APPLIED MICROBIOLOGY

Microbial Treatment of Domestic and Industrial Wastes for Bioenergy Production

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Introduction

Waste generation is an unavoidable component of our daily life. Almost all human activities generate waste. The real problem associated with waste generation is its disposal and management. Its magnitude is increasing at an alarming rate. Our abilities and resources to dispose of the wastes are quite inadequate. The available disposal facilities are very scarce. The indiscriminate use of natural resources, rapid industrialization and urbanization are the main reasons for rapid deterioration of environment. An associated issue is the high rate of fossil fuel consumption and emission of obnoxious gases. It has forced us in to a polluted environment and an energy crisis. It is thus imperative for us to manage the waste in an organized manner, reduce waste generation, conserve energy and look for alternative sources of energy. In fact there is a need for awareness about adopting efficient, scientific and safe methods of treatment and disposal of wastes, including conversion of the waste into energy.

Wastes can be grouped based on the source of origin: i) Domestic, ii) Municipal, iii) Agricultural and iv) Industrial. The quantum of these wastes varies from region to region and depends upon the cultural background of that area or country. The estimates of quantum of waste generation in India **(Table 1)** vary according to parameters and the surveying agency. Agriculture and municipal sectors are the main contributors to the waste produced. Since the waste production is increasing at the rate of 1.33%, we can anticipate higher expenditure on their disposal and management. In fact, Industrial sectors have not been able to handle and treat their wastes or control the emission of gases into the atmosphere. Various laws have been enacted in the field of air and water pollution control and hazardous waste management. National standards and limits have also been set up for discharge of pollutants in the environment. The environmental impact analyses are mandatory for large and medium scale industries. However, the industrial firms are still not in a position to take up effective steps to fall in line with these statutory requirements primarily due to lack of awareness of pollution problems and their effects, awareness of and access to cost-effective technologies and services and finance at affordable cost. Microbial methods are certainly the best for treating organic wastes in particular.

Table 1: Estimated quantities of waste generation in India

Waste	Quantity
Municipal solid	27.4 mty
Pressmud	9 mty
Food and fruit processing	4.5 mty
Willow dust	0.03 mty
Municipal liquid (121 class I and II cities)	12145 mld
Dairy industry (COD level 2 kg/m^3)	50–60 mld
Distillery (243 nos)	8057 kld
Paper and pulp industry (300 mills)	1600 m^3 /day
Tannery (2000 nos)	52500 m^3 /day

mty: million tones/ year mld: million litres/day
kld: kilo litres/day COD: Chemical Oxygen Demand

Microorganisms have been known to be operational in natural ecosystems as a dynamic population. Microbes such as bacteria, fungi, protozoa and crustaceans play an important role in maintaining the rivers and streams as a clean source of potable water. Man has learned from natural systems and these microbes are now being employed as cleaning agents in man made polluting sources: domestic and industrial waste waters. Recent improvements in Microbial treatment systems have made them to be more advantageous over chemical or physical technologies in use for the last few decades. Wastewater treatment involves mechanical, physical, biological, and chemical methods. Some of the available wastewater treatment technologies are primarily aerobic in nature and have a heavy demand on energy for aerating the effluent. The energy required for reducing chemical and biochemical oxygen demand (COD and BOD) levels is quite substantial. New processes are being developed to treat sewage, analyze wastewater and evaluate the effects of pollution on the environment. In spite of these efforts however, expanding population and economic growth continues to exacerbate water pollution

Wastewater treatment processes are guided by the technical feasibility, simplicity, economics, societal needs and political priorities. The need and demand for a sustainable society will provide the necessary impetus to shift the focus from waste treatment to resource exploitation. Microbial processes have the potential to provide a solution to control pollution with a concomitant generation of energy or valuable products. Wastewaters from domestic and food processing industrial sources being rich in organic matter are in fact among the most suitable for microbial exploitation. In fact, the association of wastewater treatment with the recovery of energy in the form of hydrogen, methane, ethanol and high value chemicals such as enzymes, proteins, fatty acids, polyhydroxyalkanotes (bioplastic), etc. can lead to reduction in treatment costs. Consequently, it might reduce to a certain extent our dependence on fossil fuels.

Sources of Pollution

Increased human and industrial activities have rendered most of the Indian rivers vulnerable to pollution and health hazards. River water is thus becoming unfit for human consumption. The primary sources of this pollution are the release of untreated effluents and domestic sewage in to rivers and other water bodies. Domestic sewage contributes about 60% of the total pollution load in terms of BOD. On the other hand, water pollution is also caused by certain industries, which release toxic wastes and organic pollutants through untreated effluents: agro-based industries, refineries, petrochemicals, fertilizers, and industrial chemicals. These industries in India are estimated to release about 3000 million litres per day (MLD) of industrial effluents. Food and agro-product industries such as distilleries, sugar factories, and pulp and paper mills, dairy, starch, slaughter house and tannery to name a few (Tables 2-3) account for almost 65% to 70% of the organic pollutants released in the water bodies in India. Disposal of untreated wastes in to the environment is the basic cause of environmental pollution including the release of greenhouse gases like methane and carbon dioxide. Consequently, it leads to health related problems. The generation and disposal of biodegradable wastes are issues of significant social and economic importance.

Table 2: Contribution of pollution load[a] by different industrial effluents

Industry	Share of waste water[a] (%)
Industrial Chemicals	29
Iron and steel	0
Non-ferrous metals	10
Other chemicals	1
Food products	38
Paper and pulp products	19
Non-metallic mineral products	0
Petroleum refineries	2
Textiles	1

a: In terms of BOD

Table 3: Characteristics of wastewater generated by different industries

Source of waste water	Pollution load generated (mg/l)	
	COD[a]	BOD[b]
Distillery	90000 - 110000	35000 - 50000
Sugar	1800 - 3200	720 - 1500
Pulp & paper	5900	1800
Dairy	1100 - 3400	300 - 1700
Edible oil	3200 - 6000	
Coffee	2800	1500

a: Chemical Oxygen Demand, b: Biochemical Oxygen Demand

Status of Waste Generation

A large quantity of waste is generated by domestic and industrial sectors. According to an estimate made in 1999 from large number (120) of Indian cities, sewage generation rate was 12000 MLD. According to a more recent survey of 350 Indian cities and 10 industrial sectors it is likely to increase from 14000 MLD in 2007 to 19500 MLD by 2017. The quantities of different kinds of waste vary depending upon the industrial sector (Table 2). Within the industrial sector, chemical producers contribute towards 40 to 45% of the total pollutants, whereas the rest of the organic pollution is discharged largely by food and fruit processing units and agro-based industries (Table 1). The average daily per capita sewage generation is estimated at about 150 litres. The total sewage generated in India is about 30 billion litres/day. However, the total treatment capacity available is only about 10% of this quantum generated.

Microbial Treatment of Wastes

There is an urgent need for solving the enormous environmental pollution due to municipal and industrial wastes. The common practice of open dumping of solid wastes and release of untreated sewage in the cities and towns in the country should be stopped. The approach to handle this situation is the use of micro-organisms via bio-deterioration or bio-degradation. Primarily we have two options to treat wastewaters: a) Aerobic and b) Anaerobic. Treatment of waste streams by conventional means like aeration is energy intensive and expensive. In addition, it leads to the generation of significant quantities of sludge, which also demands effort for its disposal. Anaerobic digestion (AD) produces energy in the form of biogas (methane) and offers many other advantages such as ability to tolerate wastewaters of high organic loads. Recycling and stabilization of waste through AD is a better approach for treatment than aerobic treatment or composting (Table 4). Bioenergy in the form of methane can substitute conventional fossil fuels and reduce release of green house gases (GHGs). Although the benefits of AD were realized almost a century ago, a greater emphasis was laid only after the oil crisis of the 1970s. This laid the foundation for energy conservation and implementation of stringent pollution control regulations. In response to the need to make a coordinated effort to protect the environment, the National Environmental Policy Act (NEPA) was enacted in 1970. AD process emerged as an acceptable alternative to treat wastes (Table 5). As discussed later, unlike uncontrolled and slow fermentation of wastes in a landfill, biodegradation in a biogas digester results in energy generation and production of nutrient rich biomanure.

Table 4: Comparison of Aerobic with Anaerobic Microbial Treatment Systems

Feature	System	
	Aerobic	**Anaerobic**
Effluent quality	Excellent	Moderate to poor
Sludge production	High	Low
Nutrient requirement	High	Low
Energy requirement	High	Low
Temperature sensitivity	Low	High
Methane production	No	Yes
Nutrient removal	Possible	Negligible

Aerobic Digestion

Aerobic digestion is a biological process for treating organic waste sludges prior to final disposal. The system involves, 12 to 25 days of aerating the waste sludge, where by microbes break down the organic material. As the process proceeds and the concentration of nutrients goes down, the organisms consume their own cell material and reduce the organic content even further. The process of aerobic digestion is accomplished in multi-stage systems where most of the digestion is accomplished in the first tank and the last stage is used for concentrating the solids. Supernatant produced during these steps is recycled. The major advantages in aerobic sludge digestion is the production of a more stable sludge, and fewer odour problems. Since no methane and carbon dioxide are produced the associated safety problems do not arise. However, aerobic digestion produces a sludge which is difficult to thicken, resulting in disposal problems. Sludge handling and disposal is a major part of the wastewater cycle. Water continues to be a major part of the overall sludge volume. Sludges are often conditioned for subsequent dewatering or disposal. Prior to dewatering, the conditioning steps used are thickening, elutriation, and chemical coagulation During thickening, the sludge is placed in specifically designed tanks and continuously stirred for periods of 6 to 24 hours. Supernatant is continually drawn off. It usually doubles the sludge concentration. Elutriation washes the digested sludge prior to further conditioning. It involves the extraction of alkaline carbonate, phosphates, and fine sludge particles from the sludge. The alkalinity is removed to reduce the amount of coagulant necessary for mechanical dewatering. Elutriation is carried out in tanks similar to sedimentation tanks. Rapid mixing of sludge and wash-water is carried out just prior to entering the sedimentation tanks. Sludge is often chemically treated prior to undergoing the dewatering process. The addition of certain chemicals helps to bring about coagulation of the solids and also produces a more rapid release of the water from the sludge. Chemicals used in this process include lime, ferric chloride, ferric sulphate, alum, and organic polymers. Dewatering reduces the moisture content of the sludge for easy handling and disposal. The three principal methods of dewatering sludge are drying beds, vacuum filtration and centrifugation. Using sludge beds, it is possible to obtain a sludge water content of approximately 25%. Disposal of dewatered sludge in a properly run sanitary landfill is one of the best disposal methods available.

