 0.136L for sewage sludge alone, 80:20% mix of ss:yw and 60:40% mix of ss:yw respectively. There is an apparent trend in the graph that the variations in the volumes associated with VS removed were substantial compared to variations in volumes associated with COD removed.

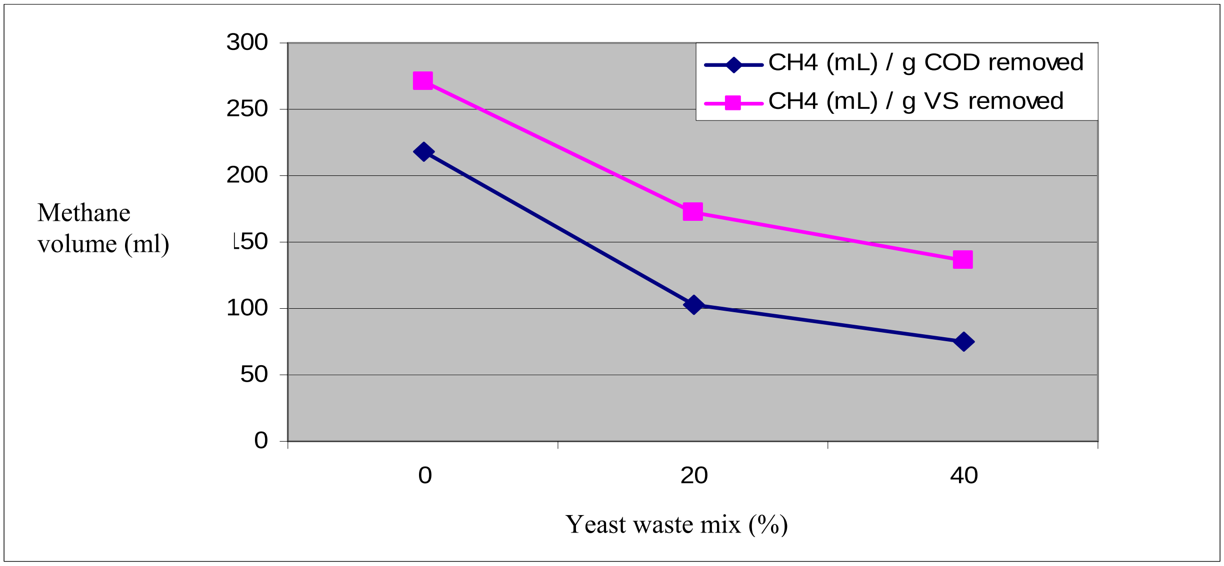


Figure 4.10 Volume of methane produced per gram COD and VS removed in different mix.

Co-substrate can change the digestion behavior. High COD containing co-substrate increase the loading rate eventually the concentration of metabolites like NH_4, H_2S and VFA. Sulphate containing distillery slops, yeast and yeast like wastes, and protein rich wastes from slaughter houses and the food and pharmaceutical industries can cause H_2S contents that might be inhibitory [81].

The interaction between free ammonia, VFA and pH may lead to an inhibited steady state ‘a condition where the process is running stably but with a lower methane yield [44]. This is the most probable reason for the low methane content in the mixed digestion.

More over as a feed stock for biogas production co- digestion of sewage sludge and brewery yeast waste have the same problem in foaming and choking of digester observed for green pea shells and water hyacinth anaerobic digestion [84], this may have contribution in low methane content.

Minimum quantities of methane were detected when sewage sludge and brewery yeast waste mixed suggesting that methanogenesis was not the dominant microbial reaction for such types of waste. The lower pH and extreme COD value in these wastes probably contributed to this fact.

5. DESIGN OF ANAEROBIC DIGESTER

UASB digester design based on the sewage sludge characteristics in this study (Table 5.1) for the treatment of sewage sludge in Addis Ababa waste water treatment plant is described hereunder:

5.1 Applicability of anaerobic digestion process for the treatment of sewage sludge and selection of appropriate digester

The search for alternate treatment systems due to the high capital, operational and maintenance costs associated with aerobic systems resulted in the development of treatment systems that utilize anaerobic digestion for the removal of organic material from human wastes.

Although literature on the direct use of anaerobic digestions processes for the treatment of nightsoil and toilet sludges is sparse, published work and this study indicate that it is feasible to use anaerobic digestion process for the treatment of nightsoil and toilet sludge. The main task is getting the right environmental conditions and applying the treatment process suited to the socio-economic needs of a developing country like Ethiopia.

The mean characteristics of sewage sludge in Addis Ababa as described in the result and discussion section:

- High COD with mean value 33,000 mg/L
- Slightly above neutral pH
- 3.9% total solid and considerable volatile portion

Anaerobic processes are specially suited to the treatment of heavily contaminated organic wastes with COD greater than 5000 mg/L [53]. Thus with the characteristics of sewage sludge being within or close to the ranges optimal for the anaerobic digestion conversion process, it should be possible to stabilize such sludge by anaerobic treatment process as evidenced by the use of the process technology throughout the available literature and in this study.

The new direction of research efforts towards energy-saving alternatives like anaerobic treatment, has resulted in more knowledge and understanding of the anaerobic process. Properly designed modern or high rate anaerobic treatment systems can now attain high removal efficiency for biodegradable organic matter, even at very short retention times. These high removal efficiencies are being attributed to the presence of a high concentration of active bacterial mass within the anaerobic reactor and the intense interaction between the influent and the active bacterial mass. The upflow anaerobic sludge blanket (UASB) reactor is one such modern or high rate anaerobic treatment system.

After waste stabilization pond (WSP), UASB in combination with final polishing unit (FPU) gives better proposition in terms of investments as compared to other technologies. In terms of sustainability the use of UASB reactors as the core unit of sewage treatment facility is most suited for resource recovery. Based on the life cycle cost evaluation of sewage treatment technologies, it can be concluded that UASB in combination with adequate post-treatment option like FPU or extended aeration system (EAS) still offers best proposition compared to other treatment systems. The potential for application of anaerobic treatment systems in the developing world is enormous, the use of UASB reactors as a core unit can improve the sustainability of sewage treatment system in these countries [85].

5.2 The UASB reactor concept and design consideration

Lettinga [31] state basic ideas underlying the process as:

- The anaerobic sludge develops and maintains superior settling characteristics if chemical and physical conditions favorable to sludge flocculation and to the maintenance of a well flocculated sludge are provided.
- A sludge blanket (bed) may be considered as a separate - more or less - fluid phase with its own specific characteristics. A well-established sludge blanket frequently forms a rather stable phase, capable of withstanding relatively high mixing forces. The re-dispersion of the sludge in the liquid phase therefore may require a significant amount of mixing energy.
- The washout of discrete sludge particles (flocs) released from the sludge blanket can be minimized by creating a quiescent zone within the reactor, enabling the sludge particles to flocculate, settle, and/or be entrapped in a secondary sludge blanket present in the settler compartment.

These ideas are incorporated into the process design of the UASB to meet the basic requirements for a high rate anaerobic wastewater treatment system in the following ways [29]

- For the conversion of organic influent material the UASB relies on the formation of well settleable, flocculent or granular type of anaerobic sludge forming a blanket in the bottom section of the reactor, known as the digestion zone. The influent is uniformly distributed over the reactor bottom and follows an upward path to the level of effluent abstraction at the top of the reactor. As the influent passes through the sludge blanket, the organic material is taken up and metabolized by the sludge and to a large extent transformed into biogas.
- For the required intense contact between the influent organic material and the bacteria in the sludge, the system relies on agitation caused by the rising biogas bubbles and the kinetic energy of the influent when it enters the reactor. Under most circumstances the natural agitation will be sufficient for good contact between the organic material and the bacteria, so that mechanical mixing is not applied.
- A large mass of well-settleable sludge can be retained in the reactor by installing a separator to separate the three phases in the reactor: gas, biogas; liquid, the effluent; and solid, the sludge in the top part of the reactor.

