Characteristics and Performance of Anaerobic Wastewater Treatment (A Review)

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Summary: Pakistan's current population of 180 million is expected to grow to about 221 million by the year 2025. In developing countries such as Pakistan water pollution is a major threat to the livelihood of people. Pakistan is also currently experiencing profound demographic, economic changes and energy crisis that have major implications for water management. The contamination of aquatic and terrestrial ecosystems with heavy metals is a major environmental problem. Each pollution problem calls for specific optimal and cost effective solution so if one technology proves less or ineffective other takes its place. Every day the vast amounts of the municipal, industrial and agricultural wastes are released in to the environment and create serious problems. Anaerobic digestion is very attractive and cost-effective option and technology for the highly loaded waste water treatment and energy conversion. The anaerobic process is in many ways ideal for waste treatment. It has several significant advantages over other available methods. In this process organic matter is utilized as source of electron donor to reduce carbon dioxide to produce methane gas. It involves three bacterial groups namely: hydrolytic, acetogenic and methanogenic bacteria that work optimally at pH and temperature ranges of 6.8 to 7.5 and 30-35 ºC, respectively. The residence time in a digester varies with the amount and type of feed material, the configuration of the digestion system, and whether it be one-stage or two-stage. It is ideal for all kinds of wastewaters. Currently anaerobic technology is being operated at full scale in many industrialized nations.

Keywords: Anaerobic digestion, domestic wastewaters, industrial wastewaters, methanogensis.

Introduction

Pakistan's current population of 180 million is expected to grow to about 221 million by the year 2025. This increase in population will have direct influence on the water sector to meet the demands of domestic use, industry and agriculture. The per capita water availability has dropped from 5600 m^3 in 1953 to below 1000 m^3 currently. Pakistan has now essentially exhausted its available water resources and is on the verge of becoming a water deficit country [1]. It was reported [2] that water scarcity is a major constraint on food production, human health and environmental quality. Pakistan is also currently experiencing profound demographic, economic changes and energy crisis that have major implications for water management. The ecology of the region too is changing due to climate change and will seriously impact water resources. The core water issues facing Pakistan are: defining water rights and entitlements for both surface and ground water, creating trust and transparency in equitable water distribution, improving services, rationalizing water charges and increasing productivity, clearing the backlog of maintenance, modernizing existing infrastructure and developing new infrastructure for storage, distribution and delivery [3]. Pakistan needs to invest soon in increasing storage capacity, improving water-use efficiency, and managing surface-water and groundwater resources in a sustainable way. Building capacity of individuals and organizations and strengthening water-related institutions are key elements for sustaining irrigated agriculture [4].

In developing countries such as Pakistan, water pollution is a major threat to the livelihood of people. The sustainability of freshwater ecosystems in Pakistan is disturbed by the industrial wastewater discharges from most of the industrial zones. Hattar Industrial Estate (HIE) is located near Kot Najibullah, Haripur. The major types of industries in HIE are furniture, food, engineering, marble, and pharmaceutical. Several types of industries like large chemical plants, pharmaceutical, heavy electrical engineering, textiles, food, steel, and vegetable oil release a diverse nature of toxic substances polluting the ambient air, water courses and soils. These pollutants have very long lasting effects on the sustainability of local ecosystems and pose a serious threat to human health. Water pollution is a source of danger to the health of people living in developing countries such as Pakistan. The main industries located at various industrial zones of Pakistan cause water pollution, which ultimately result in various diseases [5]. Industrial wastewater pollution is a primary type of point pollution and metals are the main cause of toxicity in living organisms. Moreover,

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these industrial wastewaters may also contain many recalcitrant hazardous organics like PCB, PAH, VOCs etc which cause damage to delicate aquatic ecosystems. The contamination of aquatic and terrestrial ecosystems with heavy metals is a major environmental problem. Some of these metals are potentially toxic or carcinogenic at sufficient concentrations and can cause serious human health hazards if they enter the food chain. Investigations have been made of the extent of the heavy metal pollution of surface water, ground water, soils, air, and vegetation by mining and associated industrial activities, particularly thermal power plants and opencast coalmines [6-10]. However, no serious effort has been put forth by any agency in Pakistan to characterize the exact nature and concentrations of contaminants found in wastewaters originating from Hattar Industrial Estate. There are so many ways for the reduction of wastewater volume at industrial plants by conservation of water use within industrial processes and reuse of municipal and industrial treatment plant effluents as a water supply and elimination of batch or slug discharges of process wastewater [11]. A large number of Physico chemical and mechanical treatment technologies are available for wastewater treatments which are very costly, in situation where capital is scarce, technical expertise is lacking and the land is readily available. A number of approaches have been adapted to treat wastewaters depending on the type and extent of contamination which will not only preserve the ecosystem, but also protect biodiversity [12]. Wastewater treatment is necessary for allowing it to mix with other water bodies that are used for irrigation, drinking and other purposes. Each pollution problem calls for specific optimal and cost effective solution so if one technology proves less or ineffective other takes its place. A large number of wastewater chemical and mechanical treatment technologies are very costly, in situation where capital is scarce, technical expertise is lacking and the land is readily available. Wastewater technologies include physical, chemical and biological treatment processes [13]. Today multifarious treatment technologies are to maintain chemical, physical, biological reliability of the country waters [14]. One of the most promising methods of the treatment is biological method to treat to industrial wastewaters. Treatment processes are generally identified as aerobic, anaerobic and hybrid technologies. Aerobic treatment requires large input of energy and produces excessive amounts of sludge which present a bottleneck for its application in countries with energy crisis and limited economic resources. Anaerobic treatment has been considered as one of the most effective and economical method in treating both industrial wastewaters as well as domestic wastewater [15, 16]. One of its outstanding characteristics is that the anaerobic microorganisms can aggregate and form the biological granules and biogas is produced as a byproduct. The excellent settling ability of the granular sludge, high biomass and rich microbial diversity in the reactor, improves the treatment capacity and efficiency [16]. Anaerobic digestion has a tendency to degrade certain compounds and dyes, such as poly chloro-aromatics and poly nitro-aromatics as well as the azo dye. Constructed wetlands (CW) offer a simple and economical solution for post treatment of anaerobic digestion. CW is defined as shallow and large lagoons consisting of saturated substrates, emergent and sub-emergent vegetation and animal life. They are easy to construct, operate, maintain, and do not require import of any equipment. It is a cost effective, environmental friendly, aesthetically pleasing approach most suitable for developing countries. A sustainable operation of anaerobic wastewater treatment plants in developing countries could be achieved as they are low in investment costs, maintenance demand and sludge production, good in performance, net energy production [17]. If combined with an appropriate post treatment then the effluent values reach the same level as the aerobic activated sludge, which could be widely applied in industrial sector. Keeping in view the pollutants concentration and demand for the supply of clean water; there is a need of an integrated anaerobic treatment technologies. Focusing on cost effective and environmental friendly technologies [18] depending upon the possibilities of waste water treatment plant [12] a constructed wet lands seem to be a viable option for the post treatment of the effluent from the anaerobic treatment. A wide range of environmental and water quality problems will be solved by the application of combining the wet lands with anaerobic treatment methods. In Pakistan such wastewater treatment technology has not yet been adopted. The objective of the treating the anaerobic effluent with wetlands is to polish the effluent to an acceptable level. The wetlands offer a great potential for waste water polishing to a suitable standard for reuse [19]. The wetland nutrient removal efficiency can be greatly enhanced by the appropriate wetland plant selection [20]. The constructed wetlands offer a low cost tertiary biological nutrient removal which is more attractive option for developing communities [19]. Different schemes for wastewater treatment have been evaluated [21] like ozonation followed by a microfiltration polishing and chemical disinfection, membrane bioreactors followed by reverse osmosis and anaerobic facultative and maturation ponds. In last year's important advances have been made in the development of new types of membranes with

