A Path to Sustainability: Biogas Recovery towards Energy Self Sufficiency Wastewater Treatment Plant

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Abstract

The concept of Sustainability is vigorously introduced into the curriculum of Wastewater Treatment Plants (WWTP) due to worldwide concerns over increasing energy demand coupled with growing volumes of sewage sludge. This paper evaluates anaerobic digestion of bio-sludge as a method for alleviating environmental, economic and social challenges surrounding current energy source, demand and strict sludge disposal standards. Gaza Strip has been selected as a case study area to assess the applicability of such approach; as AD is proposed to be integrated into Wastewater Treatment Plants in the Gaza Strip to reduce the volume of sludge produced as well as recovering biogas. Results show that AD is an attractive strategy along the path of sustainably managing WWTPs delivering the two key objectives of recovering enough energy to make WWTPs self sufficient and minimizing waste generation.

Keywords: key words, anaerobic digestion, sludge reduction, sustainability, wastewater treatment plant

1. Introduction

As part of the global developments, Wastewater Treatment Plants (WWTP) is witnessing a strong orientation towards sustainability. This entails implementing optimization strategies to make the plant more energy-efficient and generate less sludge waste.

Considering that wastewater treatment is an energy intensive process, energy costs associated with operating WWTP represents a substantial portion of the plant's total budget (Long and Cudney, 2012). Evidently, for the last few years, WWTPs energy consumption has increased due to rapid population growth as well as demand for higher level of sewage sludge treatment tied to stricter disposal regulations. In addition, the continual rise in electricity cost along with growing awareness over green house gases emissions from fossil fuels energy production makes WWTPs in urge need to switch to renewable energy sources.

WWTPs are also faced with the challenge of sustainably managing the generated sewage sludge. A Variety of sludge disposal practices has been applied globally including ocean dumping, landfills, incineration and land applications (Supakata and Chunkao, 2011).The impact of these different techniques on environment and human health has been subject of intense debate. Historically, Ocean dumping is the oldest sewage sludge disposal method where sludge has been discharged into the nearest sea or ocean. In recognition of the related negative impact on aquatic ecosystems, federal Ocean Dumping Act was released in 1988 prohibiting sewage sludge dumping into ocean. With this Act taking effect in 1992, great pressure was placed on finding other pathways for sludge disposal. Landfill of sewage sludge has then emerged as a natural disposal options. For many years after, landfill was the primary option for sewage sludge disposal. However, different environmental problems arise from using such technique due to gases and leachate releases to underlying soil and groundwater (Renou et *al.,* 2008).

In response, the United States Environmental Protection Agency introduced rigorous regulations regarding sludge being disposed of to landfills in 1993 (U.S EPA, 1994). In particular, limit values were set for nine toxic compounds contained in the sludge; in turn making landfill a costly option in terms of the advanced treatment requirements. Alongside USA, landfill sites were limited in the European countries as a consequence of the enforcement of the European Landfill Directive in 1999, covering both design and operation of landfills legislations (Macklin et *al.*, 2011).

As an alternative to disposal by landfill, land application recycles sewage sludge as a soil fertilizer. Sewage sludge content of organic matter, nitrogen, phosphorus and potassium supports soil structure and enhances crop production. Clearly, this practice plays a vital role in closing nutrient cycles, especially phosphorus where global reserves vary widely. In wider context, although sludge contains nutrients of agricultural value, concentrations of contaminants such as heavy metals and persistent organic pollutants limit its use in agriculture (Vácha et *al.*, 2006). Among the most commonly detected heavy metals in sewage sludge with hazardous influence to human health and plants are Cadmium, lead, Zinc, Copper, and Nickel. In response to addressed risk and great opposition to such practice, only sludge waste meeting certain criteria stated in “The Standards for the Use or Disposal of Sewage Sludge”, (Title 40 of the Code of Federal Regulations [CFR], Part 503), can be disposed to land application.