5.2.1 Design Criteria

The design criteria described in the literature apply to UASB reactors treating sewage and some industrial wastewater assumed to be applicable in this research.

- Loading Rates

The load on a UASB reactor is limited to either the organic or the hydraulic load depending on the nature of the wastewater. Hydraulic load is used in the design when the wastewater is relatively low strength such as domestic sewage. The maximum hydraulic load 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 1 m/h in the UASB reactor and is calculated as follows:

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

Where:

v_i = liquid upward velocity (m/h);
Q_i = average wastewater flow (m^3/h);
A = surface area of the UASB reactor (m^2);
V_r = volume of the reactor (m^3);
(HRT) = hydraulic retention time (h); and
H = height of the UASB reactor (m).

Van Haandel et al. [29] state that from available experimental results, an average retention time of six hours is sufficient in tropical and subtropical regions (T > 18 ^{0}C) to achieve satisfactory treatment efficiency in one compartment UASB reactors.

- Organic Load

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:

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

Where:

l_0 = applied specific COD load (kg COD m^{-3} d^{-1})
L_0 = organic (COD) load (kg COD d^{-1})
V_r = volume of the reactor (m^3);
Q_i = average wastewater flow (m^3/d);
S_{ti} = 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^3d 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 [31].

5.2.2 Physical Design considerations

- Shape of reactor

UASB reactors are either circular or rectangular in cross section. 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 UASB reactors are generally constructed in rectangular or square cross sections and small reactors are generally constructed in cylindrical shape. Furthermore, when more than one reactor unit is constructed, the rectangular shape is advantageous because sidewalls can be shared by different units.

- Height (or depth) of reactor

In practice, the choice of the appropriate height or depth of the reactor depends on the required performance and economic considerations. A higher depth/volume ratio reduces the required area for the treatment and thereby increases the upflow velocity which results in increased turbulence in the system and hence better contact between biological sludge and incoming wastewater. High upflow velocities can result in excessive sludge washout; the greater the depth of the UASB reactor the higher the static pressure. High static pressure causes an increase in the solubility of carbon dioxide which may result in a lowering pH. If the pH is lower than optimum value the anaerobic digestion can be jeopardized. Most UASB reactors have a height or depth between 4 and 6 m. This range has proved to be the economic optimum and adequate from the process point of view [31].

5.2.3 Start-up of UASB Reactor Treating Domestic Wastewater

The start-up of anaerobic treatment process is time consuming and sometimes rather difficult compared to aerobic treatment process. This is due to the slow growth rate of anaerobic bacteria and adaptation of the bacterial mass to the particular characteristics of the wastewater to be treated. Domestic sewage however differs from other wastewaters of industrial origin in that it already contains the bacterial populations necessary for anaerobic digestion. Thus, a reactor for anaerobic treatment of domestic sewage can be started without the need for inoculation. The bacterial populations for acid and methanogenic digestion develop spontaneously. To bring down on the length of time required for the start-up, the reactor may be seeded.

5.2.4 Steady-State behavior in the UASB Reactor

During the start-up period of the operation of the UASB reactor, the correct bacterial populations capable of converting organic material into methane develop and grow. Sludge mass begins to accumulate in the reactor and the extent of accumulation of this sludge is limited by the physical size of the UASB reactor. Some time after the beginning of the operation, the UASB reactor becomes filled up with sludge. When this condition is attained, there are two basic ways of dealing with the sludge production of the system [31]. The first is to discharge the sludge periodically so that the concentration of settleable solids in the effluent remain as low as possible. The second option is to operate the reactor at maximum sludge hold-up, consequently accepting the washout of excess sludge. In this latter mode, the concentrations of settleable solids will be relatively high.

In practice, the first option is adopted if the UASB reactor is the only biological treatment unit. This ensures that the effluent COD and TSS concentrations as low as possible. The second option is adopted in practice when some kind of post treatment, such as a waste stabilisation pond, is employed.

With respect to sludge build-up, the start-up period can be considered as being complete and steady state established when the sludge mass present in the reactor remains constant, both qualitatively and quantitatively and the effluent quality remains constant at the design load. After the establishment of a steady state, the total daily flux of settleable solids in the effluent is equal to the daily sludge production rate.

With regards to the organic material (COD) present in the waste, a steady state is established when organic matter does not accumulate in the treatment system. When this is attained, the daily mass of influent COD is equal to the sum of the daily mass of COD leaving the system as methane, in the excess sludge produced, in the effluent, and the daily amount of COD oxidized.

$$MS_i = MS_e + MS_x + MS_m + MS_o$$

Where:

MS_i = daily mass of influent COD
MS_e = daily mass of effluent COD
MS_x = daily mass of COD in the discharged sludge
MS_m = daily mass of COD in produced methane
MS_o = daily mass of oxidized COD

5.3 Design of UASB reactor for sewage sludge treatment collected in Kaliti waste water treatment plant

In this section an upflow anaerobic sludge blanket (UASB) reactor are designed for the city of Addis Ababa using the current quantity of sewage sludge managed. The purpose of the design is to treat the sewage generated in the city for energy and resource recovery as well as to avoid green house gas emission and pollution prevention with regard to such waste management.

Table 5.1 Design Assumptions and Requirements

Population[1]	2,738,248
Current sewage managed in the study site[2]	904 m^3/d
COD[3]	33,000 mg/L
Total Solids[3]	39,531 mg/L
Volatile solid[3]	26,843 mg/L
Mean temperature[1]	16 ºC

1-CSA, 2008 [1]; 2- Asefa Alemu, 1998 [2]; 3- present study

- Design Calculations for UASB

The design of the UASB is based on organic loading rather than hydraulic loading because of the concentrated nature of the wastes. The necessary design equations used are:

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

Where

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

L_0 = Organic (COD) load (kg COD d^{-1});

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

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

S_{it} = influent organic material (COD) concentration (kg /m^3);

HRT = hydraulic retention time (d).

- *Volumetric Load*

Total volume of sewage sludge currently collected and managed in the study site = 904 m^3 /d
Assume dilution ratio of 1:5
Volumetric load, V_{load} = 4,520 m^3/d

- *COD Load*

Total COD_{load} = COD concentration x volumetric load
= 33,000 mg/L x 904 m^3 /d = 33,000 * 1000 mg/m^3 * 904 m^3 /d
= 29,832,000 * 1000 mg COD/d = 29,832 kg COD/d
Influent COD concentration = [29,832 kg COD/d] / 4,520 m^3/d
≈ 6.6 kg COD/m^3
Assume applied specific COD load (l_o) = 17 kg COD/m^3.d
Volume of reactor, $Vr, = L_o / l_o$
= [29,832 kg COD/d] / 17 kg COD/m^3.d
= 1,755 m^3; assuming 85% effective volume and the total reactor volume including free space is equal to 2065 m^3
More than one reactor would have to be constructed to accommodate this volume. Rectangular section reactors would be used for reasons stated in section 5.2.2
Using a reactor of dimensions (length x width x height) 12.5m x 7m x 6m, four compartment digester 516.3 m^3 each and a total volume of 2065 m^3 can accommodate the waste to be digested
Daily flow to each reactor = [4,520 m^3/d] / 4 = 1,130 m^3/d
Organic load to each reactor = 6.6 kg/m^3 x 1,130 m^3/d = 7,458 kg COD/d
Applied specific COD load l_o = [7,458 kg COD/d] / 516 m^3. = 14.45 kg COD/m^3.d which is < 20 kg COD/m^3.d
Total cross-sectional area of 4 compartment reactor = 4 x 12.5m x 7m = 350 m^2
Hydraulic retention time, $HRT, = S_{ti} / l_o$ = [6.6 kg/m^3] / [17 kg COD/m^3.d] = 0.39 d = 9.36 h
Upflow velocity, v_i (m/h) = $H / (HRT)$ = 6m /9.36h = 0.64 m/h it is < 1 m/h**.**

- *Storage/Flow Equalization Tank*

Due to the variability of the characteristics of faecal sludges and the intermittent manner of collection and transportation, an equalization/storage tank is required to even out the variations in the pollution strength of the faecal sludges and also ensure a continuous flow to the UASB reactor.