reduced costs, and the researchers [22-25] suggested the research should be carried out in order to find out better reactor configurations and operational procedures that decrease energy consumption and fouling. There are several favorable characteristics of the anaerobic processes, these processes are low cost, simple in operation, no energy consumption and low produced solids [26]. Anaerobic treatment has been considered as one of the most effective and economical method in treating both industrial wastewaters as well as domestic wastewater [15]. In the treatment of wastewater, anaerobic biological treatment appears to be a promising technology as methane gas is generated from anaerobic digestion and can be utilized as renewable energy. One of its outstanding characteristics is that the anaerobic microorganisms can aggregate and form the biological granules. The excellent settling ability of the granular sludge, high biomass and rich microbial diversity in the reactor, improves the treatment capacity and efficiency. Anaerobic digestion has a tendency to degrade certain compounds and dyes, such as poly chloro aromatics and poly nitro-aromatics as well as the azo dye. Anaerobic digestion (AD) is very effective in treating wastewaters [27].

The History and Process Performance

The advantages of the anaerobic processes such as low cost, operational simplicity, no energy consumption and low production of solids are highly associated with the favorable environmental conditions [26]. Scientific interest in the manufacturing of gas produced by the natural decomposition of organic matter was first reported in the 17th century by Robert Boyle and Stephen Hale, who noted that flammable gas was released by disturbing the sediment of streams and lakes [28]. In 1808, Sir Humphry Davy determined that methane was present in the gases produced by cattle manure [29, 30]. The first anaerobic digester was built by a leper colony in Bombay, India, in 1859. In 1895, the technology was developed in Exeter, England, where a septic tank was used to generate gas for the sewer gas destructor lamp, a type of gas lighting. Also in England, in 1904, the first dual-purpose tank for both sedimentation and sludge treatment was installed in Hampton. In 1907, in Germany, a patent was issued for the Imhoff tank [31] an early form of digester. Through scientific research, anaerobic digestion gained academic recognition in the 1930s. This research led to the discovery of anaerobic bacteria, the microorganisms that facilitate the process. Further research was carried out to investigate the conditions under which methanogenic bacteria were able to grow and reproduce [32]. This work was developed during World War II, during which in both Germany and France, there was an increase in the application of anaerobic digestion for the treatment of manure. In Anaerobic Digestion (AD) organic matter (in the form of carbohydrates, proteins, lipids or more complex compounds), is transformed in to methane, carbon dioxide and anaerobic biomass, in an oxygen free environment. This biological process simultaneously treats waste and wastewater to produce biogas [33]. Anaerobic digestion is a series of complex microbial processes in which a variety of bacteria are involved which break down biodegradable material in the absence of oxygen [34] used for industrial or domestic purposes to manage waste and/or to release energy. A flow chart of the anaerobic digestion is shown in the Fig. 1. Many microorganisms are involved in the process of anaerobic digestion including acetic acid-forming bacteria (acetogens) and methane-forming archaea (methanogens). These organisms feed upon the initial feedstock, which undergoes a number of different processes, converting it to intermediate molecules including sugars, hydrogen, and acetic acid, before finally being converted to biogas [36]. Different species of bacteria are able to survive at different temperature ranges. Ones living optimally at temperatures between 35–40 °C are called mesophiles or mesophilic bacteria. Some of the bacteria can survive at the hotter and more hostile conditions of 55–60 °C; these are called thermophiles or thermophilic bacteria [37]. Methanogens come from the domain of Archaea. This family includes species that can grow in the hostile conditions of hydrothermal vents. These species are more resistant to heat and can, therefore, operate at high temperatures, a property that is unique to thermophiles [38]. As with aerobic systems, the bacteria in anaerobic systems the growing and reproducing microorganisms within them require a source of elemental oxygen to survive [39]. Anaerobes access oxygen from sources other than the surrounding air. The oxygen source for these microorganisms can be the organic material itself or may be supplied by inorganic oxides from within the input material. When the oxygen source in an anaerobic system is derived from the organic material itself, the 'intermediate' end-products are primarily alcohols, aldehydes, and organic acids plus carbon dioxide. In the presence of specialised methanogens, the intermediates are converted to the 'final' end-products of methane, carbon dioxide, and trace levels of hydrogen sulfide [40]. In an anaerobic system the majority of the chemical energy contained within the starting material is released by methanogenic bacteria as methane.