Tightened regulations and related environmental measures have eliminated both landfill and land applications as sludge disposal options. Thus, increased attention has been directed towards finding new technologies for sludge reduction. This situation has created a strong trend in the direction of incineration as a mean of reducing the amounts of sludge to be disposed. The incineration process reduces the sludge volume by the combustion of organic matter and evaporating water. The primary advantage of incineration is achievement of approximately 90% reduction in the volume of the waste (Lam et *al*., 2010). Consequently, a number of technologies have emerged based on sludge reduction strategy. These include Anaerobic Digestion (AD) which has the potential of both reducing the amount of sludge produced and recovering energy. This technique is gaining popularity across the world as a result of high cost of fossil fuels energy as well as calls for increased use of renewable energy sources.

In an effort to contribute to a long-term WWTP sustainability, this study investigates the technical feasibility of AD in attaining an energy self-sufficient facility using the Gaza Strip as a case study. This will be accomplished by utilizing the produced biogas and converting it to electricity thus fulfilling the goals of minimizing: the WWTP energy consumption and the quantity of sludge produced.

2. The Gaza Strip

Gaza is a narrow strip of land along the Mediterranean coast consisting of five governorates including Gaza, Middle, Northern, Khanyounis and Rafah. With population of approximately 1.7 million and a total area of 365 km^2, it is considered to be one of the most populated regions across the world. Currently, Gaza Strip (GS) is confronted with environmental and human health crisis related to steady increase in wastewater volume production without particular attention given to safe disposal of the generated sewage sludge. Increasing treatment costs and large deficit in energy supply are the main barriers to efficiently managing sewage sludge.

The current demand of electric power is approximately 350 Megawatts (MW). The vast majority of needed power is imported; from Israel, 120 MW or from Egypt, 22 MW. Gaza Power Plant (GPP) is the sole electricity generation facility in Gaza functioning at only 65% of its design capacity and contributing to 92 MW to the overall demand. Considering this situation, Gaza Strip is facing electricity shortage of about 160 MW towards meeting the overall demand. Furthermore, the Gaza Strip continues to witness a dramatic decline in the fuel and power supplies since 2007 due to the tightened economic siege and restrictions on fuel entering the area (Musalam, 2013). Consequently, people are experiencing blackouts of 6-18 hours a day as the GPP’s production capacity has sharply reduced. Occasionally, it was forced to totally shut down as it is fully dependent on diesel supplied from Israel to operate. This chronic electricity deficit and power cuts disrupt almost all aspects of civilian life as it mainly influence the delivery of basic services.

2.1 Brief overview of the current Wastewater Treatment Plants in the Gaza Strip

Sewage systems in GS are combined systems where sanitary sewage, including domestic and industrial wastewater, is carried along with storm water in one system. Domestic wastewater is discharged from residential, commercial and institutional collected through sewage system. It consists of proteins, carbohydrates, fats, oils, and a large amount of organic compounds. Meanwhile, industrial wastewater is normally generated by large and medium scale industries and contains pollutants such as suspended solids, heavy metals, oils, and other toxic organic and inorganic chemicals.

Three main treatment plants are available for collecting and treating wastewater. These plants are placed in Gaza, Beit Lahia and Rafah. Gaza Wastewater Treatment Plant (GWWTP) was initially built in 1977, located to the southwest of Gaza City. The plant includes: two sedimentation ponds, one anaerobic pond, one aerated lagoon, eight sludge drying beds and one pool for holding sludge. The Beit-Lahia Wastewater Treatment Plant (BWWTP) in the northern area of Gaza is functioning since 1976 with a maximum flow capacity of this wastewater plant is 5,000m³/ day (Abdelati et *al*., 2012). It was designed as two anaerobic lagoons, two actively aerated lagoons, two facultative lagoons and one setting tank. About 75% of population are connected to sewage system in this area. Rafah Wastewater Treatment Plant (RWWTP) in the south of Gaza was established in 1989 and upgraded since to accommodate 20,000 m³/day of sewage. It consists of a grit removal, two anaerobic lagoons, Settling pond, two bio-towers and sludge drying bed. Only 65% of the population in the Rafah City is connected to the existing wastewater system.