Volumetric Load = 4,520 m^3/d (delivered in 8 hours) i.e. Influent flow rate into tank = 565 m^3/h

Flow rate from storage tank = 189 m^3/h

Daily storage volume required = 4,520 m^3 – (189 m^3/h * 8 h) = 3,008 m^3

Assume depth of tank = 3 m

Area of tank = 1,003 m^2 and take 8 compartment of equalizing tanks each with 126 m^2.

Using a width to length ratio of 1:2, the tank would have dimensions 15.7m x 8m.

Table 5.2 Assumed Treatment Performance for UASB Reactor [53]

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 = 6.6 kg/m^3

Total Solids = TS concentration * volumetric load

= 39,531 mg/l * 904 m^3/d = 39.531 kg/m^3 * 904 m^3/d = 35,736 kg TS/d

TS concentration = [35,736 kg TS/d] / [4,520 m^3/d] ≈ 7.9 kg TS/m^3, i.e. 7,900 g/m^3 or mg/l

Volatile Solids load = VS concentration * volumetric load

= 26,843 mg/L * 904 m^3/d = 26.843 kg/m^3 x 904 m^3/d = 24,266 kg VS/d

VS concentration = [24,266 kg VS/d] / [4,520 m^3/d] ≈ 5.4 kg VS/m^3, i.e. 5,369 g/m^3 or mg/l

Using the above treatment performances (Table 5.2), the effluent characteristics from the UASB reactor would be:

Effluent COD = 0.3 x 6,600 g/m^3 = 1,980 g/m^3

Effluent BOD (assuming COD/BOD is 3.4:1) = 582 g/m^3

Effluent TS = 0.4 x 7,900 g/m^3 = 3,160 g/m^3

Effluent VS = 0.25 x 5,369 g/m^3 = 1,342 g/m^3

This waste strength can be further reduced using the existing pond to meet the criteria [80]

- *Methane Production*

Using the total volatile solids, the volume of methane produced is:

VS removed = 24,266 kg VS/d x 0.75

= 18,200 kg VS/d = 18,200,000 g VS/d

Volume of methane = 9.6 ml/g VS * 18,200,000 g VS/d

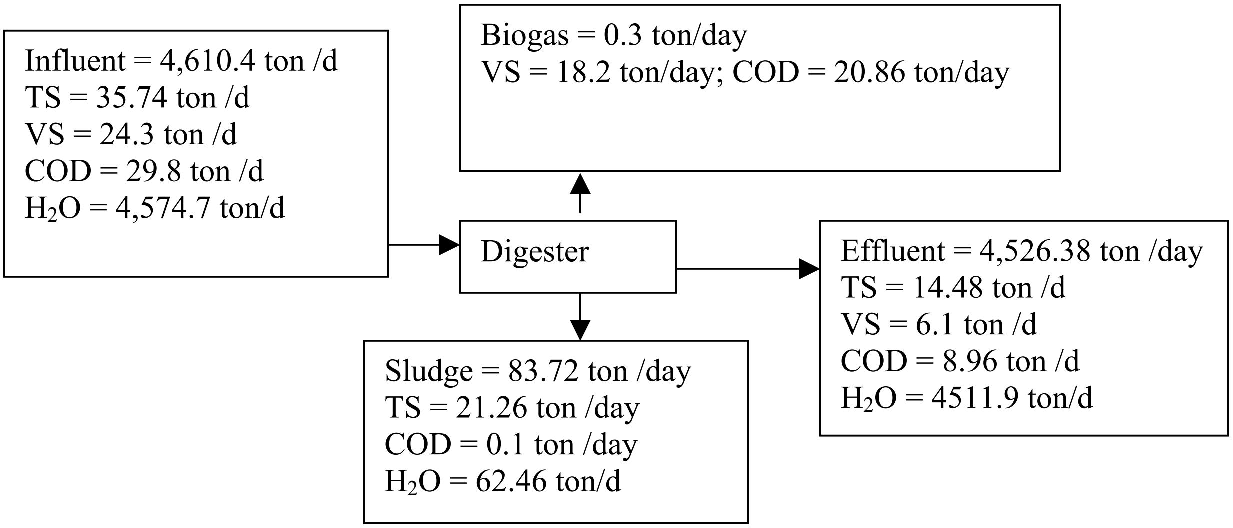
= 174,720,000mL/d = 174,720 L/d ≈ 175 m^3/d;

Since anaerobic digestion operates in a closed system, substantial reductions in greenhouse gas emissions, methane, is achieved; which is 21 times greater than carbon dioxide in causing global warming.

Annually 52, 500 cubic meter methane will be produced using UASB reactor. This brings an electric energy equivalent of 335,642.89 kWh and income of 142,811.05 ETB/year with the current price of around 37cents per kWh. In addition using the digester can reduce 1,102,500 cubic meter CO_2 equivalent emissions into the atmosphere.

- *Mass balance*

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 has the units of mass/time [53]. Assuming all the wasted biological solids in the effluent stream and taking solid residence time 20 days [3] and the treatment efficiency of UASB [53] the following mass balance is computed.



- *Heat required to maintain the required digester temperature*

Assumption based on Metcalf and Eddy [3] and present study:

- Specific heat capacity of sludge = 4,200 J/kg. ^{0}C
- Concrete digester with dimension 12.5m * 7m * 6m
- Daily flow to the reactor 4,520 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
  - Fixed concrete cover, 100 mm thick and covered with built up roofing = 4-5 W/m^2.^{0}C

Compute the heat requirement for the sludge

$Q_s = m_s C_p \Delta T$

= (4,520 m^3/d) (1020 kg/ m^3) (4,200 J/kg. ^{0}c) (35 ^{0}c – 13 ^{0}c) = 4177 *10^8 J/d = 4835 kW

Compute area of wall, floor and roof

Wall = 2[2(12.5 * 6) + 2(8 * 6)] = 342 m^2

Floor = 2* 12.5 * 7 = 175 m^2

Roof = 2* 12.5 * 7 = 175 m^2

Compute heat loss by conduction ($q = UA\Delta T$)

Wall:- = (5 W/m^2.^{0}c) (342 m^2) (35 ^{0}c -16 ^{0}c) (86400 sec/d) = 57 * 10^8 J/d

Floor:- = (1.7 W/m^2.^{0}c) (175 m^2) (35 ^{0}c -16 ^{0}c) (86400 sec/d) = 9 * 10^8 J/d

Roof:- = (5 W/m^2.^{0}c) (175 m^2) (35 ^{0}c -16 ^{0}c) (86400 sec/d) = 25 * 10^8 J/d

Total loss = (57 * 10^8 + 9 * 10^8 + 25 * 10^8) J/d = 91 * 10^8 J/d = 105 kW

Compute the required heat exchanger capacity

= heat required for sludge and heat required for digester

= 4177 *10^8 J/d + 91 * 10^8 J/d

= 4268 *10^8 J/d = 4940 kW

Mass flow of hot water, assuming change in temperature 17 ^{0}C

$Q_w = m_w C_p \Delta T$; $m_w = Q_w / C_p \Delta T$

= (4268 *10^8 J/d) / (4,200 J/kg. ^{0}C * 17 ^{0}C) = 6 * 10^6 kg/d = 6,000 m^3/d

- Power needed for hot water pump

Turbine type shaft power = (volumetric flow rate * pressure drop) / intrinsic efficiency in the pump. Assuming 75% intrinsic efficiency in the pump and 2 times pressure drop of heat exchanger; therefore the energy needed = ($0.069m^3/s$ * 2* $60799.26N/m^2$)/0.75 = 11.2kW.