Table 5: Advantages of Anaerobic Wastewater Treatment

Feature	Advantages of Anaerobic system
Efficiency	Highly efficient, as organic matter degradation occurs even at high loading rates and mesophilic operating temperatures
Economy	Low cost of construction and simplicity in operation
Flexibility	Can be applied on a wide range of scale and at any place
Space requirements	Because of ability to withstand high loading rates, reactor size is significantly reduced
Energy demand	Operations possible at ambient temperatures, so no energy required for heating. The system produces energy in the form of biogas (methane)
Biomass/ sludge production.	Very low, only 5% compared to 50% sludge production in aerobic system
Nutrients requirement	None in case of Domestic sewage
Biofertilizer	Nitrogen, potassium and phosphorus are in the mineralised form and can be used as manure
Removal of pathogens	Plant, animal and human fecal pathogens are removed
Post treatment	It destroys a large proportion of COD and BOD
Aeration	The process being anaerobic, has no demand for oxygen

Biological Treatment in Effluent Treatment Plants (ETPs)

Wastewater flowing out of primary treatment contains a large amount of organic matter. The potential to utilize pollutants in the effluents as carbon sources for metabolism varies enormously among microorganisms. The most rapid and complete degradation of pollutants present in the ETPs is brought about under aerobic conditions through catabolic pathways. Correspondingly, anaerobic, nitrifying–denitrifying and methanogenic bacteria that carry out the detoxification of effluent contaminants have been discovered from various ETPs. These bacteria are capable of degrading complex chemical mixtures including aromatic, nitroaromatic and cyclic compounds. The activated sludge process is the most popular biological treatment process for both industrial and municipal wastewater treatment.

Wastewater from domestic and industrial sectors has a greater concentration of pollutants. It is mandatory for every industry to comply with the prescribed wastewater disposal norms. Industries thus set up wastewater treatment systems comprising preliminary treatment, primary treatment and secondary treatment. Preliminary wastewater treatment generally includes screening and grit removal. Secondary treatment involves biological removal of dissolved organic matter from wastewater into water, carbon dioxide and bacterial cells (sludge). The sludge is then separated from the wastewater through settling (secondary sedimentation). The water is disinfected by chlorination, ozonation, etc. Solids (sludge) are normally processed in three steps: digestion, dewatering and disposal. The digestion stage removes organic matter and stabilizes the sludge. Dewatering brings down the water content of sludge and also decreases its volume. Final disposal can be land application or incineration.

Although it is mandatory for each industry to treat its wastewater, this problem is tackled by providing a common infrastructure for collection, treatment and disposal of the effluents from dense industrial clusters inhabited by small-scale units. Such ‘Common Effluent Treatment Plants’ (CETPs) have solved the ultimate objective of control of pollution from small-scale units. Unlike an ETP, a CETP receives a diverse load of influents from varied sources and hence is difficult to operate and maintain. CETPs are invariably also challenged by hydraulic shock loads.

Aerobic Digestion Technologies for Industrial and Domestic Wastewater Treatment

Secondary treatment options employed on-site in ETPs include diverse biological reactors that are able to convert pollutants in the wastewater to carbon dioxide and water. The most common technologies involving these biological processes include trickling filters, rotating biological contactor (RBC), aerated lagoons and activated sludge process and are discussed in brief below:

(i) Trickling filter: A trickling filter consists of distributor arms that spray wastewater over a bed of rocks or other media. The interstitial space between the rocks/media allows maintenance of aerobic conditions. A layer of biological slime consisting mainly of bacteria decomposes the waste trickling through the rocks/media. The slime also includes fungi, algae, protozoa and rotifers. Generally at higher loading rates there is lower BOD removal i.e. inefficient treatment.

(ii) Rotating biological contactor consists of a series of closed spaced, circular plastic disks. Each disk is partially submerged in a tank containing the wastewater being treated. The rotating disks provide oxygen to the microbial film growing on its surface.

(iii) Lagoons/oxidation-stabilization ponds are large, shallow earth basins where wastewater gets treated by natural processes involving algae and bacteria. Aeration is provided in some cases to enhance the organic removal efficiency, but anaerobic systems are also in use. High-performance aerated lagoons are quite similar to activated sludge. These can be modified and designed to nitrify the waste material. In contrast to activated sludge plants, the active biomass is essentially a fixed biological film at the bottom of the lagoon.

(iv) Membrane bioreactors integrate biological waste degradation with membrane filtration. Filtration enables complete removal of suspended solids and control of the solid retention time (SRT) and hydraulic retention time (HRT). It ensures optimum control of microbial population and flexibility in operation. The membrane modulates the treatment and prevents the loss of enzymes and soluble oxidants creating a more active biological mixture capable of degrading a wider range of carbon sources. The biomass retained on the membrane is able to withstand fluctuations in nutrient concentrations in the influent. The membrane is cleaned by frequent permeate back-pulsing and occasional chemical backwashing.

(v) Activated sludge process is the most popular biological treatment process for industrial and municipal wastewater treatment. The key unit in an activated sludge process is an aeration tank, in which microorganisms are mixed with incoming wastewater. Air is pumped into the tank and the mixture is kept thoroughly agitated. A portion of these solids is recycled to the aeration tank to maintain the proper bacterial biomass. The activated sludge comprises of a complex microbial community, where bacteria are abundant organisms and are responsible for removal of about 85–90% of the BOD remaining after primary treatment. Sequencing batch reactors are a modification of activated sludge process, operated in fill and draw mode. These reactors have inherent flexibility of cyclic phasing enabling operation in various modes.

Anaerobic Digestion

Anaerobic digestion is a process for the stabilization of organic matter, present in the biological wastes by anaerobes. Degradation of complex organic matter involves the breakdown of almost all kinds of biomass (waste) into soluble compounds. Methane and carbon dioxide are the principal products and minor quantity of nitrogen, hydrogen, ammonia and hydrogen sulphide gets generated. Thus, this process consists of complex sequences of biological reactions, during which the product by one group of organisms serves as the substrate for the next and the methanogens are the terminal organisms in the microbial food chain. The out standing feature of this decomposition process is that its successful operation depends on the interaction of metabolically different bacteria. Effective fermentation of organic matter to biogas is a result of combined and coordinated metabolic activity of the anaerobic bacterial population, in the absence of oxygen or other strong oxidizing chemicals. Anaerobic digestion of biodegradable wastes involves a large spectrum of bacteria of which three main groups are distinguishable. The most generally accepted relationship and pathways active in anaerobic digestion are shown in Figure 1 and detailed below:

(1) **Hydrolysis** - In the first step, putrefying bacteria hydrolyse the complex insoluble substrate macromolecules into simpler and more soluble intermediates. These reactions tend to depend on extra-cellular enzymes for example cellulase, amylase, protease and lipase that degrade even biopolymers (carbohydrates, proteins and lipids) into smaller

units sugars, amino acids, fatty acids and glycerol. This step is normally a rate limiting step for the anaerobic treatment of insoluble wastes such as biomass.

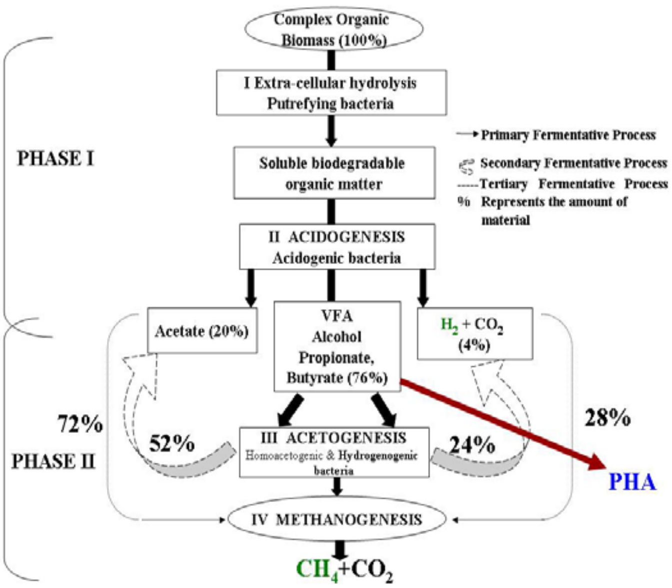


Figure 1: Anaerobic Digestion Process

(2) Acidogensis - In the second step of anaerobic digestion the fermentation / acidification of soluble substrate in to more oxidized intermediates primarily the volatile fatty acids (VFAs) (Table 6) occurs by hydrogen producing acidogens. These bacteria play a very important role as they utilize oxygen present in water, added or inoculated in the feed to produce acetic acid. Moreover they reduce the low molecular weight compounds into alcohol, propionate, butyrate, hydrogen and carbon dioxide. Some of these reactions are thermodynamically endergonic under standard conditions and the metabolism of acidogenic bacteria demands a low partial pressure of hydrogen. It thus seems obvious that metabolic interactions in the form of interspecies hydrogen transfer reactions are operative in anaerobic environment which maintains a low partial pressure of hydrogen of 10^{-6}M. As a consequence, the anaerobic degradation of substrate tends to shift to the formation of acetate by passing the formation of higher acids. This step however, is fastest step in the anaerobic conversion of complex material in the liquid phase digestion. Acidogens are fast growing bacteria, with minimum doubling time of around 40 minutes.

(3) **Acetogenesis** - The third major reaction of anaerobic digestion process is acetogenesis. About 76% of organic matter are degraded via reduced organic intermediates, which can be oxidized further to the methanogenic substrates by homoacetogenic and hydrogenogenic bacteria. Hence, acetogenesis is a key process in the mineralization of organic matter in methanogenic environment. The acetogens are slow growing (doubling time of about 14 days) and depend on low partial pressure of hydrogen conditions for making their conversion energy yielding. Thus these reaction occurs in syntrophic association, where several anaerobic microorganisms can share the energy available in the bio-conversion of a molecule to methane and carbon dioxide and thus can achieve intermediate reactions which are endergonic under standard conditions (Table 7).