2.2 Current Disposal Methods in the Gaza Strip

At the present time, landfill is the most widely practiced method for disposing sewage sludge in GS. Sludge from Gaza's WWTPs is first transported to central waste collection stations towards final disposal alongside solid waste. Currently, there are three main disposal sites in which two are located in southern part of Gaza, and one in the centre. The landfills in southern Gaza are uncontrolled dumpsites located on impermeable soil. While, the landfill in central Gaza has a liner, leachate collection and treatment system installed. These landfills are overloaded and have exceeded their maximum capacity (Ouda, 2013). Simultaneously, land application presents the other route available for depositing sludge in the area; as sewage sludge contains compounds of agricultural value such as organic matter, nitrogen, phosphorus and potassium.

Observations and projections of both disposal techniques on environment indicate an urge need for exploring another alternative to deal with sewage sludge generated in GS. Such implications include groundwater contamination caused by leachate from uncontrolled landfill leading to inevitable problem with the primary source of water in the area. Many studies have documented that more than 80% of the groundwater wells have high concentrations of nitrate, chloride and some heavy metals which exceed drinking water standards set by the World Health Organization (WHO); (El-Nahhal, 2006), (Shomar et *al.,* 2008) and (Moghier and Aiash, 2013).The presence of heavy metals such as lead, Zinc and Copper reflects the nature of wastewater being treated; as industrial wastewater is discharged without pretreatment.

On the other hand, disposing sludge with heavy metals contents as compost results in land contamination. Despite the fact that certain heavy metals are nutritionally rich; the accumulation of large amounts cause soil quality degradation, poor agricultural products and have serious health consequences (Pandey, 2008). These contaminants can be transmitted to humans directly from the environment or indirectly through the food chain. Over time, these pollutants accumulate in the human body and cause serious health complications such as cancer and behavioural abnormalities. Another factor which places constraint on the reuse of sewage sludge as compost is high concentrations of Zinc and Adsorbable organic halogen compounds (AOX). An average concentrations of 550 mg Cl/kg and 2000 mg/kg of Adsorbable organic halogen compounds (AOX) and Zinc has been observed in sludge produced from two Wastewater treatment plants operating in Gaza Strip, exceeding standards of developed and industrial countries for sludge to be used for land application (Shomar et *al.,* 2005).

Besides looming danger to human health and environment, social acceptance of both disposal methods in GS is an important topic in need of addressing. Due to space limitation in GS, landfill sites are located near residential areas which expose people living nearby to aesthetics nuisance especially high levels of odour and vectors, such as insects, creating social opposition to landfill. Another sensitive aspect is related to the attitudes and perceptions of people towards recycling human excreta to land applications. GS is a religious-cultural society where Quranic edict and Islamic custom stipulate the boundaries by which belief, acts of worship and even daily interactions are carried out. In this context, some controversy is seen among Islamic scholars about the permissibility of recycling human excreta to land applications. Scholars from different schools of thought hold various opinions over the issue; as Imam Malik and Iman Shafi' permit the use of human excreta as a fertilizer, meanwhile, the Hanbali school of thought holds the view that it is not allowable to consume any fruit or vegetables that had traces of human excreta used as compost; even if the state of the substance has been changed. They think that the impurity is not removed from it even if it has been attempted to change its original state. Some people following this thought do not accept the current practice of using sludge waste for agricultural purposes. This argument is mainly based on what Ibn Abbas narrated: "We used to lease out the Prophet's land and stipulate that they don't use human waste".

To that end, growing volumes of sewage sludge in the Gaza Strip without effective management strategy laid in place poses severe environmental risk to the area as well as causes social dissatisfaction. With particular attention to the detected problems related to both landfill and land application, there is a pressing need to adopt new technologies allowing suitable reuse of sewage sludge.

3. Anaerobic Digestion

AD has been exclusively utilized as a method for reducing and stabilizing waste sludge for since early twentieth century (McCarty 2001). However, AD has attracted more interest recently due to stringent pollution control regulations as well as calls for increased use of renewable energy source. Extensive research has been conducted on AD technology in the last few years including; Chynoweth 2001, Saleh and Mahmood 2004, Banks et *al.* 2007, Chen et *al.* 2008, Rao et *al.* 2010, AlMaliky 2010, Kullavanijaya and Thongduang 2012, Morken and Sapci 2013.