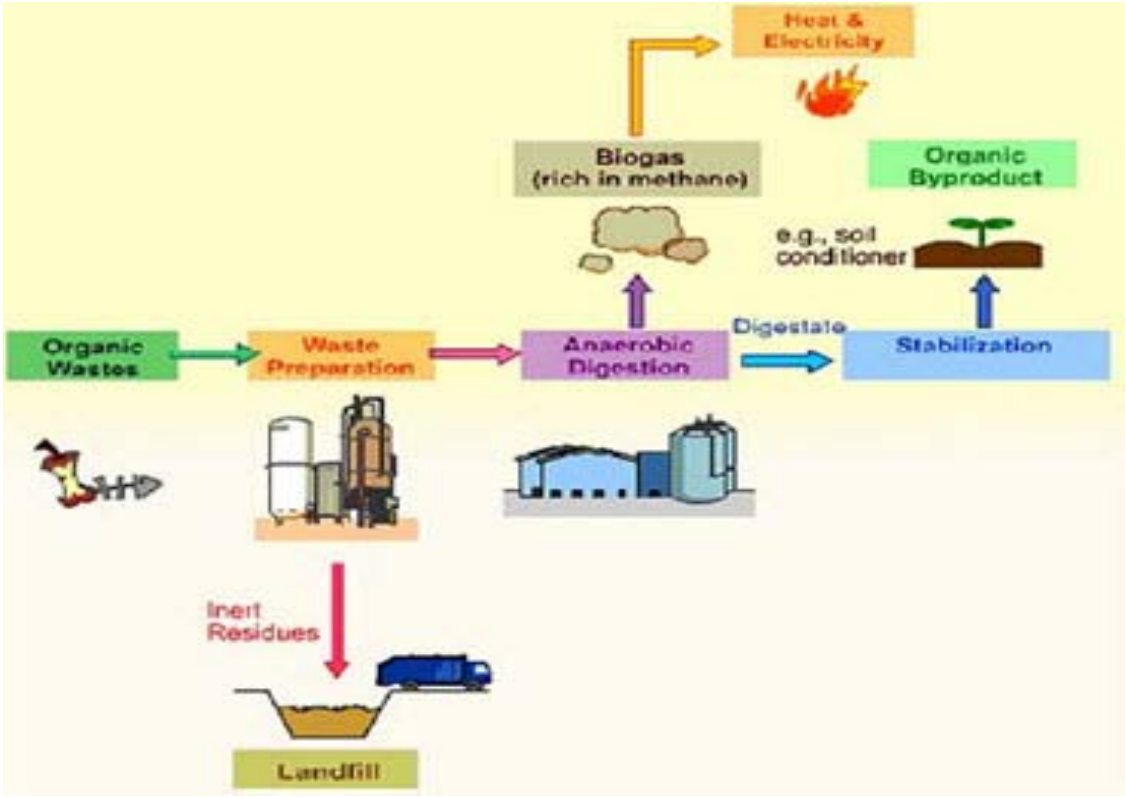

Fig. 1: A Flow chart of anaerobic digestion [35].

Stages

There are four key biological and chemical stages (Fig. 2) of anaerobic digestion. In most cases, biomass is made up of large organic polymers. In order for the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore, hydrolysis of these high-molecular-weight polymeric components is the necessary first step in anaerobic digestion [41].http://en.wikipedia.org/wiki/Anaerobic_digestion - cite_note-48#cite_note-48 Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids. Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFAs) with a chain length that is greater than that of acetate must first be catabolized into compounds that can be directly utilized by methanogens. The biological process of acidogenesis is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created along with ammonia, carbon dioxide, and hydrogen sulfide, as well as other by-products [42]. The process of acidogenesis is similar to the way that milk sours. The third stage of anaerobic digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen. The terminal stage of anaerobic digestion is the biological process of methanogenesis. Here, methanogens utilize the intermediate products of the preceding stages and convert them into methane, carbon dioxide, and water. It is these components that make up the majority of the biogas emitted from the system. Methanogensis is sensitive to both high and low pH and occurs between pH 6.5 and pH 8 [43]. The remaining, non-digestible material that the microbes cannot feed upon, along with any dead bacterial remains, constitutes the digestate. A simplified generic chemical equation for the overall processes outlined above is as follows:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \quad (1)$$

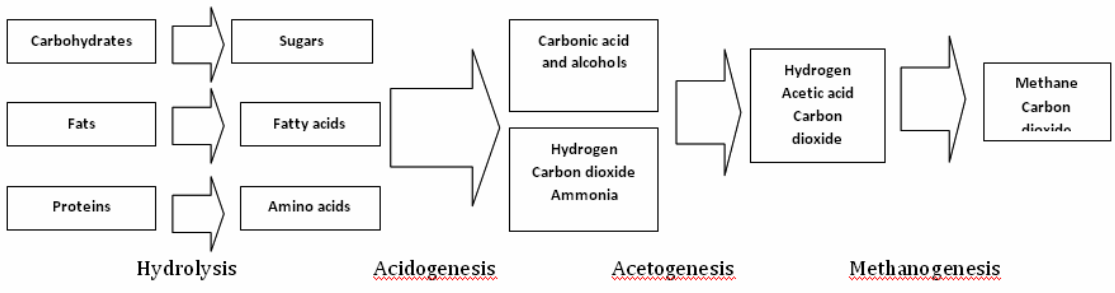

Fig. 2: The key Process Stages of Anaerobic Digestion

Hydrolysis

During hydrolysis, the first stage, bacteria transform the particulate organic substrate into liquefied monomers and polymers i.e. proteins, carbohydrates and fats are transformed to amino acids, monosaccharides and fatty acids respectively. Equation 2 shows an example of a hydrolysis reaction where organic waste is broken down into a simple sugar, in this case, glucose [44].

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \quad (2)$$

Acidogenesis

In the second stage, acidogenic bacteria transform the products of the first reaction into short chain volatile acids, ketones, alcohols, hydrogen and carbon dioxide. The principal acidogenesis stage products are propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid (HCOOH), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH), among other. From these products, the hydrogen, carbon dioxide and acetic acid will skip the third stage, acetogenesis, and be utilized directly by the methanogenic bacteria in the final stage (Fig. 2). Equations 3, 4 [44] and 5 [45] represent three typical acidogenesis reactions where glucose is converted to ethanol, propionate and acetic acid, respectively.

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \quad (3)$$

$$C_6H_{12}O_6+2H2\leftrightarrow 2CH_3CH_2COOH+2H_2O \quad (4)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (5)$$

Acetogenesis

In the third stage, known as acetogenesis, the rest of the acidogenesis products, i.e. the propionic acid, butyric acid and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the hydrogen partial pressure is low enough to thermodynamically allow the conversion of all the acids. Such lowering of the partial pressure is carried out by hydrogen scavenging bacteria, thus the hydrogen concentration of a digester is an indicator of its health [46]. Equation 6 represents the conversion of propionate to acetate, only achievable at low hydrogen pressure. Glucose (Equation 7) and ethanol (Equation 8) among others are also converted to acetate during the third stage of anaerobic fermentation [44].

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (6)$$

$$C_6H_{12}O_6+2H_2O\leftrightarrow 2CH_3COOH+2CO_2+4H_2 \quad (7)$$

$$CH_3CH_2OH+2H_2O\leftrightarrow CH_3COO^- + 2H_2 + H^+ \quad (8)$$

Methanogenesis

The fourth and final stage is called methanogenesis. During this stage, microorganisms convert the hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide (Equations 9, 10 and 11) [47]. The bacteria responsible for this conversion are called methanogens and are strict anaerobes. Waste stabilization is accomplished when methane gas and carbon dioxide are produced.

$$CO_2+4H_2\rightarrow CH_4+2H_2O \quad (9)$$

$$2C_2H_5OH+CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (10)$$

$$CH_3COOH\rightarrow CH_4+CO_2 \quad (11)$$

Applications

Every day the vast amounts of the municipal, industrial and agricultural wastes are released in to the environment and create serious problems. Anaerobic digestion is very attractive and effective option and technology for the highly loaded waste water treatment and energy conversion [48, 49]. Anaerobic digestion is a simple process that can

greatly reduce the amount of organic matter including biodegradable waste materials such as waste paper, grass clippings, leftover food, sewage, and animal waste. Co-digestion or co-fermentation plant is typically an agricultural digester that accepts two or more input material for simultaneous digestion [50]. At the present time, projects for anaerobic digestion in the developing world can gain financial support through the United Nations Clean Development Mechanism if they are able to show that they provide reduced carbon emissions [51]. The anaerobic digestion of solid wastes is now a widely used technology in Europe with more than 50 full- scale plants operating [52]. Pressure from environmentally related legislation on solid waste disposal methods in developed countries has increased the application of anaerobic digestion as a process for reducing waste volumes and generating useful by-products. Anaerobic digestion may either be used to process the source separated fraction of municipal waste or alternatively combined with mechanical sorting systems, to process residual mixed municipal waste. Utilizing anaerobic digestion technologies can help to reduce the emission of greenhouse gasses by replacement of fossil fuels, reducing or eliminating the energy footprint of waste treatment plants, reducing methane emission from landfills, displacing industrially produced chemical fertilizers, reducing vehicle movements.