- Power needed by mixer for equalization tank

The power for liquid –solid mixing by propeller type mixer by converting the selected 3 horse power propeller in to kW which is equal to 3hp / 0.7457hp kW^{-1} = 4 kW. Let take 8 mixers for eight mixing tank compartment which need 32kW.

  - *Sizing of shell and tube heat exchanger*

- General equation for heat transfer across a surface, $Q = UA\Delta T_m$

Where: Q = heat transferred per unit time, W

U = the overall heat transfer coefficient, $W/m^2.^0C$

A = heat transfer area, m^2

ΔT_m = the mean temperature difference, the driving force, ^0C

- Exchanger type and dimension

Even number of tube passes is usually the preferred arrangements as this positions the inlet and out let nozzles at same end of the exchanger which simplifies the pipe work.

- using 1 shell pass and 4 tube passes counter current

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{T_2 - t_1)}}$$

Where: ΔT_{lm} = log mean temperature difference

T_1 = inlet shell side temperature

T_2 = outlet shell side temperature

t_1 = inlet tube side fluid temperature

t_2 = outlet tube side fluid temperature

$$\Delta T_{lm} = \frac{(55-35)-(38-13)}{\ln \frac{(55-35)}{(38-13)}} = 22.4\ ^0C$$

The usual practice in the design of shell and tube exchanger is to estimate the true temperature difference from logarithmic mean temperature by applying a correction factor to allow for the departure from true counter current

$$\Delta T_m = F_t * \Delta T_{lm}$$

Where, F_t is temperature correction factor. It is normally correlated as a function of two dimensionless temperature ratios

$$R = \frac{(T_1 - T_2)}{t_2 - t_1} = 0.77$$

$$S = \frac{(t_2 - t_1)}{T_1 - t_1} = 0.52$$

From the graph in Coulson [86] F_t value with this dimensionless ratio is 0.9

$\Delta T_m = 0.9 * 22.4 = 20.16$

- Heat transfer area

$$Q = UA\Delta T_m$$

Assuming U = 800 W/m^2. ^{0}c [86]

$$A = \frac{(4940\,kW)}{800\,x\,20.16} = 306.3\text{, let say } 310 \text{ m}^2$$

- Lay out and tube size

using a split ring floating head exchanger for efficiency and easy of cleaning, neither fluid is corrosive and operating pressure not high; so a plain carbon steel can be used for the shell and tubes. Sewage sludge is dirtier than hot water so put the sewage sludge through tube and hot water in the shell. 19.05 mm outside diameter, 14.83 mm inside diameter, 5 m long tubes (a popular size) on a triangular 23.81 mm pitch (pitch /diameter = 1.25)

Number of tubes: area of one tube neglecting thickness of tube sheets

$$A = \pi * 0.01905 * 5 = 0.2992 \text{ m}^2$$

Number of tubes = 310 m^2 / 0.2992 = 1036.09, let say 1036

So, for 4 passes, tubes per pass = 259

The tube side velocity at this stage: tube cross-sectional area

$$A = (\pi * 0.01483 * 0.01483) \div 4 = 0.0001727 \text{ m}^2$$

So area per pass = 259*0.0001727 = 0.04473 m^2

Volumetric flow = 4520 m^3/d = 0.0523 m^3/s

Tube side velocity = 0.0523 / 0.04473 = 1.17 m/s, it is satisfactory which is between 1 to 2 m/s but may be a little low. This will show up when the pressure drop is calculated

- Bundle and shell diameter: four pass K_1 = 0.175 and n_1 = 2.285 from Coulson [86]

$D_b = d_o\,(N_t / K_1)^{1/n}{}_1 = 19.05(1036 / 0.175)^{1/2.285}$ = 852.7 mm, let say 853mm

For a split ring floating head exchanger the typical shell clearance from figure 12.10 in Coulson is 65, so the shell inside diameter is D_s = 853 + 65 = 918mm

- Tube side heat transfer coefficient (h_i)

Re = (1020 kg/m^3 * 1.17m/s * 14.83 * 10^{-3} m) / 1.33 *10^{-3} kg/m.s = 13,306

Pr = (4200 J/kg.0c * 1.33 *10^{-3} kg/m.s) / 0.134 W/m.^{0}C = 41.69

L/d_i = 5000 / 14.83 = 337

Therefore, heat transfer factor j_h from figure 12.23 in Coulson [86] = 2.8*10^{-3}

Nu = 2.8 * 10^{-3} (13306) (41.69)$^{0.33}$ = 127.59

h_i = 127.59 (0.134 W/m.^{0}c) / 14.83 *10^{-3}m = 1153 W/m^2.^{0}C

- Shell side heat transfer coefficient

Take the baffle spacing = Ds/2, say 400mm. this spacing should give good heat transfer without too high a pressure drop

$$A_s = \frac{(P_t - d_o)}{P_t} D_s l_B$$

Where, P_t is tube pitch; d_o is tube outside diameter; D_s is shell inside diameter; l_B is baffle spacing

$$A_s = \frac{(23.81-19.05)}{23.81} 918 * 400 = 73409.16\ \text{mm}^2 = 0.073409\ \text{m}^2$$

Equivalent diameter (d_e) for equilateral triangular pitch arrangement

$d_e = (1.10 / d_o)\,(P^2{}_t - 0.917d\,^2{}_o) = (1.10 / 19.05)\,(23.81^2 - 0.917*19.05^2)$ = 13.52 mm

Volumetric flow rate on shell side = 6000 m^3/d = 0.069 m^3/s

Shell side velocity = 0.069 / 0.073409 = 3.76 m/s

Re = (1000 kg/m^3 * 0.94 m/s * 13.52 * 10^{-3} m) / 5.974 *10^{-4} kg.m^{-1}.s-^{1} = 2.1274 *10^4

Pr = (4200 J/kg.0c * 5.974 *10^{-4} kg.m^{-1}.s-^{1}) / 0.59 W/m.^{0}C = 19

Use segmental baffles with a 25% cut. This should give a reasonable heat transfer coefficient with out too large a pressure drop. j_h from figure 12.29 in Coulson is 2.3*10^{-3} and neglecting the viscosity correction

$h_s = k_f/d_e) * j_h$ * Re * Pr

h_s = (0.59 W.m^{-1}.^{0}C^{-1} / 13.52 *10^{-3} m) * 2.3*10^{-3} * 2.1274*10^4 *4.3$^{0.33}$ = 6009 W/m^2.^{0}C

- Overall coefficient

$$\frac{1}{U_o} = \frac{1}{h_o} + h_{od} + \frac{d_o \ln(\frac{d_o}{d_i})}{2k_w} + \frac{d_o}{d_i} * h_{id} + \frac{d_o}{d_i} * \frac{1}{h_i}$$