It operates in similar way to incineration as it decomposes organic matter but with oxygen-free condition through four fundamental steps: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis (Kangle, et *al.,* 2012). Firstly, hydrolysis is an essential step, as biomass is normally comprised of very large organic polymers, which are otherwise unusable. Throughout hydrolysis, large polymers, namely proteins, fats and carbohydrates, are broken down into smaller molecules such as amino acids, fatty acids, and simple sugars. Secondly, acidogenic microorganisms further break down the biomass products after hydrolysis. Volatile Fatty Acids (VFA) are generated along with ammonia, carbon dioxide and hydrogen sulphide as well as other by-products. Then, in the third Acetogenesis stage, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen. Methanogenesis constitutes the final stage of anaerobic digestion during which the organic acids produced during preceding stages are converted to bio-gas. Biogas primarily consists of a mixture of about 60-70% methane (CH_4), carbon dioxide (CO_2) and traces of other gases (Nallamothu et *al.,* 2013). Mainly, there are two temperature ranges that allow different species of bacteria to survive providing optimum digestion conditions – mesophilic and thermophilic. The optimum temperature for the mesophilic range is between 35°C-45°C while, the thermophilic temperature range is between 55°C-60°C (Ji-shi *et al.* 2006). The methane can be captured from the anaerobic digesters and be used directly as Bio-fuel or converted to electricity.

4. Calculations & Discussion

In the present calculations, AD is integrated into Wastewater Treatment Plants in the GS to reduce the volume of sludge produced as well as recovering biogas. The total estimated wastewater production in the Gaza Strip is calculated to be 170000 (m^3/d) assuming wastewater generation of 100 (L/capita.day) and 1.7 million populations (Palestinian Central Bureau of Statistics, PCBS). Based on data provided from the three WWTPs in the area, the average influent concentrations for both the Biological Oxygen Demand (BOD_5) and the Total Suspended Solids (TSS) are 500mg/L and 470mg/L respectively.

Both primary and secondary sludge are suitable to produce biogas via anaerobic digestion due to their high organic solid content. The treatment process begins with the raw wastewater passing through a grit removal which removes grit and debris from the influent and prevent operational problems of mechanical equipments. As shown in Figure (1), the next step in the treatment process is called Primary Sedimentation (P.S) where the flow velocity is reduced allowing the heavier solids in the wastewater to settle down. The P.S can effectively remove 30% of BOD_5-load and 60% of Suspended Solids mass from the wastewater. The settled sludge at the bottom of the tank is called primary sludge. This sludge is then pumped to the thickener tank, while the effluent from P.S is then passed as an influent to the Aeration tank (A.T). The A.T provides a location where biological degradation of the wastewater constituents takes place. Initially, microorganisms oxidize the carbon compounds in the wastewater to produce carbon dioxide, new cells and biomass. Likewise in a process called Nitrification, the ammonia (NH_4) is also oxidized to nitrate (NO_3) for which pumped oxygen is required. Then, under anoxic conditions, nitrate (NO_3) is further converted into nitrogen (N_2) and oxygen (O_2) through Denitrification. Concurrently, phosphate elimination is achieved in A.T by adding iron or aluminium salts as flocculants. From the A.T, the treated wastewater flows to Final Sedimentation (F.S) tank where a fraction of the settled biomass is recycled to the A.T while, the reminder biomass is called excessive sludge and pumped to the thickener tank to keep a constant concentration of Total Solids in A.T.