Power Generation

Most widely used method of organic waste disposal is the anaerobic digestion due to the production of biogas that makes it more profitable [53]. AD is a biological process in which microorganisms break down biodegradable solids and soluble substances in the absence of oxygen. It is widely used for the treatment of industrial and domestic wastes with the production of biogas [54].http://en.wikipedia.org/wiki/Anaerobic_digestion - cite_note-34#cite_note-34 Some waste heat from the engine is then used to heat the digester. It turns out that the waste heat is, in general, enough to heat the digester to the required temperatures. The power potential from sewage works is limited. The scope for biogas generation from non-sewage waste biological matter – energy crops, food waste, abattoir waste, etc. - is much higher, estimated to be capable of about 3,000 MW. Farm biogas plants using animal waste and energy crops are expected to contribute to reducing CO_2 emissions. Anaerobic digestion of dairy manure has been demonstrated to be an attractive treatment that provides several benefits including the improvement of manure fertilizer quality; reduction of odors, pathogens and greenhouse gas emissions; and production of a renewable fuel, the biogas[55-59]. Anaerobic digestion of human and animal waste provides sanitation by reducing the pathogenic content of substrate materials (Table-1). Hence biogas installation can dramatically improve the health of users. This is particularly the case where biogas plants are linked to public toilets and/or where waste is no longer stored openly. Rapid public health improvements following biogas implementation have been observed in rural China, with reductions in schistosomiasis and tapeworm of 90–99% and 13% respectively [60, 61]. Advantages and Disadvantages associated with anaerobic digestion are listed in Table 1 adopted from [60]. Solid retention times of 3 weeks at mesophilic conditions are enough to kill pathogens leading to typhoid, cholera, dysentery, schistosomiasis and hookworm [62]. However, for eliminating other pathogens mesophilic anaerobic processes are rather ineffective, with typically 50% inactivation of helminth eggs and modest reductions of tapeworm, roundworm, *E. coli* and Enterococci [62, 63]. Thus, the WHO suggests pathogen reduction by mesophilic anaerobic digestion is in sufficient to allow subsequent use of human excreta as fertilizer [64]. Moreover, pervasive health benefits are associated with a switch to a cleaner cooking fuel. In Guatemala, an association between domestic use of wood fuel and reduced birth weight, independent of key maternal, social, and economic confounding factors has been documented [65]. Of over 1,700 women and newborn children, the percentage of low birth weights was 19.9% for open fire users, compared with 16.0% for those using electricity or gas.

Table 1: Advantages and disadvantages associated with anaerobic digestion.

Advantages	Disadvantages
Improved sanitation	laborious operation and maintenance
Reduced Pathogens	Limited life span (-20 years for many plants)
Reduced disease transmission	Construction cost
Low cost energy source	Less suitable in cold regions
	Cooking, lightning etc.
Improved living conditions	Negative perceptions where low functionality of existing plants
Low cost fertilizers	Less suitable in arid regions
Improved crop yields	
Improved living conditions	Negative perception where low functionality of existing plants
Improved air quality	Requires reliable feed source
Reduced green house emissions	Requires reliable outlet for treating sludge
Reduced nitrous oxide emissions	Poor hygiene of sludge from mesophilic digestions
Less demand for alternative fuels	High construction relative to income of many potential users
Conservation of woodland	
Less soil erosion	
Time saved collecting firewood	

Configuration

The configuration of the anaerobic digester is of paramount importance in anaerobic fermentation processes. The relatively low biosynthesis rate of methanogens in an anaerobic system demands special consideration for bioreactor design. The selection of bioreactor types depends on the requirement of a high SRT/HRT ratio, in order to prevent the washout of slow-growing and sensitive methanogenic bacteria. Therefore, the anaerobic digestion performance of the bioreactors is based on their capability to maintain a high SRT/HRT ratio and thus to retain biomass. Another approach for reactor configuration selection is based on required effluent quality. Because of relatively high half-saturation constants for anaerobic microorganisms, continuous stirred tank reactors may not be suitable, as immediate dilution of the waste leads to low concentrations of organic matters, but still too high to meet the effluent discharge standards, which are below the range of anaerobic degradation. Under such conditions, a staging or plug flow type reactor would be more appropriate [67]. Anaerobic digestion processes are classified by critical operating parameters and reactor design such as continuity (batch or continuous), number of stages (one or multiple), operating temperature (psychrophilic, mesophilic and thermophilic), reactor design, and solid content (wet or dry) [68].

Batch or Continuous

Batch system is the simplest form of digestion. Biomass is added to the reactor at the start of the process in a batch and is sealed for the duration of the process. Mesophilic and thermophilic anaerobic digestion of three maize varieties were compared by the mini batch digester. Parameters such as biogas production and biogas composition from maize silage were measured and calculated [69]. The amount of biogas production (methane) was observed by the mini digester. Mini batch digester comprised twelve gas cells. Each cell consisted of a reaction vessel (500 ml fermenter) and a well closed gas pipe. The gas pipe - eudiometer was of 350 ml size and contained the confining liquid. It was connected to the leveling vessel with solution. The biogas produced in fermenter supplants the confining liquid in the gas pipe into the outside leveling vessel of 750 ml volume. The gas produced was read on the gas pipe. A sample of Nile perch fish processing wastewater (FPW) was investigated in 500 ml batch bioreactors consisting of wide mouth Erlenmeyer conical flasks with a working volume of 0.36 L. This study reported improvement of anaerobic digestion of Nile perch FPW by co-digestion, physical and biological pre-treatment methods and could be used as a basis for designing a pilot scale process [70]. The batch digesters is loaded with raw feedstock (inoculated with digestate) once and then left until complete degradation has occurred. It is particularly advantageous when using more digester with different startup times to guarantee a continuous yield of biogas. On the contrary, the substrate is regularly and continuously fed in continuous digesters. In continuous digestion processes, organic matter is constantly added (continuous complete mixed) or added in stages to the reactor (continuous plug flow; first in – first out). Here, the end-products are constantly or periodically removed, resulting in constant production of biogas. One-stage dry batch systems typically employ a system whereby high solids content feedstock is entered into a vessel without initial dilution. Recirculation of leachate is employed and no mixing takes place, and as such energy demand is very low [68]. Upflow Anaerobic Sludge Blanket (UASB), Expanded Granular Sludge Bed (EGSB) and Internal Circulation (IC) reactors are the examples of anaerobic digestion including continuous stirred tank reactors.