Where: U_o = the over all coefficient based on the outside area of the tube, W/m^2.^{0}C

h_o = outside fluid film coefficient, W/m^2.^{0}C

h_i = inside fluid film coefficient, W/m^2.^{0}C

h_{id} = inside dirt coefficient (fouling factor), W/m^2.^{0}C

h_{od} =outside dirt coefficient (fouling factor), W/m^2.^{0}C

k_w = thermal conductivity of the tube wall material, W/m.^{0}C

d_i = tube inside diameter

d_o = tube outside diameter

$$\frac{1}{U_o} = \frac{1}{6009} + 0.0002 + \frac{19.05*10^{-3} \ln(\frac{19.05}{14.83})}{2*55} + \frac{19.05}{14.83}(0.00035 + \frac{1}{1153}) = 507 \text{ W/m}^2.^0\text{C}$$

This is below the initial estimate of 800 W/m^2.^{0}C

- Pressure drop

Tube side: 1036 tubes, 4 passes, tube internal diameter 14.83 mm, u_t 1.17m/s, Re = 13,306, from figure 12.24 in Coulson friction factor $j_f = 4.3 *10^{-3}$

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i}\right)\left(\frac{\mu}{\mu_w}\right)^{-m} + 2.5 \right] \frac{\rho u_t^{\,2}}{2}$$

Where: ΔPt = tube side pressure drop, N/m^2 (Pa)

N_p = number of tube side passes

u_t = tube side velocity, m/s

L = length of one tube, m

$$\Delta P_t = 4\left[8*4.3*10^{-3}\left(\frac{5000mm}{14.83mm}\right) + 2.5 \right] \frac{1020\,kg/m^3 * 1.17^2\,m/s}{2} = 59369.767 \text{ N/m}^2 = 0.59 \text{ bar}$$

It is with in the recommended value of pressure drop [86]

- shell side: from figure 12.24 in Coulson friction factor $j_f = 3.6 *10^{-3}$

$$\Delta P_s = \left[8 j_f \left(\frac{D_s}{d_e}\right)\left(\frac{L}{l_B}\right) \right] \frac{\rho u_s}{2} \left(\frac{\mu}{\mu}\right)^{-0.14}$$ Where, l_B is baffle spacing

$$\Delta P_s = \left[8 * 3.6 * 10^{-3}\left(\frac{918}{13.52}\right)\left(\frac{5000}{400}\right)\right]\frac{1000 * 0.94^2}{2}$$ = 60799.26 N/m^2 = 0.60 bar which is also with in the specification allowed, below 0.7 bar or 70 k N/m^2

U_0 required = Q / A_0 *ΔT_{lm} = 4940 kW / 310 m^2 * 22.4 ^{0}C = 711 W/m^2.^{0}C

The estimated over all coefficients is well above that required for design

- Summary of the proposed design of exchanger

Split ring, floating head, 1 shell pass, 4 tube passes, 1036 carbon steel tubes, 5 m long

Number of tube	1036
Tube out side diameter	19.05 mm
Tube Inside diameter	14.83 mm
Triangular pitch	23.81 mm
Shell inside diameter	918 mm
Heat transfer area	310 m^2
Tube side coefficient	1153 W/m^2.^{0}C
Shell side coefficient	6009 W/m^2.^{0}C
Over all coefficient estimated	800 W/m^2.^{0}C
Over all coefficient required	711 W/m^2.^{0}C
Dirt / fouling factor	
Tube side	0.00035 (W/m^2.^{0}C)$^{-1}$
Shell side	0.0002 (W/m^2.^{0}C)$^{-1}$
Pressure drop	
Tube side	0.59 bar
Shell side	0.60 bar

5.4 Cost – Benefit of the project

- Cost estimate of the digester for feasibility study purpose

Width, length and height of the reactor proposed are 7m, 12.5m, and 6m, respectively

Let the thickness of the wall be 0.2m at the top and 0.5 at the bottom

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

Volume of reinforced concrete for wall = 2* (7 + 12.5) * 2.1 = 81.9 m^3 and (2*12.5 +7)*2.1 = 67.2 m^3 for the other compartment

Let the depth of foundation slab be 0.5m

Volume of reinforced concrete for the slab = 0.5m * 7m * 12.5m = 43.75 m^3

Let depth of top slab be 0.1m

Volume of reinforced concrete for the slab = 0.1m * 7m * 12.5m = 8.75 m^3

Unit rate of reinforced concrete including rebar and labour, Ethiopian birr (ETB) 6,000.00 (current market price)

Over all reinforced concrete cost = 6,000.00 * (81.9 m^3 + 43.75 m^3 + 8.75 m^3) = ETB 806,400.00 and 6000 *(67.2 m^3 + 43.75 m^3 + 8.75 m^3) = 718,200 ETB for the other compartment

Area of formwork for wall = 2* 2* (7m + 12.5m)* 6m = 468m^2 and (2*12.5 +7)*6 = 192m^2

Area of formwork for top slab = 7m* 12.5m = 87.5 m^2

Unit rate of formwork including labour cost, ETB 500.00 (current market price)

Overall formwork cost = 500 * (468 m^2+ 87.5 m^2) = ETB 277,750.00 and 500*(192 m^2 + 87.5m^2) = 139,750 ETB for the additional compartment attached to one side of the digester

Total construction cost for a digester = 806,400.00 + 277,750.00 = ETB 1,084,150.00

Total construction cost for other 3 compartment attached to one side of digester wall is therefore, 3*(718,200 + 139,750) = 2,573,850 ETB

For the four compartment digester, ETB 1,084,150.00 + 2,573,850 = *3,658,000*

- Cost estimate of storage / flow equalizer tank for feasibility

Width, length and height of the storage tank are 8m, 15.7m, and 3m respectively

Let the thickness of the wall be 0.2m at the top and 0.5 at the bottom

Cross sectional area of the wall = 0.5* (0.2 + 0.5) * 3 = 1.05 m^2

Volume of reinforced concrete for wall = 2* (8m + 15.7m) * 1.05 = 49.77 m^3 and (2*15.7m + 8m)*1.05 = 40.32 m^3

Let the depth of foundation slab be 0.5m

Volume of reinforced concrete for the slab = 0.5m * 8m * 15.7m = 62.8 m^3

Let depth of top slab be 0.1m

Volume of reinforced concrete for slab = 0.1m * 8m * 15.7m = 12.56 m^3

Unit rate of reinforced concrete including rebar and labour, ETB 6,000.00 (current market price)

Over all reinforced concrete cost = 6,000.00 * (49.77 m^3 + 62.8 m^3 + 12.56 m^3) = 750,780.00 and 6000 *(40.32 m^3+62.8 m^3 + 12.56 m^3) = 694,080 ETB

Area of formwork for wall = 2* 2* (8m + 15.7m)* 3m = 284.4m^2 and (2*15.7 +8m)*3 = 118.2m^2

Area of formwork for top slab = 8m* 15.7m = 125.6 m^2

Unit rate of formwork including labour cost, ETB 500.00 (current market price)

Overall formwork cost = 500 * (284.4 m^2 + 125.6 m^2) = ETB 205,000.00 and 500*(118.2m^2 + 125.6 m^2) = 121,900 ETB

Total construction cost for a storage tank = 750,780.00 + 205,000.00 = ETB 955,780.00

Total construction of other 7 compartment = 7*(694,080 +121,900) = 5,711,860

For the eight compartment storage tanks = 955,780.00 + 5,711,860.00 = *6,667,640 ETB*

- cost estimate of heat exchanger

Exchanger type: shell/tube, floating head large area 3,444 ft^2, carbon steel, internal pressure 150 psi rating cost 2007 US $ 91,900 [87]; with the 11.14 birr per Us dollar current exchange to ETB 1,023,766

- Solar water heater

Heat required 4940 kW, assuming radiation of 5.62 kWh /m^2.day and the power collected per square meter is (5.62 kWh /m^2.day) * (day/24 hours) = 487.5 W/m^2). Heliostat area required is therefore; (4940 kW) / 487.5 W/m^2 = 10,133 m^2, let say 10,200 m^2. The area of a unit heliostat is 120m^2 and its cost is $48. Number of heliostat required for such activity is: 10,200 m^2/ 120 m^2 = 85. The total cost is 85 * $48 = $4080 which is equal to 45,451.20 ETB with the current exchange rate of 11.14 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 [87] which is equal to 41,218 ETB.