Table 6: Characteristics of Organic acid producing bacteria

Bacteria	Growth at		Metabolic product(s)[a]
	pH	Temp (°C)	
Bacillus cereus	5.2	25-30	A, L
B. knelfelkampi	5.2-8.0	25-35	A, L
B. megaterium	5.2-7.5	28-35	A, L
Bacteroides succinogenes	5.2-7.5	25-35	A, S
Clostridium carnofoetidum	5.0-8.5	25-37	-
C. cellobioparus	5.0-8.5	36-38	F, A, L, CO_2, E
C. dissolvens	5.0-8.5	35-51	F, A, L, S
C. theymocellulaseum	5.0-8.5	55-65	F, A, L, S, E
Pseudomonas formicans	7.5	33-42	F, A, L, S, E
Ruminococcus flavefaciens	5.0-7.0	33-38	F, A, S

a: A-Acetic acid; E-Ethanol; F-Formic acid; L-Lactic acid; S-Succinic acid

Table 7: Free energy status of certain acetogenic and methanogenic reactions occurring during anaerobic digestion

Reaction	Free Energy (ΔG°, kJ)
Propionate → Acetate + CO_2 + $3H_2$	76.1
Butyrate → 2 Acetate + $2H_2$	48.1
Ethanol → Acetate + $2H_2$	9.6
Lactate → Acetate + CO_2 + $2H_2$	-4.2
Acetate + H_2O → Methane + CO_2	-104.6
CO_2 + $4H_2$ → Methane + $3H_2O$	-135.6

(4) **Methanogenesis** - This is the major step of anaerobic digestion, where methanogens catabolize acetate and one carbon compound to methane (Table 8). Methanogens are unique among prokaryotes and are classified as members of archaeal bacteria, a group of phylogenetically different microorganisms. These obligate anaerobes are very sensitive to inhibitions. All methanogens can utilize hydrogen and carbon dioxide as growth substrates and some of them can also catabolize acetate and one carbon compound to methane. Other possible methanogenic substrates like formate, methanol, carbon monoxide, and methylamines are of minor importance in most anaerobic digestion processes.Other unique property of methanogens include, a different autotrophic growth in which carbon dioxide fixation does not involve Calvin cycle and presence of co-enzyme M, unusual electron carrier like co-enzyme F_{420}, factor F_{420} and pseudo-murin in cell walls.

About 72 % of methane from organic matter are produced via acetoclastic methanogens, although these bacteria grow very slowly (doubling time 2-6 days). Thus this pathway is generally a rate limiting step. Other pathway is hydrogenotrophic where hydrogen from fermentation and acetogenic reaction is converted to methane by hydrogen consuming methanogens. And only 28% methane is produced via hydrogen pathway. This syntrophic coupling of many acetogenic/acidogenic reactions is critical as 80% of the methane production occur via this pathway. Moreover doubling time for these hydrogenotrophic methanogens is 6 hours. Due to these reasons although a large amount of hydrogen is produced in this process, hydrogen is rarely detectable in final product that is biogas. Moreover, this pathway is more energy yielding and plays a major role in regulation of anaerobic digestion process. These methanogens have a very great affinity for hydrogen, as they are the only anaerobic organisms capable of utilizing electron in the form of hydrogen (Table 7). Thus to maintain a low partial pressure of hydrogen value that makes thermodynamically unfavourable reactions to occur or in other words this hydrogen is of special concern because of its importance a key metabolite in anaerobic process and its potential for feed back control of acetogenic reaction.

Table 8: Characteristics of Methanogenic bacteria and their utilizable substrates

Bacteria	**Oxidizable substrates**	**Metabolic product**
Methanobacterium formicum	H_2, CO_2, CO, Formate	CH_4
M. mobilis	H_2, CO_2, Formate	CH_4
M. omelianskii	H_2, CO_2, Alcohols, Formate	CH_4
M. propionicum	Propionate	Acetate, CO_2, H_2
M. ruminatium	Formate, H_2, CO_2	CH_4
M. soehngenii	Acetate, Butyrate	CH_4, CO_2
M. suboxydans	Butyrate, Valerate	CH_4, CO_2
Methanococcus razei	Acetate, Butyrate	CH_4, CO_2
M. vannielli	H_2, CO_2, Formate	CH_4
Methanosarcina barkerii	H_2, CO_2/ Methanol	CH_4
M. barkerii	Acetate	CH_4, CO_2
M. methanica	Acetate, Butyrate	CH_4, CO_2

In addition to these three main groups, hydrogen consuming acetogenic bacteria are always present in small numbers in an anaerobic digester. They produce acetate from carbon dioxide and hydrogen and, therefore, compete for hydrogen with the methanogenic bacteria. Also, the synthesis of propionate from acetate, as well as production of longer chain VFA, occurs to a limited extent in anaerobic digestion. Competition for hydrogen can also be expected from sulphate reducing bacteria in the case of sulphate containing wastes. It was a long accepted belief that anaerobic digestion was feasible only for the treatment of concentrated wastes such as manure and sewage sludge with long retention times. Around 1950, anaerobic treatment of wastewater was attempted and the concept of high rate systems received importance with the use of mixing devices. The latter helped to break scum in the digester and increase contact between organisms and the substrate. Special reactor types for wastewater treatment such as the anaerobic contact processes were also developed. The energy crisis in 1973 greatly increased the interest in anaerobic digestion for all biodegradable wastewater. Advanced methods such as the up flow anaerobic sludge blanket (UASB) process and various fixed film reactor types based on the principle of cell immobilization were introduced at this point. At present, anaerobic digestion is a popular option and is a widely used wastewater treatment method.

Anaerobic Digestion Technologies for Energy Recovery from Industrial and Domestic Wastewater Treatment

Anaerobic digestion of biodegradable waste results in both energy generation and reduction of greenhouse gas emissions. Conventional digesters such as sludge and anaerobic continuous stirred tank reactors (CSTR) have been in use in India for many decades in sewage treatment plants for stabilization of the activated sludge and sewage solids. The area is well-researched and sufficient information and operating experience is therefore available on the subject. In recent times, the emphasis has shifted to high rate biomethanation systems, which are based on the concept of cell immobilization techniques (UASB, fixed films, etc). Details of these reactors (Figure 2) are given below.

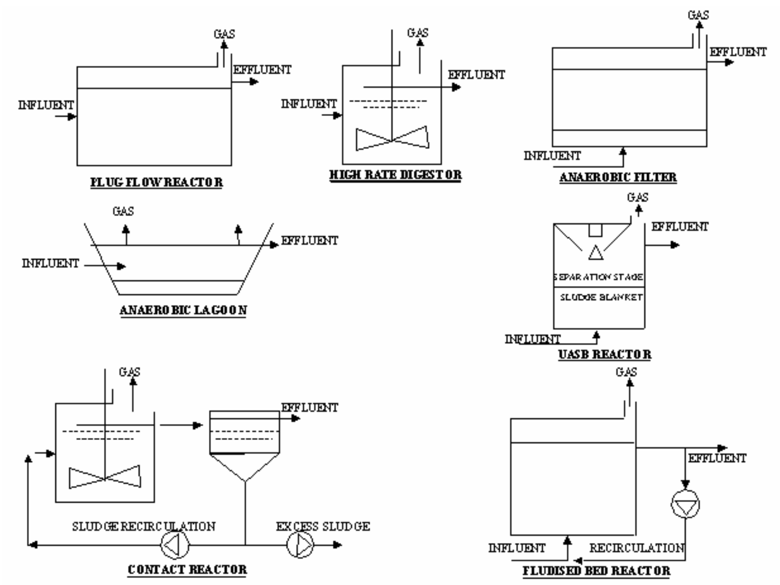


Figure 2: Diagrammatic representation of reactor designs for wastewater treatment by anaerobic digestion

Upflow Anaerobic Sludge Blanket (UASB): This technology combines the well-mixed attributes of the contact system with an internal gas separation and clarification mechanism. The UASB is an anaerobic reactor fed from the bottom. It can be divided into four compartments (from the bottom to the top); the sludge bed, the fluidized zone, the gas-liquid separator and the settling compartment (Figure 2). As efficient feed distribution system is installed in a UASB reactor, effluent recycle (to fluidize the sludge bed) is not necessary. It allows sufficient contact between wastewater and sludge which is guaranteed even at low organic loads. In the sludge bed, the organic compounds present in the wastewater are hydrolysed and acidified by the hydrolytic and acidogenic bacteria. These intermediates are further converted into hydrogen, methane and carbon dioxide. The reactor contains no mechanical components, but does have a top works baffle arrangement, which acts to separate the gas, liquid and solid phases. It is being used extensively for a large number of different types of industrial effluents such as distilleries, food processing units, tanneries, etc., in addition to municipal wastewater. It enables to provide highly cost effective designs since it employs sludge granules as a means of achieving high mean cell residence time (MCRT). UASB processes have been found to be effective in treating high strength and low/medium strength wastewater. In comparison to an anaerobic filter or a fluidized bed system, UASB is more economical. However, it has certain associated demerits as well: a) long start-up period, b) requires large amount of granular seed sludge for faster start-up, and c) there are significant quantities of wash-out of sludge during the initial stages.

Completely mixed stirred tank (CMST): A CMST (also called CSTR) is similar to the conventional activated sludge aerobic process widely used in the treatment of municipal wastewater. It became the industry standard in the 1970s and represents an improved design of an anaerobic lagoon to treat effluents. The CSTR contains a mixer to maintain good contact between biomass and the organic material being digested, and a post-clarification step after which the biomass returns to ensure a steady quantity of the mixed liquor suspended solids within the reactor.

Anaerobic filter: The anaerobic filter was commercialized in the late 1970s and, as the name implies, relies on a media substrate to retain the biomass within the reactor vessel. Different types of substrate materials have been utilized for this purpose, and different flush out methods have been developed to reduce the possibility of plugging.

