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Suitability of UASB Reactor System in Tropical Developing Countries like India

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Abstract: ***Tropical countries such as India have a lot of scope for anaerobic wastewater treatment due to the fact that for most part of the year temperature remains above 20^{0}C. This led to growing interest in developing new or modifying existing anaerobic wastewater treatment technologies. Maharashtra pollution control board (MPCB) has defined consent limits about the quality of wastewater from the industries under section 26 of the Water (Prevention and Control of Pollution) Act 1974. This made the treatment of effluent water from various industries mandatory. Having a lot of advantages such as less energy and very small sludge formation as compared to conventional wastewater treatment methods, anaerobic treatment is the obvious choice nowadays. The detailed advantages of anaerobic treatment over conventional methods are deeply covered in this paper. There are many types of anaerobic wastewater treatment processes depending on their application. A simple septic tank method has been used since ancient times. Since then there have been significant advances in reactor design. These include anaerobic fluidized bed (AFB), anaerobic fixed bed, sequencing batch reactor (SBR), up flow anaerobic sludge blanket (UASB), expanded granular sludge blanket (EGSB), etc. Among these UASB technology is the most widely used trend in recent years. UASB offers a continuous operation with large loading rates in short retention time. Gas generated in the form of methane can be used for energy generation. This paper reviews all the designs of UASB reactor and their suitability for application in tropical and subtropical regions. More emphasis is given on the applications of UASB in various industries. An attempt has been made to resolve most of the existing challenges in design as well as operation of UASB by reviewing recent work in this area. This will help in optimizing the current UASB technology.***

Keywords: UASB reactor, advantages, applications, challenges, performance enhancement.

1. Introduction

Water has always been the center for development of any civilization since ancient times. Even today all the major cities are situated alongside a natural source of water like river and sea. Water is used for residential, agricultural as well as industrial purpose. This also generates a large amount of wastewater as effluent. Rapid urbanization and heavy industrialization in developing countries like India in recent years has made it very difficult to collect treat and safely dispose these effluents which is getting worse every year. Earlier much attention was not given to the treatment of effluent and they were dumped directly into the natural sources of water. This led to severe health problems by deteriorating natural water resources. Organic wastes from industries, municipalities and agricultural sector decomposes in the environment resulting in large scale contamination of land, water and air. These wastes also possess a potential energy value which is not fully utilized despite the fact that they are cheap and abundant in most parts of the world. Organic waste dumped in the open leads to contamination of land as well as air. In order to protect the environment and prevent health hazards it is necessary to provide adequate treatment for the wastewater to reduce its pollution potential.

Based on the source, wastewater can also be classified as municipal, domestic and industrial. Wastewater collected in municipal sewers is termed as municipal wastewater; domestic wastewater is a discharge from residential and commercial establishments whereas industrial wastewater is from industries or process plants. Wastewater produced by a community is also termed as sewage. It can be categorized as low strength, medium strength, high strength and very high strength based upon the concentration of chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS) and nutrients such as nitrogen (N) and phosphorous (P). Generally stronger the effluent, greater will be the investment in infrastructure and energy inputs required to achieve environmentally safe objective. Maharashtra pollution control board (MPCB) defines consent to operate under Section 26 of the Water (Prevention and Control of Pollution) Act, 1974. This is illustrated in table 1.1.

Table 1: MPCB consent limits

Sr. No.	*Parameter*	*Unit*	*MPCB Consent Limits*
1	pH	-	5.5 - 9.0
2	Total Suspended Solids	mg/l	100
3	COD	mg/l	250
4	BOD at 3 days 27^{0}C	mg/l	100
5	Oil & Grease	mg/l	10
6	Total Metal	mg/l	10
7	Temperature	^{0}C	Should not exceed 5^{0}C above ambient temperature

A typical wastewater treatment process includes pretreatment, treatment and post treatment. Pretreatment includes separation of visible solids for which membranes of different sizes can be used. It is dependent on the type of biological treatment to be undertaken as well as the waste material being treated. Heavy particles are also allowed to settle in this stage. Treatment stage includes a bioreactor where bacteria are used for degradation of wastewater to form sludge and gas. It can be aerobic as well as anaerobic process. Post-treatment stages may require filtration or sedimentation before the cleaned effluent is discharged. These may be followed by sludge

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dewatering, solidification or incineration. Aerobic treatment involves blowing air through the water phase continuously whereas anaerobic treatment needs no such provision. Comparison of both aerobic and anaerobic treatment is illustrated in table 2.