Temperature

There are two conventional operational temperature levels for anaerobic digesters, which are determined by the species of methanogens in the digesters [71]. Mesophilic which takes place optimally around 30-38 °C or at ambient temperatures between 20-45 °C where mesophiles are the primary microorganism present Thermophilic which takes place optimally around 49-57 °C at elevated temperatures up to 70 °C where thermophiles are the primary microorganisms present. A limit case has been reached in Bolivia, with anaerobic digestion in temperature working conditions less than 10 °C. The anaerobic process is very slow, taking more than three times the normal mesophilic time process. In experimental work at University of Alaska Fairbanks, a 1000 liter digester using psychrophiles harvested from mud from a frozen lake in Alaska has produced 200–300 liters of methane per day, about 20–30 % of the output from digesters in warmer climates [72]. There are a greater number of species of mesophiles than thermophiles. These bacteria are also more tolerant to changes in environmental conditions than thermophiles. Mesophilic systems are, therefore, considered to be more stable than thermophilic digestion systems. Since thermophilic digestion systems are considered to be less stable, the energy input is higher, and more energy is removed from the organic matter. However, the increased temperatures facilitate faster reaction rates and, hence, faster gas yields. Operation at

higher temperatures facilitates greater sterilization of the end-digestate. A drawback of operating at thermophilic temperatures is that more heat energy input is required to achieve the correct operational temperatures. This increase in energy may not be outweighed by the increase in the outputs of biogas from the systems. Therefore, it is important to consider an energy balance for these systems. Anaerobic fermentation considerably reduces the total mass of wastes, generates solid or liquid fertilizer and yields energy. It can be maintained at psychrophilic (12-16 °C, e.g. in landfills, swamps or sediments), mesophilic (35-37 °C, e.g. in the rumen and in anaerobic digester) and thermophilic conditions (55-60 °C; e.g. in anaerobic digesters or geothermally heated ecosystems) [73]. Disadvantages of thermophilic anaerobic fermentation are the reduced process stability and reduced dewatering properties of the fermented sludge and the requirement for large amounts of energy for heating, whereas the thermal destruction of pathogenic bacteria at elevated temperatures is considered a big advantage. Biogas production and composition in mesophilic (35 degrees C) and thermophilic (55 degrees C) conditions was compared by [69]. For biogas plants with mesophilic digesters they suggested an up gradation of existing mesophilic digesters (35°C) to thermophilic digesters (55°C), which was an economically beneficial solution compared to construction of additional mesophilic digesters. While a research carried out with aim to enhance anaerobic digestion of Nile perch fish processing wastewater. The experiment consisted of thirteen anaerobic incubation periods: 0, 3, 6, 9, 12, 15, 18, 21, 24, 36, 48, 60 and 72 h for each setup. All batch bioreactors were incubated at 28 degrees C while shaking at 75 rpm. For addition of mixed cultures, 72-h broth cultures of the two bacterial strains were mixed in the ratio of 1:1. Co-digestion of the wastewater with 10% g VS of brewery wastewater optimally enhanced methane yield to an increment of 66% and was the simplest enhancement method [68, 70] suggested that the new technology should be based on mesophilic temperature range (27-28 °C), dry, co-digestion concept. As for the low cost requirements, the one-stage batch system could be used. This batch dry digestion has a significant advantage; the simplicity. Few moving part and not diluted feedstock make this technology suitable for our use. As for biogas production, it starts from zero, increases, peaks and decreases. For this reason a set of batch digesters is required. The retention time is normally longer than 30 days. On the proposed recommendations [74] carried out a research for the selection of optimal anaerobic digestion technology by using mesophilc conditions (27- 28°C) in digester. He concluded that common technologies used in developing countries were considered as inapplicable because of their need of large amount of water for wet type of AD. Dry batch technology was recommended as suitable for the area in southwest Madagascar.

Solids

In a typical scenario, there are three different operational parameters associated with the solids content of the feedstock to the digesters: High-solids (dry—stackable substrate), High-solids (wet—pumpable substrate), Low-solids (wet—pumpable substrate), High-solids (dry) digesters are designed to process materials with a high-solids content between ~25-40%. Unlike wet digesters that process pumpable slurries, high solids (dry – stackable substrate) digesters are designed to process solid substrates deposited in tunnel-like chambers with a gas-tight door. They typically have few moving parts, require minimal or no pre-grinding or shredding, and do not use water addition. Wet digesters can be designed to operate in either a high-solids content, with a total suspended solids (TSS) concentration greater than ~20%, or a low-solids concentration less than ~15% [75]. High-solids (wet) digesters process thick slurry that requires more energy input to move and process the feedstock. The thickness of the material may also lead to associated problems with abrasion. High-solids digesters will typically have a lower land requirement due to the lower volumes associated with the moisture. High solids digesters require correction of conventional performance calculations (e.g. gas production, retention time, kinetics, etc.) originally based on very dilute sewage digestion concepts, since larger fractions of the feedstock mass are potentially convertible to biogas [76]. Low-solids (wet) digesters can transport material through the system using standard pumps that require significantly lower energy input. Low-solids digesters require a larger amount of land than high-solids due to the increase volumes associated with the increased liquid-to-feedstock ratio of the digesters. There are benefits associated with operation in a liquid environment, as it enables more thorough circulation of materials and contact between the bacteria and their food. This enables the bacteria to more readily access the substances they are feeding off and increases the speed of gas yields. A feedstock was prepared for AD and found an increase in the biogas production and reduction of volatile solids. It includes pre-treatment or reduction of feedstock particle size. The use of pre-treatments is particularly useful in the digestion of biomass rich in cellulose or lignin. Pre-treatment can also break down these polymers, but it could increase the price

for technology. As for the low cost treatment, only size reduction and water maceration can be used. Particle size can affect the yield of AD as it affects the availability of a substrate surface for anaerobic reactions. Maceration reduces the size of fibers and was found to increase biogas production [77].

Complexity and Number of Stages

Digestion systems can be configured with different levels of complexity, one stage or single-stage and two-stage or multistage. A single-stage digestion system is one in which all of the biological reactions occur within a single sealed reactor or holding tank. A single-stage digestion system is one in which all of the biological reactions occur within a single sealed reactor or holding tank. Therefore, the biological reactions of the different species in a single-stage reactor can be in direct competition with each other. Another one-stage reaction system is an anaerobic lagoon. A multi staged mini digester was used for the comparison of mesophilic and thermophilic anaerobic digestion. The mini digester consisted of twelve units and served to produce the biogas. Three tests with three repetitions simultaneously were possible, whereas three units served for the control (inoculums). During the test the biogas production was read daily. The volume produced was let out in case of each reading, each day at the beginning of test, later on every two or three days, when the gas formation diminished [69-70] investigated sample of Nile perch fish processing wastewater (FPW) in a multi staged digester. [68] Suggested one-stage dry batch digesters are relatively new and innovative digesters used for bio-waste and grass silage. There is need to increase the use of such type of digesters. In comparison of all technologies, one stage, dry and batch digesters are seen as less expensive or cost-effective. [77] is concerned about the number of stages, in one-stage digestion all the microbiological phases occur in one tank, however, in two-stage digestion different microbial phases can be separated. Generally multi-stage digesters are found to have a higher performance than single-stage digesters, but are more expensive to build and maintain.