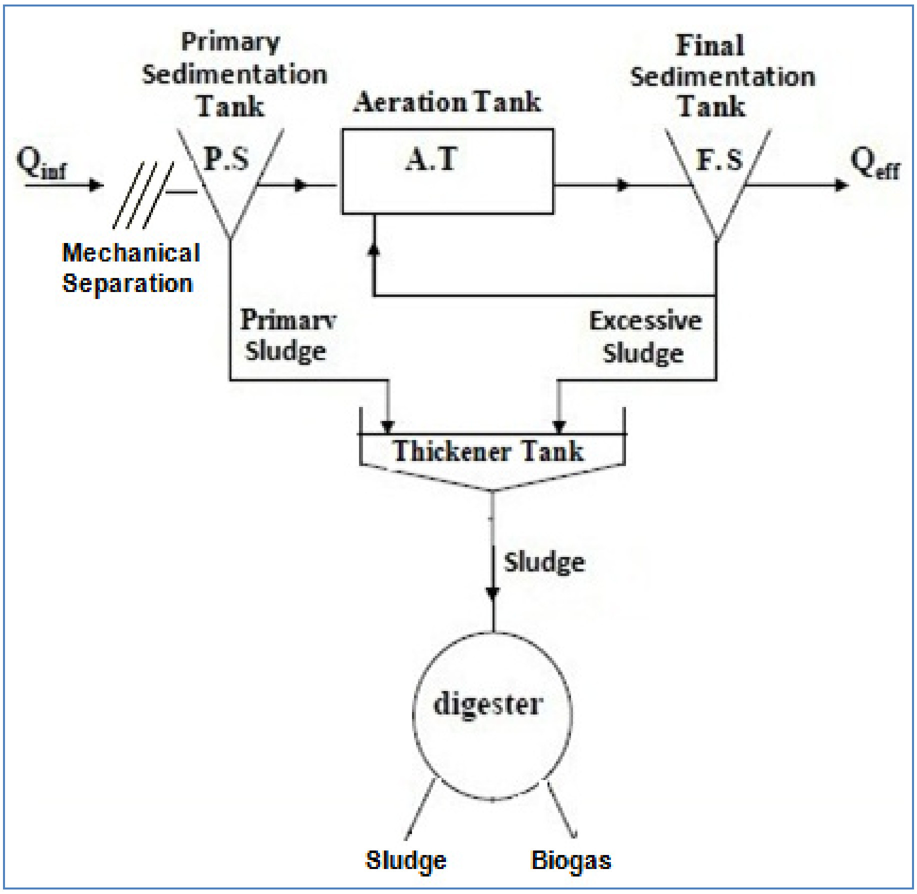

Figure 1. layout of the treatment process

Total Solid and organic solid are important parameters in determining the characteristics of the sludge. Total Solids (TS) are used to estimate the loading rate of the AD; meanwhile, the organic solids provide an approximation of the amount of substrate that can potentially be converted to methane.

The following are the calculations carried out for both Primary and Secondary Sludge.

Mass of Total Solid (TS) in the influent wastewater:

$$Mass_{TS,Inf} = \mathrm{Q_{Inf}} \times \mathrm{C_{TS,Inf}}$$

Where, $\mathrm{Q_{Inf}}$ is the flow rate for the whole population
$\mathrm{C_{TS,Inf}}$ is the average concentration of TSS

Therefore,

$$Mass_{TS,Inf} = 170000(\mathrm{m^3/d}) \times \frac{470}{1000}\ (\mathrm{kg.TS/m^3}) = 79900\ (\mathrm{kg.TS/d})$$

Mass of Total Solid in Primary Sludge:

As the primary sedimentation tank generally removes 30 % of the total BOD and 60% of suspended solids from the raw sewage (Bourke et *al.*, 2002), then the mass of TS in the primary sludge can be calculated as:

$$Mass_{TS,primary} = 79900\ (\mathrm{kg.TS/d}) \times \frac{30}{100} = 23970\ (kg.TS/d)$$

Given that the average primary sludge TS concentration is 165g/l (based on data provided from GWWTP), then,

The primary sludge flow rate is:

$$Q_{TS,primary} = \frac{23970\ (kg.TS/d)}{165\ (g/l)} = 145\,m^3/d$$

Generally, the TS concentration in the effluent treated wastewater is 20 mg/l (based on data provided from GWWTP):

$$Mass_{TS,Eff} = 170000(\mathrm{m^3/d}) \times \frac{20}{1000} = 3400\ (kg.TS/d)$$

Following the mass balance equation:

$$Mass_{TS,Secondary} = (79900 - 23970 - 3400)\ (\mathrm{kg.TS/d}) = 52530\ (kg.TS/d)$$

Given that the average secondary sludge TS concentration is 25g/l (based on data provided from GWWTP), then