Anaerobic Upflow Fluidized bed: This process reduces the loading rates and reactor size significantly. A later generation of "ultra high rate" reactor eliminates the need for carrier material, but still maintains a fluidized or expended bed to facilitate biomass contact. In the anaerobic fluidized bed (Figure 2), the media for bacterial attachment and growth is kept in the fluidized state. It is achieved and maintained through application of high upflow velocities by recycling the effluent. The design of a fluidized bed thus consists of a wastewater distributor, a media support structure, media, head space, effluent draw off, and recycle facilities. The different characteristic bed regeneration, size and density of the inert media and upflow velocity ensure a good quality of biofilm. Excess sludge can be removed from the top of the fluidized bed reactor. Earlier systems attached biomass to heavier particulate matter (e.g., sand) so the bacteria would not be swept out of the reactor by very strong hydraulic flow through rates. Fluidized bed technology is more effective than anaerobic filter technology as it favours the transport of microbial cells from the bulk to the surface and thus enhances the contact between the micro-organisms and the substrate. These reactors have several advantages over anaerobic filters. The risk of clogging is reduced due to a low hydraulic head loss combined with better hydraulic circulation. It can also have low retention times and/or higher loading rates. The stationary packed bed technology is adequate for the treatment of easily biodegradable wastewater or where high COD removal is not required, while the fluidized bed technology is especially suitable for treatment of hazardous wastes with recalcitrant compositions.

Dry Continuous Digestion: This process involves a continuously fed digestion vessel with a digestate dry matter content of 20-40 %. Both completely mixed and plug flow systems are used. Plug flow systems rely on external recycle of a proportion of the outgoing digestate to inoculate the incoming raw feed materials. In both the cases, the requirement for only minimal water additions makes the overall heat balance very favourable for operation at the thermophilic digestion temperature (50-55 ºC).

Dry Batch Digestion: This process is closest to the accelerated landfill concept. While the containment vessel is being loaded with raw MSW, it is inoculated with digestate from another reactor. It is then sealed and left to digest naturally, during this closure period, leachate from the base of the vessel is recirculated to maintain a uniform moisture content and redistribute soluble substrates (VFA) and methane bacteria throughout the mass of MSW within the vessel. When digestion is complete, the vessel is reopened, uploaded and refilled with fresh charge of raw MSW feedstock. The main advantages are the simplicity of the containment vessel and the need for only minimal feed preparation and mechanical handling.

Leach-Bed Processes: This concept is generally similar to dry batch digestion, except that leachate from the base of the vessel is exchanged between established and new batch to facilitate start-up, inoculation and removal of the volatile acids in the reactor. After a while, when methanogenesis becomes established in the solid waste, the industrial digester is uncoupled and reconnected to fresh solid waste in a second vessel. This concept has also been described as “sequential batch anaerobic composting” (SEBAC).

Wet Continuous Digestion: MSW feedstock involves slurring with a large portion of water to provide a dilute (10% dry solids) feedstock that can be fed to a conventional completely mixed digester similar to those commonly used for sewage sludge or farm slurries. Effective removal of glass and stones is required in the feed preparation stage to prevent their rapid accumulation in the bottom of the main digestion tank. When used for MSW digestion alone, filter pressing of the wet digestion to recover liquor to recycle for feed preparation is required to avoid generating an excessive volume of diluted digestate for disposal. Alternatively, this concept lends itself towards codigestion of MSW with more dilute feedstocks such as sewage sludges or animals manures. The concept of codigestion is especially well established in Denmark where there is a major program of cooperative biogas plants for animal manures.

Multistage Wet Digestion: This includes a range of proprietary multistage wet digestion processes where the MSW is slurried with water or recycled and fermentative bacteria to release VFA, which are then converted to biogas in a specialised high rate industrial anaerobic digester, usually an anaerobic filter or an UASB reactor.

Improved anaerobic sludge bed (ASB) reactor system

Expanded granular sludge bed (EGSB) reactor: The EGSB reactor was the first modified form of the USAB reactor. This reactor concept was introduced by De Man et al. to increase the hydraulic mixing intensity, which is low in the UASB reactor. The EGSB reactor is characterized by an expansion of the granular sludge bed. This expansion is due to the application of a high upflow velocity (5-10mh^{-1}) which is 5-10 times higher than that of a UASB reactor.

UASB-septic tank: The originality of the UASB-septic tank compared to the conventional UASB reactor is that the former includes accumulation and stabilization of the sludge. It also differs from the conventional septic tank in the fact that it operates in upflow mode. In practice, the UASB-septic tank operates as a continuous system with respect to the liquid and as well as a batch system with respect to the solids. This reactor concept for the treatment of wastewater was first investigated by Bogte et al. in the Netherlands.

Hydrolysis upflow sludge bed (HUSB) reactor: The HUSB reactor concept for raw domestic wastewater treatment was proposed in 1985. It was first tested at pilot scale at the Gao Beidian (China) wastewater treatment plant as reported by Wang. The system achieved a very satisfactory suspended solids removal (75-84%) at a short HRT (2.5-5h) and ambient temperature (18-31^{0}C). However, the total COD removal of the system was only 40-48% and the soluble COD removal was very low.

Two-stage reactor concept: There is confusion between the expression: two-phase and two-stage or two-step reactor. The former implies a process configuration employing separate reactor, for acidification and methanogenesis, connected in series. The later is designed so that acidification in the first reactor is incomplete. The main advantage of the two-phase system appears to be improvements in the process control and low accumulation of biomass in the methanogenic phase.

Anaerobic hybrid (AH) reactor: The AH reactor is a combination of a UASB reactor or an EGSB reactor and an anaerobic filter (AF) in one reactor. The reactor bottom is a sludge bed and top is a filter on which biomass can be attached. This reactor is designed to tolerate large fluctuations in loading rate. Strong adhesion of microbes to the support material ensures that changes in fermentation conditions do not affect the microbes strongly in an irreversible manner. Biofilms are strong enough to withstand very high upflow velocity of effluent. The reactor is designed to allow good separation of the different phases of anaerobic digestion such as the separation of acidogenic from the methanogenic phase. Thus, the differences in the growth rates and pH requirements of these two sets of microbes are provided to maintain a good population through out the digestion process, which normally is the limiting factor in a USAB reactor. The hybrid reactor is good for industrial effluents of different origins and qualities. The inert matrix and highly porous material increases the retention of the granular sludge and prevents the washout of the microbial population. The enhanced concentration of activated sludge and the high rate of mass transfer in the reactors are some of the other associated advantages of this reactor, which makes it economical for industries. Although eight hybrid reactor plants have been built in Mexico. Recently, some workers studied an AH reactor for the treatment for wastewater under low temperature condition (13 ºC) using small sludge granules instead of large sludge granules. The main advantage of AH system seem to be related to the prevention of sludge floatation and the good removal of suspended solids.

Fixed film reactor: In stationary fixed film reactors (Figure 2), microbial cells are immobilized on large sized solid support. There are provisions for uniform distribution of wastewater, effluent draw off and recycle facilities. It also offers other unique advantages like simple design for easy construction, no mechanical mixing, stability even at higher loading rates, tolerance to toxic / organic shock loads, and pH & temperature shocks. The reactors can process different waste streams without any effect on capacity. It can tolerate fluctuations in the influent characteristics. Along with these merits, the system has a limitation in its design, which results in high reactor volume compared to other high rate processes and erratic growth pattern of the biofilm, which may even clog due to its stationary nature. Although recirculation is not necessary, it may be applied to over come these problems of clearing the film and keeping the particles in suspended mode. Activated carbon, polyvinyl chloride (PVC) supports, hard rock particles, and ceramic rings are the various types of film support which have been tried. Reactor performance gets affected by the configuration and operation (upflow or downflow mode).

Constraints in implementation of anaerobic digestion technology in selected industries

Anaerobic digestion technology has a wide range of tolerance limits for the influent loading and other characteristics; however, the major wastewater generating industries such as distilleries, pulp and paper, and dairy encounter certain problems. Dairies and Distilleries have the effluent with maximum potential to adopt anaerobic digestion technology, but with the existing aerobic effluent treatment the switch over seems “un-economical” since there is lack of awareness of successful and economically operating anaerobic digesters, such as UASB reactors. Another potential problem is the toxic and biologically inert nature of certain effluents where generating microbial population becomes problematic.

Problems leading to instability of Anaerobic Digesters

Most common disturbances causing imbalance in anaerobic digestion process are organic loading rates, the presence of inorganic or organic toxins or other disturbances in the process conditions such as temperature, pH and substrate composition. However, combinations of hydraulic and organic over loading (high influent concentration) of the reactor are the major causes of process failure, which are indicated by:

- Mixed liquor volatile suspended solid (MLVSS) wash out.
- Increase in total Volatile fatty acid (VFA) concentration in the system.
- Reduction in the system COD removal efficiency.
- A drop in the pH of the system.
- Increase in total VFA/Alkalinity ratio.
- A reduction in methane gas production and
- An increased effluent total VFA concentration.

Organic Loading

When the digesters are overloaded by an increase in influent concentration equivalent to 15.5 kg COD/m^3/day the concentration of hydrogen and short chain fatty acids increase with the concomitant decline in gas production and COD removal efficiency, resulting in the inhibition of stimulated methanogenesis. This may be a result of shift in metabolic pathway to a less favourable one, causing an imbalance for VFA producers (Acidogens and acetogens) and consumers (methanogens and sulphate reducing bacteria) ratio inside the reactor. Under these conditions of unstable operation, intermediates such as volatile fatty acids and alcohol accumulation leads to the process failure. The degradation rate may decrease at low substrate concentration due to mass transport limitation and degradation of acetate is also inhibited by low pH (due to acid accumulation) and moreover dissociated acid cannot penetrate the cellular membrane. Thus anaerobic digestion process at short retention time is restricted by the relative slow rate of conversion of organic matter by anaerobic bacteria, so that the degree of waste conversion to methane is reduced significantly as its retention time is decreased below ten days. The growth rate of methanogens is relatively slow. The maximal specific growth rate of slowest growing bacteria is about 0.08 to 0.15 per day. Hence requires a minimal retention time of 7-12 days and if waste retention time is reduced below 5 days it will lead to washout of bacteria and process failure. There is also a possibility of process failure at short retention time through the accumulation of hydrogen or/and VFA which inhibits further waste degradation either directly or through reducing the digester pH.