Two-Stage or Multi-Stage Digestion System

In a two-stage or multi-stage digestion system, different digestion vessels are optimised to bring maximum control over the bacterial communities living within the digesters. Acidogenic bacteria produce organic acids and more quickly grow and reproduce than methanogenic bacteria. Methanogenic bacteria require stable pH and temperature in order to optimize their performance [78]. Under typical circumstances, hydrolysis, acetogenesis, and acid genesis occur within the first reaction vessel. The organic material is then heated to the required operational temperature (either mesophilic or thermophilic) prior to being pumped into a methanogenic reactor. The initial hydrolysis or acidogenesis tanks prior to the methanogenic reactor can provide a buffer to the rate at which feedstock is added. Some European countries require a degree of elevated heat treatment in order to kill harmful bacteria in the input waste [79]. In this instance, there may be a pasteurisation or sterilisation stage prior to digestion or between the two digestion tanks. It should be noted that it is not possible to completely isolate the different reaction phases, and often there is some biogas that is produced in the hydrolysis or acidogenesis tanks.

Residence Time

The residence time in a digester varies with the amount and type of feed material, the configuration of the digestion system, and whether it be one-stage or two-stage. In the case of single-stage thermophilic digestion, residence times may be in the region of 14 days, which, compared to mesophilic digestion, is relatively fast. The plug-flow nature of some of these systems will mean that the full degradation of the material may not have been realized in this timescale. In this event, digestate exiting the system will be darker in color and will typically have more odors. In two-stage mesophilic digestion, residence time may vary between 15 and 40 days [35]. In the case of mesophilic UASB digestion, hydraulic residence times can be (1 hour to 1 day) and solid retention times can be up to 90 days. In this manner, the UASB system is able to separate solid and hydraulic retention times with the utilization of a sludge blanket [80]. Continuous digesters have mechanical or hydraulic devices, depending on the level of solids in the material, to mix the contents enabling the bacteria and the food to be in contact. They also allow excess material to be continuously extracted to maintain a reasonably constant volume within the digestion tanks.

Feed Stocks

The most important initial issue when considering the application of anaerobic digestion systems is the feedstock to the process. Feed stock is any substrate that can be converted to methane by anaerobic bacteria. Feed stocks can range from readily degradable wastewater to complex high-solid waste. One requirement is that a given waste/wastewater contains a substantial amount of organic matter that is finally converted mainly to methane and CO_2 [81] Digesters typically can accept

any biodegradable material; however, if biogas production is the aim, the level of putrescibility is the key factor in its successful application [82].http://en.wikipedia.org/wiki/Anaerobic_digestion - cite_note-69#cite_note-69 .The more putrescible (digestible) the material the higher the gas yields possible from the system. Substrate composition is a major factor in determining the methane yield and methane production rates from the digestion of biomass. The feed stocks for anaerobic digestion vary considerably in composition, homogeneity, fluid dynamics and biodegradability. In intensive animal farming, the excrement is commonly collected as slurry. Pig and cow slurries are reported to contain dry matter contents in the range of 3 to 12 %. Chicken manure contains 10 to 30 % TS. [83, 84]. Sources of eligible substrates for anaerobic digestion are shown in Fig. 3. Digestion of the organic fraction of municipal solid waste (OFMSW) is driven by the need to reduce waste, generate useable biogas and also optimize the horticultural compost substitute product in order to enhance the economic output of the process. For energy crops the prime driver will be the generation of biogas as a source of energy. In some cases plant biomass is pretreated and stored (i.e. silage) for the subsequent utilization as a feedstock for anaerobic digestion [85]. Most of the existing agricultural biogas plants are operated exclusively with manure. It is reported that in Germany a yearly quantity of 150-180 x 106 m^3 animal wastes is produced [86]. Techniques to determine the compositional characteristics of the feedstock are available, while parameters such as solids, elemental, and organic analyses are important for digester design and operation [87].http://en.wikipedia.org/wiki/Anaerobic_digestion - cite_note-69#cite_note-69 Possible techniques for anaerobic process of biodegradable waste are described in the Fig. 4 [88]. Anaerobes can break down material with varying degrees of success from readily, in the case of short-chain hydrocarbons such as sugars, to over longer periods of time, in the case of cellulose and hemicellulose. Anaerobic microorganisms are unable to break down long-chain woody molecules such as lignin. Anaerobic digesters were originally designed for operation using sewage sludge and manures. Sewage and manure are not; however, the material with the most potential for anaerobic digestion, as the biodegradable material has already had much of the energy content taken out by the animal that produced it. Therefore, many digesters operate with co-digestion of two or more types of feedstock. For example, in a farm-based digester that uses dairy manure as the primary feedstock, the gas production may be significantly increased by adding a second feedstock, e.g., grass and corn (typical on-site, feedstock), or various organic byproducts, such as slaughterhouse waste, fats oils and grease from restaurants, organic household waste, etc. (typical off-site feedstock). Sources, composition and biodegradability of the anaerobic feed stocks are listed in Table-2. Digesters processing dedicated energy crops can achieve high levels of degradation and biogas production. Slurry-only systems are generally cheaper but generate far less energy than those using crops such as maize and grass silage; by using a modest amount of crop material (30 per cent), an AD plant can increase energy output tenfold for only three times the capital cost, relative to a slurry-only system [89].http://en.wikipedia.org/wiki/Anaerobic_digestion - cite_note-69#cite_note-69 A second consideration related to the feedstock is moisture content. Dryer, stackable substrates, such as food- and yard-waste, are suitable for digestion in tunnel-like chambers. Tunnel-style systems typically have near-zero wastewater discharge as well, so this style of system has advantages where the discharge of digester liquids is a liability. The wetter the material the more suitable it will be to handling with standard pumps instead of energy intensive concrete pumps and physical means of movement. Also the wetter the material the more volume and area it takes up relative to the levels of gas that are produced. The moisture content of the target feedstock will also affect what type of system is applied to its treatment. In order to use a high-solids anaerobic digester for dilute feed stocks, bulking agents such as compost should be applied to increase the solid content of the input material. Another key consideration is the carbon: nitrogen ratio of the input material. This ratio is the balance of food a microbe requires in order to grow. The optimal C: N ratio for the 'food' a microbe is 20–30:1. Excess N can lead to ammonia inhibition of digestion [76].http://en.wikipedia.org/wiki/Anaerobic_digestion - cite_note-69#cite_note-69

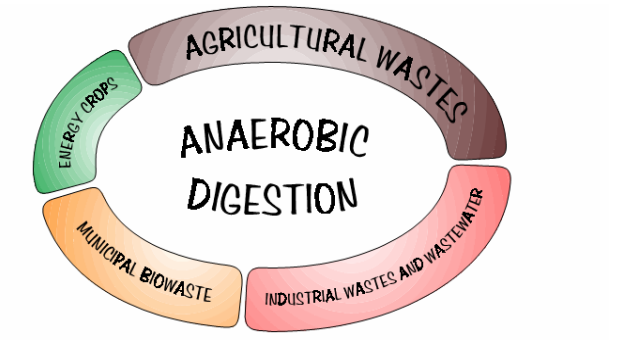

Fig.3: Sources of eligible substrates for anaerobic Digestion.