- Cost estimate for propeller top entering with 3hp working in atmospheric pressure mixing chamber agitator $4,900 [87] which is equal to 54,586 ETB. For eight mixer 436,688 ETB

  - *Computing direct cost or total physical cost of the plant*

- Civil and mechanical cost (all in ETB)

Total construction cost for digester = 3,658,000

Total construction cost for storage tank = 6, 667,640

- Process equipment cost can be calculated by factorial method (all in ETB)

Total purchase cost of major equipment items (PCE)

Shell and tube heat exchanger =1,023,766

Heliostat = 45,451.20

Hot water pump = 41,218

Mixer = 436,688

Total = 1,547,123.20 ETB

- Estimation of fixed capital cost, reference table 6.1 in Coulson [86]

The major direct cost to be added to PCE are detailed below; PCE = 1,547,123.20 ETB

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 ($1 + f_1 + f_2 + f_3 + f_4$) = 1,547,123.20 ETB * (1+0.4+0.7+0.2+0.2) = 3,867,808 ETB

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

Fixed capital cost (FC) = PPC ($1 + f_{10} + f_{12}$) = 3,867,808 ETB * (1+0.3+0.1) = 5,414,931.20ETB

Total investment required of the project = FC = 5,414,931.20ETB, including the civil and mechanical cost = *15,740,571.20 ETB*

- Annual operating cost, reference table 6.6 from Coulson [86]

Assuming operating time 300 days in a year, and two basic cost in this category

  - *Fixed cost (ETB)*

Maintenance cost 10% of fixed capital cost = 541,493.12

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

Supervision = no additional supervision would be needed

Plant overheads = 50% of operating labour and maintenance cost = 276,746.50

Laboratory 30% of operating labour = 3,600

Capital charges = not applicable

Insurance 1% of fixed capital = 54,149.31

Royalties = not applicable

Fixed cost = 887,988.93

  - *Variable costs (ETB)*

Raw materials = not applicable

Miscellaneous materials, 10% of maintenance cost = 54,149.31

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

Shipping and packaging = not applicable

Variable cost = 92,510.91

Direct production cost (DPC) = variable cost + fixed cost = 980,499.84 ETB

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

Total production cost or annual operating cost = *980,499.84 ETB*

- Estimate of total income benefit

The basic benefit from anaerobic digestion: biogas, fertilizer, and environmental, health and social benefit

- *Biogas*

Yearly methane production is 52,500 m^3 and let assume the heating value of methane 650 Btu/ft^3 therefore, the energy equivalent is 24,226,855.12 J/m^3 which is equal to 353,308.3 kWh /year. Assuming the utilization of electric energy to be more efficient than biogas utilization by 5%, thus the electrical energy equivalent of such amount of energy is 335,642.89 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 is 142,816.05 ETB.

- *Fertilizer*

Any fertilizer material will always be 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 $229 per ton. Diammonium phosphate (DAP) grade as (18-46-0), it has 18% nitrogen and 46% P_2O_5. Its price is $269, cost of 18% nitrogen and that of 46% phosphate as P_2O_5. Potash grade is (0-0-60) and its price is $169 [88].

- Nitrogen fertilizer

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

$$\text{Mass of urea} = (\text{mass of nitrogen}) / 0.46$$

Mass of nitrogen in the sewage sludge = concentration * rate of flow = 65.9 mg/L * 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 $808.37. With the current exchange of 11.14 birr, the price is *9,005.24 ETB*.

- Phosphorus fertilizer as P_2O_5

Equivalent DAP for phosphorus as P_2O_5 content in sewage sludge after digestion is given by:

$$\text{Mass of DAP} = (\text{mass of phosphorus as } P_2O_5) / 0.46$$

Mass of phosphorus in the sewage sludge = 76.35 mg/L*82.02m^3/d*300day/year = 1.88 ton/year. Mass of P_2O_5 in the sludge after digestion is given by using conversion factor 0.748 (annex 1.7) which is equal to 1.41 ton/year; hence mass of equivalent DAP is 3.065 ton/year and the price is \$824.49 which is equal to 9,184.76 ETB using the current 11.14 birr per US dollar. Mass of nitrogen in the DAP is 0.5517ton/year which is \$126.34 = 1,407.42 ETB; it is therefore the price of phosphorus fertilizer as P_2O_5 is 9,184.76 ETB - 1,407.42 ETB = *7,777.34 ETB.*

- Potash fertilizer

All potash fertilizers 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 [88] = 113.8 mg/L *1.21* 82.08 m^3/d * 300 days/year = 3.39 ton/year. The K_2O equivalent of the mass of potash fertilizer is 5.65 ton/year and its price \$954.85 which is equal to *10,637 ETB.*

- *Environmental, health and social benefit*

To estimate such issue, let take just by comparing the cost of safe disposal individual pays for vacuum truck for service they got; which is on average 12 ETB per cubic meter. The total waste collected annually 271,200 cubic meter which cost = 3,254,400 ETB. Assuming 25% of such safe disposal cost for environmental, health and social benefit in using anaerobic digester; which cost 813,600 ETB, therefore the total cost of safe disposal and benefit = 4,068,000 ETB.

5.5 Economic evaluation

- Net cash flow (NCF)

Gross profit (GP) = sales income – total production cost = 4,095,419.61 – 980,499.84 = 3,114,919.77 ETB

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

DC = (depreciable FCI –salvage value) / service life = 15,740,571/10 year = 1,574,057.10ETB

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

NP = GP – DC = 3,114,919.77 ETB - 1,574,057.10ETB = 1,540,862.67 ETB/year

Pay back period = DC / NP = (1,574,057.10) / (1,540,862.67) = 1.02, let say 1 year

Rate of return on investment (ROR) = GP / (total investment) = (3,114,919.77 / 15,740,571) *100 = 19.79%.

6. CONCLUSION AND RECOMMENDATION

To design anaerobic digester for biogas production of optimum methane composition and evaluate the fertilizing value of the digestate a set of batch experiments were carried out. The conclusion and suggestion made from the study summarized hereunder:

6.1 Conclusion

High COD containing co-substrate increase the loading rate eventually the concentration of metabolites like NH_4, H_2S, and VFA such inhibitors leads to low biogas production by preventing methanogenesis from being the dominant microbial reaction. With in the context of this experiment brewery yeast waste as co-substrate in co-digestion of sewage sludge is not appropriate since low methane content as compared with sewage sludge digestion alone was observed. In addition the feed subject to forming a thick scum and foaming on the top of digesters causing blockage of the ports

The results presented here indicate that anaerobic digestion is a feasible treatment and, energy and resource recovery option for sewage sludge produced in Addis Ababa. As all of the inhabitants producing these types of waste, developing centralized anaerobic digestion for energy and resource recovery from sewage sludge is a sustainable and environmentally friendly strategy.