Pre-treatment of Ligno-cellulosic Wastes

Substrate composition

Other major physiochemical features limiting anaerobic digestion is polymeric nature of waste biomass. Of the major biomass polymers cellulose, hemicellulose and amylopectin can be directly fermented by anaerobic bacteria whereas lignin is totally recalcitrant. Lignin is highly irregular polymer, with no precise chemical structure and thereby is not readily depolymerized as compared to cellulose and hemicellulose. Most important fact is that lignin physically surrounds but not covalently bound to cellulose in biomass. Thus lignin limits the activity of microbial cellulases and hemicellulases by stearic hindrance. Moreover as an anaerobic fermentation substrate lignin does not contain any readily hydrolyzable inter monomer bonds and requires extremely oxidative condition for biological depolymerization. Anaerobic microorganisms apparently have not evolved effective extracellular enzymes for depolymerizing lignin. Thus biomass rich in lignocellulosic content must be pretreated to remove lignin prior to fermentation. Several chemical and physical pretreatment methods used to depolymerize lignin without removing it from lignocellulosic structures have been employed. Most common are chemical methods like acid and alkali treatment and physical treatment methods like high temperature and / or high pressure. Other methods include pretreatment with sulphur dioxide gas, ozone, pure ammonia and H_2O_2 /Mn^{2+} solution, hydrogen fluoride vapours, steam exposure, hydrolysis of waste at higher temperature with aeration, reduction of particle size.

All the methods employed so far are for increasing digestion of lignin rich lignocellulosic material since lignin degradation has not been easy. Dilute acid treatment does not remove lignin from the substrate but modifies the lignin carbohydrate linkage. Thus lignin still remains a barrier for enzymatic attack, thereby affecting the overall fermentation process. On the other hand a higher acid concentration (70% H_2SO_4) leads to the significant loss of polysaccharides due to the secondary reactions. These reactions in turn could lead to the accumulation of sugar degradation products (furfurals) and release of some toxic substrate which may act as inhibitor in microbial fermentation, leading to low enzyme production. Other problems include, scum formation, clogging of digester, high bacterial sensitivity to environmental conditions (mainly pH, temperature and toxic compounds), long start-up time required which is due to slow growth rate of methanogens and higher sensitivity.

Sulphate Reducing Bacteria (SRB)

SRB play an important role in methanogenesis as in marine or brackish waters where sulphate is abundant, cellulose is converted to carbon dioxide and hydrogen sulphide by SRB. These bacteria have a parallel metabolism to the methanogens and are able to utilize hydrogen and sulphate to produce hydrogen sulphide. In sewage treatment facilities and in freshwater bodies where sulphate concentrations are low, the SRB enter into a symbiotic relationship with the methanogens wherein the SRB produce hydrogen from organic acids and alcohol. The methanogens in turn convert the H_2 to methane and carbon dioxide. The process can be described in terms of the Equation 1. The activity of SRB depends primarily on the availability of inorganic sulphate which are utilized by these microorganisms as the final electron acceptor in the respiratory chain. It follows that SRB can be used both for the reduction of sulphate and the removal of organic substance Equation 2).

$$2(CH_2O) + SO_4^{2-} \longrightarrow 2HCO^{3-} + H_2O \quad \text{(Eq.: 1)}$$

$$8H^+ + 8e^- + SO_4^{2-} \longrightarrow S^{2-} + 4H_2O \quad \text{(Eq.: 2)}$$

Since key intermediates like hydrogen and acetate are e^- donors for methanogenesis and also for sulphate reduction, the free energy change for acetate (-59.9 KJ by SRB and - 31.0 KJ per mol by MPB) and hydrogen utilization (-151.9 KJ by SRB and -135.6KJ per mol by MPB) is such that theoretically SRB should out compete MPB. In practice, free energy changes are dependent upon the activities of reactants and products. MPB can out compete SRB if e^- donors (acetate and hydrogen): SO_4 ratio becomes high or when a build up of sulphide occurs. Sulphate-reducers have the ability to out compete methanogens in both natural habitats and defined anaerobic consortia where sulphate is not limiting. Greater affinities for hydrogen or acetate, the effect of hydrogen sulphide on methanogens bacteria and energy reasons have been invoked to explain the competitive advantage of sulfidogens over methanogens. The saturation constant (K_s) for hydrogen for most of the sulfidogens is between 0.7 to 1.9 μM which is lower than hydrogen K_s values for methanogenic bacteria which is 2.5 to 13.0 μM. On the other hand accumulation of sulphide can be toxic to other microbes because hydrogen sulphide is corrosive. Toxic compounds may interfere with various co-enzymes A & M sulphide linkages causing inhibition of these key metabolic proteins. The Sulphate-reducing bacteria are dependent on the reduction of sulphate as a mode of anaerobic energy-yielding metabolism. Sulphate is therefore required as a nutrient at high levels, since it serves as the terminal electron acceptor. The range of utilizable organic substances is narrow, being confined for most strains to a few organic acids, notably lactate, malate and pyruvate. The end product of the anaerobic oxidation of organic substances in all cases is acetic acid, since these bacteria do not possess a functional tricarboxylic acid cycle. Under favourable conditions *Desulfovibrio* can form very large amount of sulphide during growth: the concentration may attain a level of as much as 10 g/L. Unlike nearly all other strictly anaerobic chemoheterotrophs, *Desulfovibrio* spp. contains Heme pigments: specially, a cytochrome of ‘c’ type, which participates in the anaerobic electron transport system.

Bioaugmentation for desired output

An essential feature for bioaugmentation treatment of industrial wastes is the use of the constructed consortium. Performance is expected to be more reproducible than that of an undefined community. Bioaugmentation of activated sludge by an indigenous 3-chloroaniline-degrading *Comamonas testosteroni* strain and 2,4-DCP degrading mixed culture enhancing 2,4- DCP removal and maintaining system stability under shock loading conditions. Design and operation of a treatment plant should be based on optimizing the microbial community structure. Sludge population optimization can be considered as a new dimension for the control of biological wastewater treatment systems.

Biogas Plant Models

Various biogas plant models have been approved by the MNES (Ministry of Non-conventional Energy Sources) for implementation. These models are based on the two basic designs: floating metal drum type or fixed masonry dome type. Besides, FLEXI, a portable model made of rubberized nylon fabric, has been approved for promotion in the hilly and other terrains.

KVIC floating drum: KVIC (Khadi and Village Industries Commission) floating drum biogas plant model was developed in the early sixties. Basically it has an underground cylindrical digester made of masonry wall with inlet and outlet connections at the bottom. An inverted metal drum resting on a wedge-type support on top of the digester serves as the gasholder. As anaerobic digestion produces biogas, the drum starts rising up. The weight of the drum and additional sand bags on it generates pressure on the gas to make it pass through the pipeline for use. As gas is used up, the drum gradually moves back to its original position.

Any sand bags used to increase pressure are removed manually. It enables smooth functioning of the digester.

Deenbandhu: In the Deenbandhu biogas plant model, there is substantial reduction in the surface area. It is achieved by joining the segments of two spheres of different diameters at their bases. This structure acts as the digester, and pressure is exerted on the slurry again which is pushed into a displacement chamber. Once the gas is drawn out from the outlet, the slurry again enters the digester. The brick masonry dome, which is fixed, requires skilled workmanship and quality material to ensure no leakage. This model was developed in 1984. As it was more economical than the previous model (KVIC), the technology could be extended to economically backward people also.

Pragati: This model is a combination of the KVIC and Deenbandhu designs. The lower part of the digester is semi-spherical in shape with a conical bottom. It has a floating drum acting as a gas storage chamber.

Modified KVIC Biogas Plants

Ferrocement digester: Ferrocement is a reinforced concrete made of welded mesh, sand, and cement. Layers of thin steel wire mesh distributed throughout the thickness of the cement, are impregnated with rich mortar. This system has the advantage of lower cost (10%–15% reduction) over the original KVIC model, usage of locally available material, less labour, and reduced maintenance.

Fibre reinforced plastic (FRP) gas holder: Fibre reinforced plastic has been used to fabricate the floating drum gas holder. Contact moulding process, a technique of moulding without the application of external pressure, is adopted to manufacture the FRP. It results in lowering the cost of the plant. Being made up of plastic, its good resistance to corrosion saves the expenditure on maintenance of the drum.

Flexi: A portable model in which the digester is made of rubberized nylon fabric. The model is particularly suitable for hilly areas where the high transportation cost of construction materials, such as cement and bricks substantially adds to the cost of regular biogas plants.

Fixed-dome biogas plant: It is a spherical type fixed-dome biogas plant. The spherical shape of the plant merges the digestion and gas storage spaces to a single dimension, making their construction easier. It also minimizes the surface area for a given volume, which reduces the cost while increasing the gas production rate. The plants have been designed for high efficiency and low maintenance.

Incentive to produce and use Biogas

Biogas technology is an energy efficient process since it permits optimum conversion of the biological wastes such as cattle dung, fuel wood, agricultural residues. Biogas produced from cattle dung has three times more calorific value compared to direct burning the dung cakes. It also preserves the nutrients to be used for soil amelioration. India being a largely rural dominated country can put this technology to maximum benefit.

Biogas as fuel: Biogas is a cheap and environmental friendly fuel for cooking. Each cubic metre of biogas (55 to 60% methane content) is equivalent of 14 kg LPG (liquefied petroleum gas), or 18 litres of kerosene oil, 44 kg of charcoal, 105 kg of fuelwood. In addition, it provides relief to woman during cooking as biogas burning does not lead to smoke and soot, which otherwise cause health problems.

Up to 85% of the diesel used for running Internal combustion engines can be replaced by biogas. These pumps have extensive use in the fields for pumping water for irrigation and for running floor, saw and oil mill. It helps to reduce the consumption of fossil fuels, which are becoming scarce and expensive. It also reduces the load on natural resources. It can also be converted to electricity for lighting remote areas where electric supplies are erratic or not easily available. Processing of biogas can lead to the production of saleable liquefied methane fuel. Other fuel can also be generated from biogas with the aid of low-temperature fuel cells

Biological Hydrogen Production

Hydrogen is also an important source of energy, which represents a highly efficient energy carrier. Production of hydrogen by anaerobic, facultative anaerobes, methylotrophs, & photosynthetic bacteria is possible. Hydrogen compares favourable with other fuels, which on combustion results in water and hence is non-polluting and environmentally safe. Hydrogen is an efficient fuel (122KJ/g). Hydrogen can be converted to steam, heat, electricity, etc. and therefore it is the most versatile fuel. It has the potential to be used as a fuel for automobiles, trucks, buses, aircraft, etc. Many chemotrophs produce hydrogen by the use of different carbohydrates. Hydrogen production from simple molecules like glucose, xylose, maltose and lactose is observed in *Bacillus*, *Clostridium* spp. and several anaerobes. Anaerobic microbes produce hydrogen and may degrade several other organic compounds including fatty acids, as well. In addition to simple sugar and carbohydrates, fermentation of raw starch of corn, potato and cassava peel also results in hydrogen generation. Among the various wastes employed for hydrogen generation, biowastes could produce 40L to 100L of H_2/ kg dry matter.