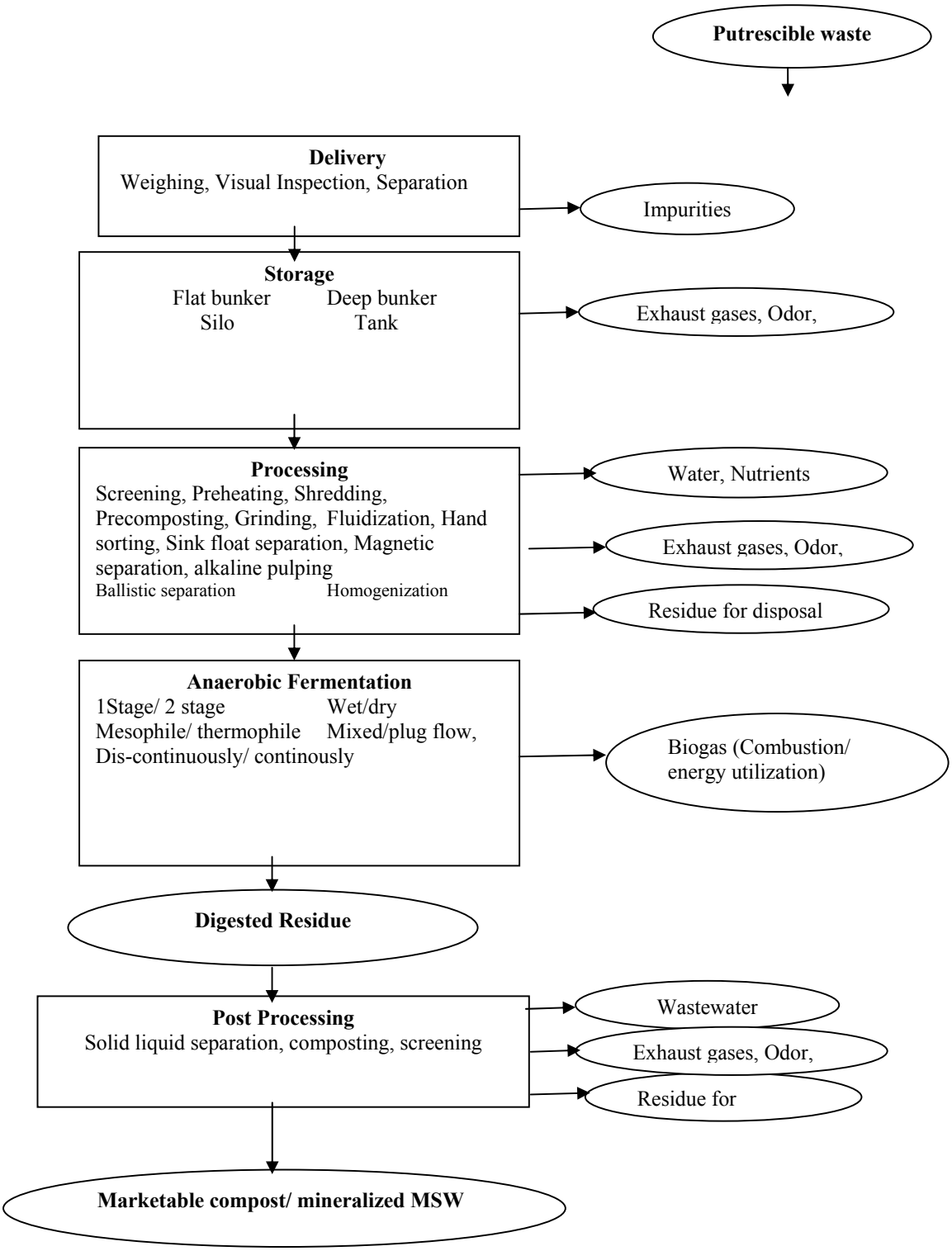

Fig. 4: Possible techniques for anaerobic processes of biodegradable waste [88].

Table-2: Sources, composition and biodegradability of the anaerobic feed stocks.

Compounds	Sources	Examples	Anaerobic Biodegradability	Disturbing effects	Inhibitory effects
Carbohydrates	Beets, Corn, Potatoes,	Sugar beet processing	Excellent	Foaming	pH decrease [2]
Sugars, Starch &	Maize, etc& Straw,	Chips and starch processing	Excellent	Lignin	
cellulose	Grass, Wood	farm yard manure, harvest remains	Poor- good	Incrustation	
Proteins	Animals & Animal products	Milk processing, Pharmaceutical industry	Excellent [1]	Foaming	pH decrease [2] Ammonia increase
Fats	Animals & Animal products	Slaughter houses, Rendering plants, Oil mills	Excellent [1]	Scum Layers, Poor Water Solubility	VFA increase pH decrease [2]
Volatile Fatty Acids (VFA)	Fats, Grease, Oils, Evaporation Condensates	Rendering plants, Oil mills	Poor	Poor water solubility of fats and oils	Specific inhibition of different bacteria groups
Trace organic compounds	Pesticides, Antibiotics, Detergents	Pharmaceutical industry manure	No	Foaming	Antibiotic reactions
Inorganic material	Salts, Food additives, Silica Gel (Filtration)	Slaughter house, manure, food & pharma. industry	No	Precipitation, Sludge Formation	
Sand, Grit	Stable Walls and Floors	Manure	No	Precipitation, Tube blocking	
Metals	Packaging Material, Process Remains	OFMSW	No	Blocking, Precipitation	
Plastic	Packaging Material	OFMSW	No	Flotation	
Heavy Metals	Metal Refining, Batteries	OFMSW	No		

[1] Necessary for high retention times; [2] depending on the buffer capacity

The level of contamination of the feedstock material is a key consideration. If the feedstock to the digesters has significant levels of physical contaminants such as plastic, glass, or metals, then pre-processing will be required in order for the material to be used. http://en.wikipedia.org/wiki/Anaerobic_digestion -cite_note-78#cite_note-78 If it is not removed then the digesters can be blocked and will not function efficiently. It is with this understanding that mechanical biological treatment plants are designed. The higher the level of pre-treatment a feedstock requires the more processing machinery will be required, and, hence, the project will have higher capital costs [90]. After sorting or screening to remove any physical contaminants, such as metals, and plastics from the feedstock, the material is often shredded, minced, and mechanically or hydraulically pulped to increase the surface area available to microbes in the digesters and, hence, increase the speed of digestion. The maceration of solids can be achieved by using a chopper pump to transfer the feedstock material into the airtight digester, where anaerobic treatment takes place.