The secondary sludge flow rate is:

$$Q_{TS,secondary} = \frac{52530\ (kg.TS/d)}{25\ (g/l)} = 2101\,m^3/d$$

Mass of Organic Total Solid in Primary and Secondary Tank

Assume 80% of organic TS is present in the primary sludge, therefore (Henze et *al*., 2000), the mass of organic TS equals to

$$Mass_{OTS,primary} = 0.80 \times Q_{TS,primary} \times C_{TS,primary}$$

$$Mass_{OTS,primary} = 0.80 \times 145 \times 165 = 19140\ (kg.TS/d)$$

Meanwhile, assuming 70% of organic TS present in the secondary sludge (Henze et *al*., 2000), therefore, the mass of organic TS equals to

$$Mass_{OTS,secondary} = 0.7 \times 2101 \times 25 = 36768\ (kg.TS/d)$$

According to Sven Giessen, the degradation efficiency of organic matter in the AD for the primary sludge is 80%, meanwhile for the secondary sludge is 30%. Then, in the AD, the mass of organic TS is found as follows:

$$Mass_{OTS,Deg.primary} = Mass_{OTS,primary} \times \left(\frac{80}{100}\right) = 15312\ (kg.TS/d)$$

and,

$$Mass_{OTS,Deg.secondary} = Mass_{OTS,secondary} \times \left(\frac{30}{100}\right) = 11030\ (kg.TS/d)$$

Taking the Specific gas production for wastewater primary and secondary sludge to be 0.90 (m^3/kg) of organic solids destroyed in the Anaerobic Digester (Bolzonella et *al*., 2005),

Therefore,

The volume of biogas production = $(15312 + 11030) \times 0.90$ =23708 Nm^3/d.

With Biogas consisting of 65% methane (Velmurugan and Ramanujam, 2011) and 38 MJ/Nm^3 heat productions for Methane, then

$$Produced\ Energy = 23708(Nm^3/d) \times 0.65 \times 38(MJ/m^3) = 585588\ (MJ/d)$$

As each KWh needs 3.6 MJ, which gives 162663 KWh/day as energy recovered from the generated biogas in AD.

Further calculations were conducted for the possible onsite use of originated biogas. Firstly, the amount of heat required to raise the temperature of the sludge in the AD is calculated to be 1627 KWh/d; accounting for 1% of the total energy recovered. Therefore, the estimated biogas produced will be sufficient for the anaerobic digesters in the three WWTPs in the Gaza Strip with an excess of 161037 KWh/day of biogas.

Based on literature, the WWTP electric consumption is 0.04 KWh/capita.day. Therefore, the daily electric demand for the treatment of wastewater generated from the population of 1.7 million in the GS is 68000 KWh; which forms 42% of the total energy recovered. This will eventually give an excessive electrical power of 93037 (KWh/d), 57% of the recovered energy, which can be utilized outside the WWTPs.

According to the above calculations, upgrading the three WWTPs located in the GS with AD transforms waste liabilities into a valuable energy source which could help offset the electricity consumption of the wastewater sector in the area. Indeed, that WWTPs can achieve energy self sufficiency eliminating the need for grid electricity and subsequently cutting energy costs. In turn, this will compromise part of the electricity deficit in the Gaza Strip and also provide a reliable source of renewable energy. Secondly, AD is a viable option for reducing sewage sludge quantities in GS, thereby, minimizing the amount requiring off-site disposal to either landfill, land application or incineration. This will contribute to soil, groundwater and air quality protection easing environmental concerns. Thirdly, AD has the potential to deliver social advantageous over current disposal practices in the area. Particularly those emerging disagreement related to land application as recycling sewage sludge using AD avoids the need for being involved in a disagreement amongst the differences arising, and gives more peace of mind to the individuals and also beneficiaries.

5. Conclusion

This study sheds light on the role of AD technology in WWTPs drive for sustainability. Findings from the case study highlighted that several benefits can be achieved by AD utilization. Mainly, recovering energy from sewage sludge using this technique has proven to be a promising strategy achieving the balance between environmental, economic and social dimensions of sustainability framework. From environmental prospective, the adaptation of such technology provides an environmental friendly solution to the problem of sludge waste disposal as it contributes to a significant reduction of sewage sludge quantities disposed to landfill or land application. Meanwhile, from economic point of view, the biogas generated has potentials in making WWTP energy self-sufficient cutting operating costs. Finally, AD overcomes negative social issues related to other methods of sludge disposal methods including odour and aesthetics problem. It also opens up the door for a creative way of making use of the sludge in a method that is not doubtful in any way.

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