Heavy metal content is not a limiting factor in the use of sewage sludge managed in Addis Ababa waste water treatment as a soil conditioner and fertilizer. Moreover, the nitrogen, phosphorus and potassium content of the sludge may satisfy specific plant uptake requirements in many land application systems. Sun drying on drying beds after anaerobically digested sludge is helpful in the viability of land application of treated sludge by completely inactivate the pathogen and reduce the potential risk.

Using upflow anaerobic sludge blanket in the existing waste water treatment plant can reduce 52,500 m^3/year methane emissions into the atmosphere which is 1,102,500 m^3 CO_2 equivalents and able to reduce the contribution to global warming effect. The installation of such anaerobic treatment system in sewage treatment plant may not be economically attractive, but technically feasible and sustainable; however a lot of work should be done on co-digestion of sewage sludge and suitable co-substrate selection to make AD at sewage treatment plant economically attractive.

6.2 Recommendation

The experimental results showed that using anaerobic digestion of sewage sludge considerable amount of methane can be captured from emitted into atmosphere so as to prevent greenhouse effect.

The literature and the present study demonstrates that it is possible to use anaerobic digester to anaerobically treat sewage sludge; however, before the system can be adopted on a large scale acceptance for the treatment of domestic sewage in different climatic conditions, it is essential to carry out further investigation at pilot level operation. In this regard the following suggestions for further research work are made:

- Pilot plant operation similar to the one undertaken in this research should be undertaken over a much longer period to establish steady state conditions that will enable correct assessments of long term treatment efficiencies, optimal loading rates, optimal hydraulic retention times, suitable dilution ratio, and gas production potentials among others. Such long term experiments should provide the required information for developing design and operation/maintenance guidelines when using anaerobic digester for the treatment of sewage sludge;
- Appropriate co-substrate should be searched and tested to increase the feasibility of the centralized sewage treatment;
- Integration of centralized sewage treatment by product, digestate, with biofuel raw material plantation in terms of fertilizer and industrial symbiosis should be considered and assessed for the management of waste and increase sustainability of the process;
- A lot should be done to link on anaerobic digestion of human waste, both on liquid and organic portion of solid waste, and current housing development program to solve energy demand and create green resident environment.

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ANNEX

Annex 1. Laboratory procedures

1.1 COD

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

- Required reagent
    - Reagent vial
    - Deionized water
- Materials used
    - C9800 Hanna reactor
    - HI 740216 test tube cooling rack
- Measurement procedure
    - Reagent blank correction
        - This method needs a reagent blank correction
        - A single vial may be used more than once
        - The blank vial is stable for several months (room temperature)
        - 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
    - Preheat the Hanna reactor C9800 to 150 ^{0}c (32 0F)
    - Remove the cap from two reagent vials
    - Add exactly 0.2 ml of sample to one vial (sample vial)
    - Add exactly 0.2ml of deionized water to the other (blank vial)
        - Keep the vial at 45 degree angle while adding the water and the sample
        - Replace the cap tightly and mix by inverting each vial a couple of times
    - Insert the vials into the reactor and heat them for 2 hours at 150 0c

    - At the end of digestion period switch of the reactor and wait for 20 minute to allow the vials to cool to about 120 0c
    - Invert each vials several times while still warm, then place them in the test tube rack
    - 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
    - Select the program number corresponding to oxygen demand, chemical HR (COD) on the secondary LCD by pressing program increase or decrease symbol

- Place the blank vial into the holder and push it completely down
- Press zero and 'sip' will blink on the display
- Wait for a few seconds and the display will show '-0.0-' now the meter is zeroed and ready for measurement
- Remove the blank vial
- Place the sample vial into the holder and push it completely down
- Press read direct and 'sip' will blink during measurement
- Instrument directly displays concentration in mg/L of oxygen demand on the crystal display
- multiply the reading on the liquid crystal display by 10 to obtain the concentration in mg/l of oxygen demand
- Interference
  - Chloride above 20000 mg/L
  - Samples with higher chloride concentration should be diluted

1.2 BOD

- Method
  - Lovibond BOD system oxidirect
- preparing the sample
- estimate the measurement reagent and select the volume for the sample
- 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
- 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
- carry out the necessary pre treatment of the sample (setting pH value 6.5 to 7.5, filtering)
  - the optimum pH value for BOD is between 6.5 and 7.5
  - if higher or lower adjust by HCL or H_2SO_4 and NaOH
  - mix well and advisable to settle or filter
- Required reagent
  - KOH to absorb CO_2
  - ATH to avoid nitrification
- Materials used
  - BOD bottle
  - BOD sensor
  - BOD bottle rack
  - Incubator
  - Measuring cylinder
- Measurement procedure
- measure the sample precisely using appropriate over flow and if necessary add nitrification inhibitor (ATH)
- insert magnetic stirring rod

- place 3-4 drop of KOH solution into the seal gasket and insert gasket in the neck of the bottle
- screw the BOD sensors to the sample bottle
- place the bottle in the bottle rack
- start the measurement
- incubate the sample in accordance with the instructions BOD_5 for 5 days at 20 ^{0}C

1.3 TS and VS

- Method
  - APHA, procedure 2540B and 2540E
- Apparatus used
  - Evaporating dishes
  - Desiccator, provided with a desiccant containing a color indicator of moisture
  - Drying oven operating at 103-105 ^{0}C
  - Analytical balance
  - Graduated cylinder
  - Beaker
  - Muffle furnace for operating at 550 ^{0}C
- Measuring procedure
  - Preparation of evaporating dish
    - Ignite clean evaporating dish at 550 ^{0}C for 1h in a muffle furnace for VS
    - Heat clean dish to 103 to 105 ^{0}C for 1h
    - Store and cool dish in desiccator until needed
    - Weigh immediately before use
  - Sample analysis
    - Pipet a measured volume of well mixed sample to a preweighed dish
    - Evaporate to dryness on drying oven
    - If necessary add successive sample portions to the same dish after evaporation
    - Cool dish in desiccator to balance temperature, and weigh
    - Ignite the residue produced by method 2540B in a muffle furnace
    - Transfer to a desiccator for final cooling in a dry atmosphere
  - Calculation

$$mg\ total\ solid / L = \frac{(A - B)}{Sample\ volume, ml} X 100$$

Where:

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

$$mg\ volatile\ solid / L = \frac{(A - B)}{Sample\ volume, ml} X 100$$

Where:

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

1.4 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
    - Reagent and culture medium – lactose peptone broth
    - Procedure
      - Prepare growth media
        - 70 gm in 1 ml distilled water
        - Sterilize at 121 ^{0}C for 15 min
      - Arrange fermentation tubes in rows of five or ten tubes
      - Add 10 ml growth media in each tube
      - Inoculate each tube in a set of five with replicate sample volumes
      - Mix test portions in the medium by gentle agitation
      - Incubate inoculated tubes or bottles at 37 ^{0}C. After 24 ± 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 ± 3h. Record presence or absence of growth, gas, and acid production. Growth with acidity signifies a positive presumptive reaction
      - Interpretation- production of an acidic reaction or gas in the tubes or bottles within 48 ± 3h constitutes a positive presumptive reaction. Submit tubes with a positive presumptive reaction to the confirmed phase
  - Confirmed phase
    - Culture medium- brilliant green lactose bile broth
    - Procedure
      - Prepare growth media
        - 40 gm in 1 ml distilled water
        - Sterilize at 121 ^{0}C for 15 min
      - Submit all presumptive tubes or bottles showing growth, any amount of gas, or acidic reaction with in 24 ± 2h of incubation to the confirmed phase
      - Gently shake or rotate presumptive tubes or bottles showing gas or acidic growth to resuspend the organisms.
      - 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
      - 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 ± 3h constitutes a positive confirmed phase

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

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

1.5 Heavy metal

- Method
    - APHA, procedure 3030E-nitric acid digestion
- Apparatus used
    - Hot plate
    - Conical (Erlenmeyer) flasks,
    - Volumetric flasks
    - Watch glasses
    - Boiling chips
    - Pipette
    - AAS (flame system) model NOV AA 400, analytikjena company, Germany
- Reagent
    - Nitric acid concentration analytical or trace metal grade
- Procedure
    - Transfer a measured volume (100 ml recommended) of well-mixed, acid-preserved sample appropriate for the expected metals concentrations to a flask or beaker.
    - In a hood, add 5 mL concentrated HNO_3
    - 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.
    - Bring to a slow boil and evaporate on a hot plate to the lowest volume possible (about 10 to 20 mL) before precipitation occurs.
    - 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.
    - 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.
    - Take portions of this solution for required metal determinations.