Table 2: Comparison of aerobic and anaerobic treatment process

Sr. No.	*Feature*	*Aerobic*	*Anaerobic*
1	Organic removal efficiency	High	High
2	Effluent quality	Excellent	Moderate to poor
3	Organic loading rate	Moderate	High
4	Sludge production	High	Low
5	Nutrient requirement	High	Low
6	Alkalinity requirement	Low	High for certain industrial waste
7	Energy requirement	High	Low to moderate
8	Temperature sensitivity	Low	High
9	Start up time	2-4 weeks	2-4 months
10	Odor	Less opportunity for odors	Potential odor problems
11	Bioenergy and nutrient recovery	No	Yes
12	Mode of treatment	Total (depends on feedstock characteristic)	Essentially pretreatment

As it is evident from the above table, anaerobic process has a lot of advantages over aerobic treatment process. In general, aerobic systems are suitable for the treatment of low strength wastewaters while anaerobic systems are suitable for the treatment of high strength wastewaters. Anaerobic reactors contain diverse groups of bacteria that catalyze the conversion of complex organic compounds to methane and carbon dioxide. These groups of bacteria include fermentative bacteria, hydrogen producing acetogenic bacteria, hydrogen consuming acetogenic bacteria, carbon dioxide reducing methanogens and aceticlastic methanogens. Following are some of the benefits and drawbacks of anaerobic wastewater treatment over conventional aerobic methods (Lettinga et al., 1984).

Benefits:

1. Very low production of excess sludge.
2. Low nutrients are required for bacterial culture.
3. No energy requirements in the form of aeration.
4. Methane is produced which can be used as a fuel.
5. This process can frequently handle high loads.
6. Anaerobic sludge can be preserved without any feed for months before causing any serious deterioration.
7. Ammonia is retained in the water which can be beneficial for the purpose of irrigation.

Drawbacks:

1. Anaerobic bacteria particularly methanogens are very susceptible to inhibition by a large number of compounds.
2. The start-up of the process is slow which can be avoided by using adapted seed sludge.
3. This process usually demands an adequate post treatment for the removal of remaining BOD, ammonia and odorous compounds.

McCarty (1982) noted that anaerobic treatment technologies are in practice from as early as 1881. Some of the most common anaerobic reactors used in the industry are septic tanks in earlier times, upflow anaerobic sludge blanket (UASB) reactor, expanded granular sludge bed reactor which is adaptation of UASB reactor, etc (Quaff et al., 2014).

2. The UASB Technology

2.1 UASB Reactor

Upflow anaerobic sludge blanket reactor commonly termed as UASB reactor was developed in 1970 in Netherlands by Lettinga and his co-workers. Since then, several full-scale plants have been put into operation and many more are presently under construction. In 2002, about 100 of UASB reactors were in use for domestic wastewater treatment systems, particularly in the developing countries. At present, over 200 full-scale UASB plants are in operation for the treatment of both domestic and industrial wastewaters worldwide (Khalil et al., 2008).

UASB is a high rate reactor system usually without any moving parts. It may be cylindrical or rectangular in shape. At approximately 60% height, baffles are provided called as degassing baffles. Above the baffles is a settling zone where a dome or funnel is inserted in inverted manner. This is used for collecting the gas produced in the reactor. Reactor is sealed at both ends to maintain anaerobic conditions.

In UASB water entering at the bottom of reactor is called as influent and water leaving the reactor from the top is called as effluent. A sparger like assembly is provided at the bottom to maintain a uniform influent flow. Influent travels inside the reactor from bottom to top passing through high concentration of biomass in the sludge bed where organic matter is degraded. The organic carbon from influent is converted into biogas containing mainly methane and carbon dioxide. This gas formed in the form of bubbles causes continuous mixing which enhances contact between wastewater and biomass. A small amount of sludge is also produced. The syntrophic association between different micro organism lead to self agglomeration within the biomass (Quaff et al., 2014). These dense near spherical agglomerates are known as granules. These granules have a high settling velocity. Hence a high upflow velocity can be maintained in a granulated sludge bed which reduces the treatment time also called as hydraulic retention time. The free gas and

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the particles with the attached gas rise to the top of the reactor. These particles collide with the bottom of degassing baffles releasing the attached gas bubbles. The degassed granules then drop back to the surface of the sludge blanket. The free gas and gas released from the granules are captured in the gas collection dome located at the top of reactor. Liquid containing some residual solids and biological granules passes through a settling chamber where residual solids are separated from the liquid. The separated solids fall back through the baffle system provided at the top of sludge blanket. To keep the sludge blanket in suspension, upflow velocities in the rage of 0.8 to 1 m/h should be maintained (Awuah et al., 2008). Finally the treated effluent is taken out at the top of reactor which is then collected in the effluent tank.

2.2 UASB Process

Mainly there are four biological and chemical stages in UASB process i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis (Powar et al., 2013).