Products

There are three principal products of anaerobic digestion: biogas, digestate and water.

Biogas

Biogas is a mixture of various gases. Independent of the fermentation temperature, a biogas is produced which consists of 60%–70% methane and 30%–40% carbon dioxide, whereas trace components of ammonia (NH_3) and hydrogen sulfide (H_2S) can be detected. However, the yield biogas depends on several factors such as temperature, pH and alkalinity, hydraulic and organic loading rates, toxic compounds, substrate type, and total solids (TS)/volatile solids (VS) content [91]. The caloric value of the biogas is about 5.5–6.0 kWh m^{-3} which corresponds to about 0.5 L of diesel oil. According to [92] the yield and composition of the biogas can be estimated from the following equation 12, when the chemical composition of the substrate is known

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 \quad (12)$$

The details and typical composition of the biogas products are given in Table-3.

Table-3: Typical composition of biogas.

Parameters	Value
Matter	%
Methane , CH_4	50-57
Carbon dioxide, CO_2	25-50
Nitrogen, N_2	0-10
Hydrogen, H_2	0-1
Hydrogen Sulfide, H_2S	0-3
Oxygen, O_2	0-2

Digestate

Digestate is the end point product, solid remnants of the process and contains organic compounds which are not susceptible by the anaerobic microorganisms (e.g. lignin) as shown in Fig. 5. It also consists of the mineralized remains of the dead bacteria from within the digesters [36].

Digestate are classified in three forms; fibrous, liquor or a sludge-based combination of the two fractions depending on the feedstock and the digestion process. In two-stage systems the different forms of digestate come from different digestion reactors. In single stage digestion systems the two fractions will be combined and if desired separated by further processing. On the completion of digestion, the residue slurry is removed and dewatered to produce a liquid stream and a drier solid. The water content is filtered out and re-circulated to the digester, and the filter cake is cured aerobically, to form compost. The screening of the final product is carried out for any undesirable materials, (such as glass shards, plastic pieces etc) before being used on the land and sold as organic soil amendment to condition and improve soil [44]. It might be possible that digestate contain ammonia that is phytotoxic as well as pathogenic microorganisms in case where the time temperature regime in not sufficient for their inactivation. However, pathogen destruction can be guaranteed at thermophilic temperatures with a high SRT [44]. Generally the digestate is composted after the digestion in order to produce high quality end product. It must be stated that anaerobic digestion does not reduce nutrient content (NPK value), making the digestate more valuable as a fertilizer [93]. Acidogenic anaerobic digestate is shown in Fig. 5.



Fig. 5: Acidogenic anaerobic digestate.

Water

Water is the final output from anaerobic digestion systems which originates from the moisture content of the original waste that was treated but also includes water produced during the microbial reactions in the digestion systems. The wastewater exiting the anaerobic digestion facility will typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). These are measures of the reactivity of the effluent and show an ability to pollute. Some of this material is termed 'hard COD', meaning that it cannot be accessed by the anaerobic bacteria for conversion into biogas. If this effluent were put directly into watercourses, it would negatively affect them by causing eutrophication. As such, further treatment of the wastewater is often required. This treatment will typically be an oxidation stage wherein air is passed through the water through any post treatment method like wetlands or Membrane bioreactor [94].

Future Research Work

So far, anaerobic wastewater treatment has been approved very successful in treating a variety of carbon rich wastewaters. The inhibitory effects of metals on the anaerobic digestion itself and various bacterial species involved in the AD still need to be thoroughly characterized. In spite of a large number of advantages associated with anaerobic reactors, there are certain limitations that anaerobic reactors hardly produce effluents that comply with usual discharge standards established by the environmental agencies [25]. If combined with an appropriate post treatment then the effluent values reach the same level as the aerobic activated sludge, which could be widely applied in industrial sector. Keeping in view of the pollutants concentration and demand for the supply of clean water; there is a need for integrated anaerobic treatment technologies. Focusing on cost effective and environmental friendly technologies [18], constructed wet lands seem to be a viable option for the post treatment of the effluent from the anaerobic treatment. Constructed wetlands (CW) offer a simple and economical solution for post treatment of anaerobic digestion. They are easy to construct, operate, maintain, and do not require import of any equipment. A wide range of environmental and water quality problems will be solved by the application of combining the wet lands with anaerobic treatment methods. In Pakistan, such wastewater treatment technology has not yet been adopted. The objective of the treating the anaerobic effluent with wetlands is to polish the effluent to an acceptable level. The wetlands offer a great potential for wastewater polishing to a suitable standard for reuse [19]. The wetland nutrient removal efficiency can be greatly enhanced by the appropriate wetland plant selection [20]. The constructed wetlands offer a low cost tertiary biological nutrient removal which is more attractive option for developing communities [19]. Use of micro and ultra filtration membranes combined with anaerobic reactors will be another post- treatment option.

Conclusion

Recent developments of anaerobic processes for wastewater treatment must be credited. The costs

of construction, installation and operation of anaerobic reactors are much lower than those of conventional aerobic units. In fact, if the environmental conditions inside the reactor are adequate an anaerobic process is mainly self-controlled. Additionally, the production of excess sludge is minimal and energy balances are quite favorable due to the production of methane, even when heating is required. In practical applications, anaerobic treatment suffers from the low growth rate of the microorganisms, a low settling rate, process instabilities and the need for post treatment of the noxious anaerobic effluents which often contains ammonium ion and hydrogen sulfide. Major limitations of the anaerobic system that the effluents from anaerobic reactors usually require a post treatment step as a means to adopt the treated effluent to the requirements of the environmental legislation and protect the receiving water bodies. The organic matter and other constituents (N, P) little affected by the anaerobic treatment can be removed by post treatment. BOD limitations imposed by the environmental agencies are expressed in terms of effluent discharge standards and minimum removal efficiencies, which almost limit the use of anaerobic treatment (without post treatment) for the wastewaters treatment. The effluents from the anaerobic reactor have high N/COD and P/COD ratios than the values desired for the good performance of biological nutrient removal processes. Concerning the microbiological indicators, low fecal coliform removal efficiencies have been reported in anaerobic reactors. Considering the inherent limitations associated with the anaerobic systems there is a need to develop technologies that are more appropriate to the reality of developing countries. So, it is essential to include a post treatment stage for the effluent generated in anaerobic reactors. This post treatment will not only polish the microbiological quality of the effluents, but also the quality in terms of organic matter and nutrients. A wide range of environmental and water quality problems will be solved by the application of combining the wet lands with anaerobic treatment methods. In Pakistan, such wastewater treatment technology has not yet been adopted. The objective of the treating the anaerobic effluent with wetlands is to polish the effluent to an acceptable level. The wetlands offer a great potential for waste water polishing to a suitable standard for reuse. The treated effluent after anaerobic, wetlands processes and the Membrane Bioreactor (MBR) will be a novel combination to treat the industrial wastewater. It is hypothesized that the efficiency of the treated effluent with anaerobic, wetlands and MBR combination will be better than three processes if applied individually.

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