1.6 Phosphorus

- Method
    - Hach method 8190: Molybdovanadate with acid per-sulfate digestion
    - Adaptation of the standard method for examination of water and waste water 20th 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
    - Potassium per-sulfate powder pillows
    - 1.54 N NaOH solution
    - Molybdovanadate reagent
    - Deionized water
- Materials used
    - Hach reactor
    - Hach spectrophotometer model DR / 2010
    - Measuring cylinder
    - Pipette
- Measurement procedure
    - Reagent blank correction
        - This method needs a reagent blank correction
        - A single vial may be used more than once
        - The blank vial is stable up to one day (room temperature)
        - 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
    - Preheat the Hach reactor to 150 ^{0}C
    - Remove the cap from two reagent vials
    - Add exactly 5ml of sample to one vial (sample vial)
    - 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
    - Add the content of one potassium per-sulfate reagent powder pillows for phosphorus analysis to each vials
    - Replace the cap tightly and shake gently the vials until all the powder is completely dissolved
    - Insert the vials into the reactor and heat them for 30 minute at 150 ^{0}C
    - 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
    - Select the program number corresponding to total phosphorus on the secondary LCD by pressing program increase or decrease symbol
    - 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
    - Replace the cap tightly and mix by inverting the vial a couple of time

- 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
- Replace the cap tightly and mix by inverting the vial a couple of time
- Place the blank vial into the holder and push it completely down
- 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
- The display will show '-0.0-' now the meter is zeroed and ready for measurement
- Remove the blank vial
- Place the sample vial into the holder and push it completely down
- Press read direct and 'sip' will blink during measurement
- Instrument directly displays concentration in mg/l of total phosphorus on the liquid crystal display
- To convert the reading to mg/L of P_2O_5, multiply by a factor of 0.748
- To convert the reading to mg/L of phosphorus concentration, multiply by a factor of 0.326

1.7 Nitrogen

- Method
    - Hach method 10072: TNT per-sulfate digestion
    - 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
    - Reagent vial-total nitrogen hydroxide reagent
    - Total nitrogen per-sulfate powder pillows
    - Total nitrogen reagent A powder pillows
    - Total nitrogen reagent B powder pillows
    - Deionized water
- Materials used
    - Hach reactor
    - Hach spectrophotometer model DR / 2010
    - Measuring cylinder
    - Pipette
- Measurement procedure
    - Reagent blank correction
        - This method needs a reagent blank correction
        - A single vial may be used more than once
        - The blank vial is stable up to one week (room temperature)
        - 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
    - Preheat the Hach reactor to 105 ^{0}C
    - Remove the cap from two digestion vials

- Add the content of one packet of total nitrogen per-sulfate reagent powder pillows
- Add exactly 0.5 ml of sample to one vial (sample vial)
- 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
- Insert the vials into the reactor and heat them for 30 minute at 105 ^{0}C
- 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
- Select the program number corresponding to total nitrogen on the secondary LCD by pressing program increase or decrease symbol
- 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
- Wait for 3 minute with out shaking the vials to allow the reaction to complete
- 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
- Wit for 2 minute with out shaking to allow the reaction to complete
- Remove the cap from two other reagent vials
- 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
- Replace the cap tightly and invert the vials 10 times
- Place the blank vial into the holder and push it completely down
- 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
- The display will show '-0.0-' now the meter is zeroed and ready for measurement
- Remove the blank vial
- Place the sample vial into the holder and push it completely down
- Press read direct and 'sip' will blink during measurement
- Instrument directly displays concentration in mg/l of total nitrogen on the liquid crystal display
- To convert the reading to NH_3, multiply by 1.22
- To convert the reading to NO_3, multiply by 4.43
- Interference
    - Bromide above 240 mg/L
    - Chloride above 3000 mg/L

Annex 2: Statistical analysis

2.1 Biogas production with respect to yeast waste mix ratio as co-substrate

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Row 1	20	35.2	1.76	1.598316
Row 2	20	59.3	2.965	0.099237
Row 3	20	72.7	3.635	0.142395

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	36.11033	2	18.05517	29.43861	1.65E-09	3.158843
Within Groups	34.959	57	0.613316			
Total	71.06933	59				

2.2 Methane production with respect to yeast waste mix ratio as co-substrate

ANOVA: Single Factor

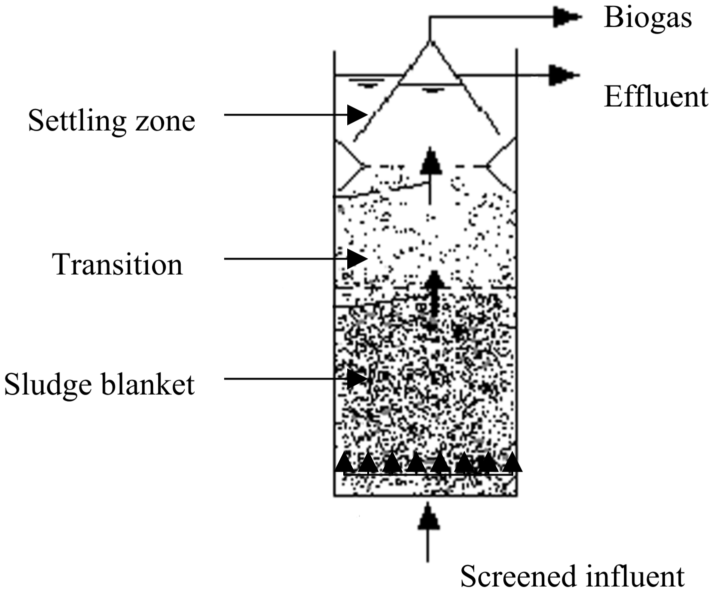
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Row 1	4	231	57.75	301.5833
Row 2	4	74.9	18.725	107.1558
Row 3	4	73	18.25	92.99667

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4111.235	2	2055.618	12.29103	0.002671	4.256495
Within Groups	1505.208	9	167.2453			
Total	5616.443	11				

Annex 3: Schematic diagram for UASB digester



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Approved by the Examining Board:

Dr.-Ing. Zebene Kifle ____________________________
Charman, Department's Graduate Committee

Dr.-Ing. Belay Woldeyes ____________________________
Advisor

Ing. Gizachew Shiferaw ____________________________
Internal Examiner

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DECLARATION

I, the undersigned, declare that this thesis entitled "*Optimization of anaerobic co-digestion of sewage sludge and brewery yeast waste*." is my original work, has not been presented for a degree in this or any other University, and that all sources of materials used for the thesis have been acknowledged.

Name: Tewodros Tilahun Geremew

Signature: ____________________

Place: Addis Ababa, Ethiopia

Date of submission: June, 2009