Criteria for considering the future fuel options systematically are:

1. Transportation - Fuel should be as light as possible and also consume as little space as possible, to make it convenient for transportation. Hydrogen being the lightest fuel, has the best mobility factor of unity. Hence it is staple fuel for space program. Hydrogen is also a fuel of choice for aircrafts as well for automobiles.
2. Versatility - Fuel must be converted with ease to other forms of energy at user end. Hydrogen has a maximum versatility factor (ϕVf) of unity as compared to other fuels ($\phi Vf = 0.4$) as they can be converted through only one process i.e. combustion. Hence hydrogen can be used for thermal and electric energy generation, and also used for refrigeration and air-conditioning.
3. Utilization efficiency - For utilization by the users, fuels transferred to various energy forms such as mechanical, electrical, and thermal, hydrogen can be converted to any desired form of energy more efficiently than other fuels. Moreover hydrogen is the most efficient fuel and hence results in conservation of resources in addition to conserving energy. Hydrogen can also be used as chemical feed stock industry as an ingredient in manufacturing chemicals like ammonia and methanol, foods (Vegetable oil), and electronics.
4. Environmental compatibility - Since utilization of fuels affects the environment it is important that fuel must not have an adverse effect on it. Hydrogen combustion when

carried out in presence of air will lead to the formation of H_2O and a very less amount of nitrogen oxides (NO_x). Hence does not lead to the phenomenon of acid rain or green house effect. Moreover when hydrogen is used for refrigeration and air-conditioning its leakage will not lead to ozone layer depletion leading to global warming.

5. Safety - This aspect of fuel involves their toxicity and fire hazards. The fuel combustion product may be toxic pollutant and toxicity increases as the C/H ratio increases. Hydrogen and its main combustion product (water or water vapor) are not toxic. Although NO_x produced through flame combustion of hydrogen displays toxic effect, but when the amount of toxic pollutants produced per unit of energy consumed is considered, it is clear that hydrogen is the safest fuel followed by methane. Hydrogen has wide range of explosive concentration in air (4-75%), which makes it a potentially good all around fuel. Moreover due to its high volatility, rapid dissemination in the event of spillage makes it safe to use.
6. Economics - The economical comparison among the competing fuels and energy systems should be based on the effective cost of the services these fuels provide. The effective cost includes the utilization efficiency, cost of fuel production, the amount of the physical damage done to environment and living beings due to harmful emissions, oil spills and leaks etc. as well as expenditure for pollution abatement.

On comparing all the candidate fuels hydrogen stands out as best possible fuel with unmatched unique properties (Table 9). Moreover hydrogen also serves as an important feedstock, and its demand as feedstock has been proposed to increase by a factor of 27 over the next 45 years. Although after energy crisis of 1970 the hydrogen has become popular fuel source and it is considered as fuel for the future. But as the prices of coal dropped other alternative energy technologies have no longer been persuaded. In 1990 due to concerns about green house effect as a new crisis regained interest in hydrogen as a fuel, as it is a long term solution to the depletion of conventional fuels, as well as for global environmental problems.

Table 9: Characteristics of hydrogen

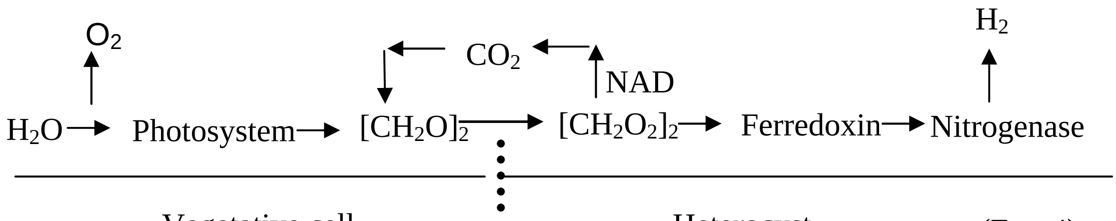
Property	**Value**
Specific energy (KJ/kg)	119.19
Mass density (kg/m^3)	70.8
Energy density (MJ/m^3)	8480
Molar Volume (cm^3/mol)	14.1
Boiling point (°C)	-253

As hydrogen does not exist naturally in the earth crust in uncombined state, there is a need to produce molecular hydrogen either by splitting of water or by utilizing biomass. Various processes involved in biological hydrogen production are:

Direct biophotolysis - This photosynthetic hydrogen production process is a two step process, where hydrogenase produces hydrogen and ferridoxin shuttle electrons from the photosynthetic membrane to the hydrogenase (Equation 3). In this process, the reductant generated by the photosynthesis is directly transferred to hydrogenase via reduced ferridoxin. But a major obstacle for this process is that these two steps are incompatible i.e. in the first step, water is splitted to produce oxygen, whereas in the second step reducing power of electron is passed to protons to produce hydrogen via hydrogenase, which is strongly inhibited by O_2. Hence, process shows inherent feedback inhibition mechanism.

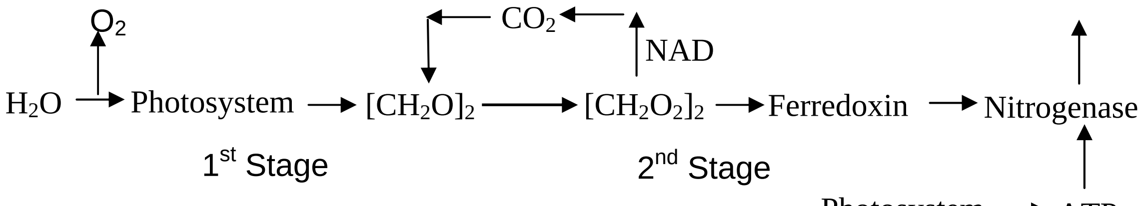
(Eq.: 3)

Heterocystrons nitrogen-fixing cyanobacteria - In this process photobiological hydrogen production occurs by algae, that compartmentalizes the two separate reactions and uses carbon dioxide as intermediate to shuttle between two compartments, e.g. *Anabaena cylindrica*, a filamentous cyanobacteria compartmentalizes these into vegetative cells, which generate oxygen from H_2O and fixing carbon dioxide, and specialized nitrogenase containing heterocyst, which evolve hydrogen when nitrogen reduction is blocked (Equation 4).



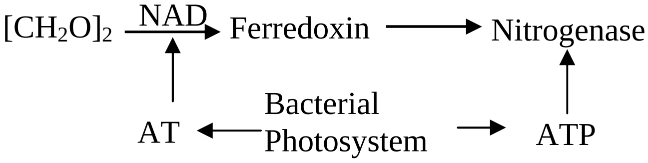
(Eq.: 4)

Indirect biophotolysis by non-heterocystrons nitrogen fixing cynobacteria - This process makes use of non-heterocystron nitrogen fixing cyanobacteria that separate the hydrogen and O_2 evolution steps temporarily such as day-night cycle, especially through separate bioreactors rather than two cell types. Here too, carbon dioxide acts as an intermediate, which joins two steps through carbon dioxide fixation and get released (Equation 5). The problem with nitrogen fixing bacteria for hydrogen production is that nitrogenase has a high ATP requirement, which lowers potential solar energy conversion efficiencies to unacceptable level.



(Eq.: 5)

Photofermentation by photosynthetic bacteria - In this process photosynthetic bacteria in the presence of light converts organic substrates, quantitatively into hydrogen and carbon dioxide (Equation 6). In principle, relatively little energy inputs are required and thus only small photo bioreactors should be required. However measured photosynthetic efficiencies have been disappointing due to the high energy demands by the nitrogenase catalyzing hydrogen evolution in these bacteria and the bacteria operates at relatively low light intensities hence preventing efficient use of full sunlight intensity.



(Eq.: 6)

Microbial Shift Reaction

Photosynthetic bacteria - This is another process, involving photosynthetic bacteria, which acts as a catalyst in the dark conversion of carbon monoxide to hydrogen (Equation 7). Such a microbial "shift reaction" can accomplish the conversion at room temperature and in one step, in contrast to chemical catalyst that requires high temperatures and multiple stages. But this process is limited due to mass transfer limitations, which could be overcome with gas phase in the reactors. Hence it is useful for small scale effective bioconversion of biomass to produce hydrogen.

$$CO + H_2O \longrightarrow H_2 + CO_2 \qquad \text{(Eq.: 7)}$$

Dark Fermentation

Another potentially viable approach is dark fermentation, which can convert waste biomass at higher yields to hydrogen. The model for such a process is fermentation of waste biomass to produce methane. Hydrogen fermentation can use similar hardware and hence makes the process promising. In addition to waste treatment credits, it could cover much of the costs of waste handling and processing. One real term option in this regard is to produce a mixture of hydrogen and methane in a two- stage process (Equation 8). The first step would produce hydrogen and organic acids, which would be converted to methane in second fermentation stage.

$$[CH_2O]_2 \longrightarrow \text{Ferredoxin} \longrightarrow \text{Hydrogenase} \longrightarrow H_2 \qquad \text{(Eq.: 8)}$$

Classification of all Hydrogen Producing Organisms

Hydrogen producing microorganisms can be grouped into four categories:

Category I - Strict anaerobic heterotrophs like *Clostridia, Micrococci, Methanobacteria* etc. are categorized in this category. These bacteria do not contain a cytochrome system but have hydrogenase enzyme and electron carrier ferridoxin protein. The following scheme represents the reaction of pyruvate degradation in *Clostridium pasteurianum*: (Equation 9). The presence of oxygen severely inhibits the generation of hydrogen, which indicates the interference or competition by oxygen with hydrogen as the terminal electron acceptor.

$$CH_3COCOOH \longrightarrow CH_3CHOX \longrightarrow 2\ \text{Ferredoxin} \longrightarrow H_2 \qquad \text{(Eq.: 9)}$$

$$CH_3COCOOH \longrightarrow CO_2 \qquad H_2 \longrightarrow 2H^+$$

$$CH_3CHOX \longrightarrow CH_3\text{-CO-Co-enzyme-A} \longrightarrow H_3PO_4 \longrightarrow CH_3COOPO_3H_2$$

Category II - Heterotrophic facultative anaerobes like *E.coli* that contain cytochromes and lyse formate to produce hydrogen in these microorganisms. Formate is oxidized to carbon dioxide and hydrogen by formate hydrogenase, which is a complex of formate dehydrogenase and hydrogenase enzyme. The following scheme represents this system: (Equation 10)

$$CH_3COCOOH + H_3PO_4 \longrightarrow CH_3COOPO_3H_2 + HCOOH \qquad \text{(Eq.: 10)}$$

$$2H^+ \longleftarrow H_2 \longleftarrow \text{Cytochrome } C_{552} \longleftarrow \text{Cytochrome reductase} \xleftarrow{CO_2} HCOOH$$

Category III - Only one microorganism is categorized in this category because of its unique characteristic. *Desulfovibrio desulfuricans* is a heterotrophic strict anaerobe with hydrogen a cytochrome system of low redox potential (E_O= -205mV). This can also use sulphate and hydrogen as terminal electron oxidant. The hydrogenase enzyme is more like category I type, whereas the actual process of pyruvate degradation produces formic acid intermediate like the mechanism of category II. Hence enzymes in *D desulfuricans* might represent a transition state.

Category IV - All photosynthetic microorganisms are placed in this category. Photosynthetic bacteria evolve hydrogen from NADH and the process depends on light. This category includes photosynthetic sulfur bacteria and the anaerobic algae.

Hydrogen Production by Chemotrophs

Chemotrophic hydrogen producing bacteria are widely distributed in nature. Some of them are symbiotic with human and other animals, while some species are pathogens of human, other animals or plants. Generally, obligate and facultative anaerobic bacteria evolve hydrogen as a result of degradation of organic substrates resulting in ATP synthesis at substrate level. The production of H_2 in some processes allows microorganism to oxidize particular substrates more efficiently, but not all substrates can be directly oxidized by microorganisms with the production of hydrogen.

In many cases, degradation steps are involved leading to the formation of intermediates that are oxidized with the evolution of hydrogen. However facultative anaerobic bacteria evolve hydrogen in anaerobic condition, but when these microorganisms are exposed to oxygen, hydrogen production is inhibited, although this inhibition may be reversible. Finally, the accumulation of hydrogen inhibits its own formation in many microorganisms and in many cases where degradation of organic compounds is obligatory related to hydrogen evolution. High partial pressure of hydrogen inhibits the growth of these microorganisms.

The inhibitory effect of hydrogen is usually strong when hydrogen formation is linked to the oxidation of NADH. As the redox potential of NADH/NAD_+ (E'_o = -320 mV) is more positive than that of H_2/H^+ (E'_o = -420 mV). For this reason, the oxidation of NADH to NAD^+ and hydrogen is possible only at a very low partial pressure of hydrogen (about 1.5 x 10^{-3} atm). In nature the low partial pressure of hydrogen is maintained as a result of interaction between hydrogen producing and hydrogen consuming microorganisms. This type of interaction between microorganisms is very important in rumen where up to 80 l of hydrogen may be formed in rumen of a cow everyday as a result of the fermentation of cellulose and other plant materials by different microorganisms. But there is no accumulation of molecular hydrogen because the methanogenic bacteria consume it.

Table 10 shows the amount of hydrogen produced by several chemotrophic bacteria from pure simple substrate and wastes. But calculation shows that efficiency of energy conversion to hydrogen does not exceed 33% of the combustible energy in organic substrates. In particular hydrogen yields are lower and efficiency of energy conversion is approximately 20%. Thus the production of hydrogen is limited and it is not produced on a large scale. However, if hydrogen production is coupled to the production of other important compounds or with the stabilization of wastes (Table 11), it may be useful. The production of hydrogen by different microorganisms is intimately linked with their energy metabolisms. In aerobic microorganisms, the released electrons from substrate oxidation are transferred to oxygen as ultimate oxidant while in anaerobic organisms, where the supply of energy is limited, electrons released from the anaerobic catabolism use many terminal oxidants such as nitrate and sulphate. However, obligate and facultative anaerobes use them as the terminal electron acceptor. Thus here hydrogen production is one of the specific mechanism to dispose of excess electrons through the activity of enzyme hydrogenase present in H_2 producing microorganisms.

Table 10: Hydrogen producing abilities of anaerobic bacteria

Bacteria	H_2 yield (mole/mole)
Bacillus licheniformis	0.58
Clostridium beijerincki AM21B	1.8-2.0
Clostridium spp. WO 2	1.9
Enterobacter aerogenes HO39	1
Enterobacter aerogenes	0.8-1.1
Pseudomonas fluorescens	0.03
Rhodobacter sphaeroides	0.19
Syhechococcus cedrorum	0.01

Substrate: Glucose

Table 11: Bioconversion of waste biomass in to hydrogen by anaerobic bacteria

Bacteria	Waste Biomass	H_2 yield
Mixed hydrogen culture	Pea shells	119 l/kg OS# red*
Bacillus licheniformis	Damaged Wheat Grains	74 l/kg OS red
B. licheniformis	Apple pomace	67 l/kg OS red
B. licheniformis	Tamarind Effluent	6 l/l Feed
Rhodobacter sphaeroides	Distillery Waste (5%)	266 ml/l sub$
R. sphaeroides	Distillery Waste (10%)	996 ml/l sub
Rhodopseudomonas	Dairy and Sugarcane Waste	6 ml/hr/g dry cell

*#OS : Organic Solids; *Red. : Reduction; $Sub. : Substrate*

Now a days microbial H_2 production by fermentative hydrogen producers is being extensively investigated. Strict anaerobes had a stoichiometry of 1:4 compared to 1:2 for facultative anaerobes with glucose as substrate. Considering all these facts about production of hydrogen by anaerobic microorganisms and their optimal stoichiometry, the later process is comparatively simpler than former, hence reduces the cost of hydrogen production and thus makes the process economically feasible. In last 25 years hydrogen energy has moved in all fronts making roads in all areas of energy. And in next 20 years the progress will be many fold greater and hydrogen energy system might provide the planet earth with the energy system, she deserves, which is hospitable to life, clean and efficient. Hence hydrogen energy system will enhance the quality of life for the people of the world and help to preserve our biosphere. India has also recognized hydrogen as a fuel of great potential and likely to be the only source of energy available to man in years to come.

Production of Bio-ethanol from Waste

Transformation of cellulosic wastes, especially those resulting from paper mills as cellulosic suspension through hydrolysis and fermentation to useful products (sugar, ethanol) represents the most profitable way for their recovery. Development of an economical process for bio-energy (Ethanol) production through enzymatic hydrolysis of lignocelluloses is hindered because of the high cost of cellulase production, low cellulase activity per unit volume and low concentration of sugar syrup obtained by hydrolysis of cellulose. A few processes for ethanol production have been reported in literature and all of those suffer with these bottlenecks. A critical analysis of literature on enzymatic hydrolysis had reveled that high cellulase activity per unit volume of fermentation broth is the most important factor in obtaining sugar concentration of 20-30% from hydrolysis of cellulose for a process for ethanol production from cellulosic material.

The Energy Potential

Sewage treatment plants in 21 Indian cities have been estimated to generate 46000 Nm^3 (normal cubic metre) of biogas per day by treating about 339 million litres/day of municipal waste water. This estimate made under the Ganga Action Plan, along with appropriate biogas power plants, will generate total electrical energy of 99 450 kWh/day. The urban municipal waste (both solid and liquid) – industrial waste coming from dairies, distilleries, pressmud, tanneries, pulp and paper, and food processing industries, etc., agro waste and biomass in different forms – if treated properly, has a tremendous potential for energy generation as shown in (Table 12-13). Processing of biogas can lead to the production of saleable liquefied methane fuel. Fuels can also be generated from biogas with the aid of low-temperature fuel cells. Many other wastes of organic nature (like vegetable, fruit, agriculture wastes) can be digested anaerobically to stabilize them. The organic acids produced during acetogenesis stage in the process of anaerobic digestion works as a substrate for methanogens which convert them to methane and carbon dioxide (Table 14).

Table 12: Estimated renewable energy potential in India

Energy source	Estimated potential
Bio energy	17000 MW
Draught animal power	30000 MW
Energy from MSW	1000 MW
Biogas plants	12 million plants

Table 13: Energy Generation Potential from Domestic Sewage and Industrial Sectors

Year	Power Generation (Mega watts)	
	Domestic Sewage	Industrial sector
2007	264	1279
2012	308	1598
2017	365	1997

Table 14: Bioconversion of waste biomass in to biogas by anaerobic bacteria

Waste biomass		Biogas yield (l /kg TS*)	CH_4 (%)
Group	Type		
Vegetable	Asparagus, Pea, Cabbage, Carrot, Cassava peel, Cauliflower, etc.	300-450	50-70
Fruit	Apple pomace, Mango peel, Apricot, Banana stem & leaves, Orange, etc.	400-550	50-60
Agricultural	Corn cobs, Cotton stalks, Rice straw, Wheat straw, Sugar cane, etc.	300-500	50-70
Others	Lantana, Hydrilla, etc.	250-500	6-80

*TS : Total Solids

National Initiatives

For over two decades, anaerobic digestion has been used in India as a low cost method of treatment for the stabilization of sewage sludge and sewage. Government of India has placed growing emphasis on new and renewable sources of energy (NRSE) in order to meet the growing energy needs of the country. So far, 2.7 million biogas plants have been installed in India, with a further potential to install 1200 million plants. The ministry of Non-conventional Energy Sources (MNES), Govt. of India has identified "Energy Recovery from Wastes" as a thrust area of its activities. A national programme of energy recovery from urban and industrial wastes, initiated by the MNES addresses the wastes management issues in urban and industrial sectors. A National Master Plan (NMP) has been developed to promote setting up of waste-to-energy projects in the country. The primary objective of the NMP is to "supplement the power needs by maximizing energy recovery from Urban and Industrial wastes in a cost effective and proven manner using technologies that are applicable to the Indian Community conditions and supports ongoing adoption to meet implementation needs and also provide vital solutions to environmental problems including reduction in GHG emissions". NMP approach is to provide R & D, promote adaptive research, integrate demonstration/pilot plants and commercialize wherever possible. The National Programme on Energy Recovery from Urban & Industrial wastes, launched during the year 1995-96, has the following objectives: a) to promote setting up of projects for recovery of energy from wastes of renewable nature from Urban and Industrial sectors; b) to create conducive conditions and environment, with fiscal and financial regime, to develop, demonstrate and disseminate utilisation of wastes for recovery of energy and c) to develop and demonstrate new technologies on waste-to-energy through R&D projects and pilot plants. The scheme which originally planned to cover 16 demonstration sub-projects has been expanded to cover a total of 29 sub-projects in nine sectors viz., sewage (3); pulp and paper effluents (3); vegetable market wastes (6); leather effluent/abattoir wastes (6); biogas utilization for power (4); food and fruit processing industry waste (2); municipal solid wastes (2); dairy wastes (1); and animal waste and agroresidues (2). Of these, four sub-projects viz., (i) biomethanation of sewage treatment, (ii) biomethanation for treatment of slaughter house waste, (iii) biomethanation of paper mill black liquor, and (iv) evaluation of biomethanation systems have already been completed.

Promotion of Biomethanation Technology in India

The new and renewable energy technologies are making a great revolution mainly in the remote areas. A total power generating capacity of over 1300 MW (megawatt) has so far been added from renewable energy sources. It accounts for 1.5% of the total installed capacity in the country. Besides, the community and institutional biogas programme has been undertaken since 1982/83, in order to promote community-sized biogas plants, which can be used for power generation in addition to meeting cooking needs. During the Ninth Five-year Plan about 1100 community-type biogas plants had been set up. It amounts to saving of about two lakh tonnes of fuel wood equivalent and production of about 18 lakh tonnes of organic manure per year during the life span of about 15–20 years of the plants. Besides, these plants accrue social benefits of reducing the drudgery of women and minimize health hazards during cooking in smoky kitchens.

Waste to Energy Projects

MNES has been the nodal agency instrumental in commissioning various waste to electrical energy conversion projects, such as those based on palm oil industry waste, cattle dung & poultry waste. The installed capacity of these projects is 5.00 MW, thus making the cumulative installed capacity of waste to energy projects in the country to around 46.50 MW. The world’s first full-scale UASB demonstration plant for municipal wastewater was built in Kanpur, Uttar Pradesh in 1989 under the Indo–Dutch Project and has been in operation since then. The plant is designed to treat 5 mld domestic wastewater and the reported biogas yield is 0.1–0.15 m^3/kg COD removed with a methane content of 75%–80%. It is able to reduce 75 to 80% of COD and BOD of the influent (COD: 552 mg/l and BOD 222 mg/l). Subsequently, under the same project, a 14 mld and 36 mld units designed and built in U.P., have been operational since March 1995. High rate anaerobic treatment technologies have also been adopted by several Indian industries. Different reactor designs like UASB, hybrid reactor and fixed film reactor have been employed for distillery and sugar waste treatment. Currently, there are two full-scale plants, which are operational for the treatment of pulp and paper mill effluent. A CSTR type anaerobic treatment plant has been installed in a paper mill in Maharashtra to treat around 250 m^3 effluent per day with a BOD and COD removal of approximately 85% and 65% respectively. Subsequently, a 3.81 m^3 wastewater treatment plant based on UASB technology was successfully commissioned in Punjab. A commercial tannery in Kanpur has installed a 10000 litres capacity UASB reactor with an ability to achieve 70% reduction in COD. Extensive pilot plant studies in the state of Maharashtra were carried out to develop an anaerobic treatment process for dairy wastewater. A case study in a milk processing unit in Maharashtra showed that anaerobic treatment can achieve savings to the tune of Rs 25 million per year in Maharashtra alone. Government of India is investing money in waste treatment projects through various agencies like Ministry of non-conventional energy Sources (MNES) and Indian Renewable Energy Development Agency Limited (IREDA) (Table 15). Some waste treatment plants generating energy are listed in Table 16.

Table 15: Energy generation capacities of wastewater treatment plants

Waste biomass		Energy production	Organisation
Type	**Quantity**		
Distillery Effluent	12000 cum/day	1MW	KM Sugar Mills Ltd.
Black liquor	450 cum/day	6050KWh	Paper & Pulp Ind.
Bagasse	520000 tonne/y	8810KW	Sugar Plant at Ajnala (Punjab)
Paddy waste	30000 tonne/y	4920	Sugar Plant at Ajnala (Punjab)

Table16 - Methane Recovery Projects Sanctioned by IREDA

Industry	No. of Projects
Distillery	54
Yeast (Baking) food processing	1
Pulp & Paper	1
Pharmaceutical	2
Misc. (Biogas boiler, Mnf. Loan for Equipment)	3
Power generation	1
Total	62

A few other Waste-to-Energy Projects envisage setting up of power projects based on poultry droppings, starch industry waste, sugar cane press mud, furfural industry waste and municipal solid wastes with an aggregate capacity of about 25 MW. A prominent example is cited below:

- **A 1.0 MW power project based on cattle manure at Ludhiana, Punjab**: Haebowal Dairy Complex in Ludhiana, spread over an area of 50 acres, has 1490 dairies with an animal population of 1,50,000 and generate about 2500 tonnes of animal droppings. The project, based on BIMA technology, has been designed to use 235 tonnes of animal waste for generating about 0.965 MW electrical energy, most of which will be for captive use. Besides, electrical energy, the project will also be producing about 75 tonnes of stabilized organic manure per day.

Considering the overall deterioration of the quality of water resources, it is of utmost importance to find consistent long term solutions. In the recent past, there has been an exponential growth in the application of anaerobic technology, both for municipal and industrial wastewater treatment. In addition to commercial operations, several laboratories in India are actively involved in the R&D of anaerobic treatment systems. A study carried out on R&D projects sponsored by the Ministry of Non-conventional Energy Sources (MNES) over the last 15 years indicates that more than half the projects were devoted to research while the remainder dealt with demonstration and evaluation of the technology.

Conclusions

Though anaerobic digestion systems have been operational in certain industries like distilleries for sometime, there is still some apprehension regarding adopting this technology in other sectors. This stems from various factors like limited availability of experienced consultants to implement the technology, little full-scale experience, lack of operator training within the industries for process maintenance, and restricted interaction between research organizations and commercial developers/ vendors. Since a large number of Indian industries are yet to establish adequate wastewater treatment facilities, the GOI is actively promoting anaerobic digestion technology. Apart from funding pilot studies, financial and fiscal incentives are also provided for establishing full-scale plants. Also, under the UNDP–GEF assistance programme, MNES is encouraging both national and international entrepreneurs to demonstrate proven anaerobic technologies in various industrial and domestic sectors. In addition, there is an urgent need for more intensive interaction between research organizations and suppliers of anaerobic systems. This is supported by the fact that over the last 15 years, even though MNES has sponsored more than 90 research oriented projects on biogas production, there is still lack of sufficient design information. Out of the nearly 60 demonstration projects, only one has been scaled up for commercial operation. This indicates a wide gap between R&D efforts and technology implementation pointing to the need for more effort towards technology adoption aspects. In spite of the fact that there is significant potential of energy generation from industrial wastewater in India, the technology is yet to be fully established. With increasing use of anaerobic technology for treating various process streams, it is expected that industries would become more economically competitive. The more judicious use of natural resources will ensure increased usage of anaerobic digestion technology in the future.

Glossary

Activated sludge: A process defined as a system in which flocculated biological growth is continuously circulated and contacted with organic waste in the presence of oxygen.
Anaerobic digestion: Stabilization of organic matter by a group of bacteria in oxygen free conditions.
Biochemical oxygen demand (BOD): It is a measure of pollution load (mg/l or ppm). It provides an estimate of oxygen required by microbes to degrade biological material.
Chemical oxygen demand (COD): It is a measure of pollution load (mg/l or ppm). It provides an estimate of oxygen requirement of inorganic and organic matter present in the waste-water.
Loading rate: It is expressed as the rate of addition of volatile matter in the mass to the digester per unit digester volume (kg VS/m^3 day).
Total Solids (TS): TS, present in a waste, is the sum total of organic solids (OS) and inorganic solids (Ash content). TS can be estimated by heating a sample at 110 ºC overnight. TS can be further heated at 600 ºC for 2 h in a Muffle furnace. The solids left after the treatment are the Ash content and the volatilized solids are equivalent to OS.
Characteristics of domestic wastewater

pH: 7 – 8; EC (µS/cm): 1-9; Na (Meq/L) 4- 8; Ca (Meq/L): 1-4; Mg (Meq/L): 1-6; Cl (Meq/L): 1-9; HCO_3 (Meq/L): 4-9; SO_4 (Meq/L): 0.2-2; BOD (mg/L) 85-400; N (mg/L) 4-0-70; P_2O_5 (mg/L) 15-25; K_2O (mg/L): 25-50.

Characteristics of Industrial wastewater: The composition of industrial sewage is quite varied, and special methods of its treatment are required for each particular case.

Metal-plating sewage contains poisons (cyanides, copper, chromium, etc.,) whose concentration is seldom below 10 mg/L and may be as high as 1000 mg/L. Cyanides of alkaline metals are especially poisonous. Their 1 mg per kg body weight is a lethal dose.

Tannery waste waters are dangerous because they can contain the causative agent anthrax. The sewage is dangerous to the personnel of the plant and if discharged to open water bodies it can present danger to cattle as well. The chemical composition of leather tanning sewage is varied. Alkali prevails in the sewage of the chrome leather manufacture. Some discharge acid sewage. A BOD demand of spent tanning solution is 4300-5700 mg/L. The sewage contains much free lime and sodium sulphate. Moreover it contains wool and soluble organic substances. The sewage of a tannery discharged after treatment of one ton of hyde is equivalent to public sewage of a of 5000 people. The presence of sodium sulphate, chromium and some tanning agents remove oxygen from water, give it an pleasant odour, and practically completely stop the self -purification process in waster bodies and kill the biota.

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