1. Hydrolysis

Wastewater contains complex organic constituents. Hydrolysis is the first step in breaking these constituents into simple sugars, amino acids and fatty acids. Acetate and hydrogen produced in the first stages can be used directly by methanogens.

2. Acidogenesis

This results in further breakdown of remaining compounds by acidogenic bacteria, also called as fermentative bacteria. Here volatile fatty acids are created along with ammonia, carbon dioxide and hydrogen sulfide as well as other byproducts.

3. Acetogenesis

Third stage is acetogenesis. Here simple molecules created by acidogenesis are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen.

4. Methanogenesis

It is the terminal stage of anaerobic digestion. Here methanogens use intermediate products of preceding stages and convert them into methane, carbon dioxide and water. These components make up the majority of biogas emitted from the system.

A simplified generic chemical equation for the overall process outlined above can be given as follows:

$C_6H_{12}O_6\ 3CO_2 + 3CH_4 \longrightarrow$

2.3 Advantages of UASB reactor

Like all the other high rate anaerobic reactors UASB too handles high flow rates of wastewater though the retention time is very less as compared to others. The unique feature of UASB reactor is Gas-liquid-solid (GLS) separator. This acts as a three phase separator where gas is collected at the top, liquid is withdrawn from the side and solids in the form of granules are settled down at the bottom. Settling of solids and at the same time, formations of gas bubbles which move upwards maintain the suspension zone within the reactor. This enhances the contact between microorganisms and wastewater molecules. Due to granulation in UASB reactor, the solids and hydraulic retention times can be manipulated independently and effectively, reducing the treatment times from days to hours (Hickey et al., 1991).

Another advantage of UASB reactor includes no need of temperature control as heat is released during methanogenesis. This heat is sufficient to maintain mesophilic conditions inside the reactor. This is applicable in tropical regions only where room temperatures are always above 20^0C. Once fed or inoculated, it does not need any nutrients to be provided. However addition of nutrients may increase performance of the reactor. As a very little amount of sludge is produced, it can be withdrawn after a much longer period of time while a small portion may be recirculated.

The cost involved in the operation and maintenance of UASB plants is less than 1% of capital cost per year. It has also been estimated that the annual operation and maintenance cost of the UASB plant is approximately 30 % of the aerobic process plants (Khalil et al., 2008).

2.4 Applications of UASB reactor

Due to simple and cost effective design, UASB reactor has a lot of domestic as well as industrial applications. Some of them are explained below.

1. Domestic Wastewater Treatment

For more than 150 years, septic tanks have been widely used for onsite anaerobic pretreatment of sewage. A significant development was achieved in the last two decades by applying upward flow and introducing GLS separator device at the top which resulted in UASB septic tank system. The UASB septic tank was firstly investigated at Dutch and Indonesian ambient conditions by Lettinga and his co-workers (Lettinga et al., 1991, 1993; Bogte et al., 1993).

Full scale UASB reactors for domestic wastewater treatment are now operational in India, Columbia and Brazil. These reactors are operated at HRTs in the range of 5-19 hours. The removal efficiencies of total COD, BOD and TSS achieved are in the range of 51-74%, 53-80% and 46-80% respectively (Vieira., 1988; Schellinkhout., 1993; Seghezzo et al., 1998). In Kanpur, India two large scale UASB plants have been implemented within the Kanpur-Mirzapur project (Kalker et al., 1999).

2. Sugar industry Wastewater Treatment

Sugarcane industry plays a vital role in social economics of rural Maharashtra especially in western Maharashtra.

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Effluent generated in sugar mills when disposed directly causes pollution of surface or ground water. If this effluent is directly released for irrigation, it affects the soil fertility, plant growth and seed germination. It also affects soil micro flora (Deshmane et al., 2015). Hence treatment of sugar industry effluent attains a high significance.

Sugar industry effluents have high organic concentration hence they are very suitable to be used as a substrate in UASB reactor (Farhadian et al., 2007). High concentration of carbohydrates corresponds to readily fermentative sugars. It also contains nitrogen and phosphorous essential for cultivation of microorganisms. Diluted sugar wastewater acts as a substrate for acidogenic process after it is made available for methanogenesis. Two separate reactors for acidogenesis and methanogenesis can be used is series to optimize the gas production where hydrogen can be collected at first reactor and methane at second (Wang et al., 2013). After several operations it was concluded that UASB design can treat sugar industry wastewater efficiently up to an OLR of 16000 mg COD/L. d. with COD removal efficiency of 89% at HRT as low as 6 hours where biogas containing more than 75% methane can be produced at the rate of 4.66 L/L. d. (Hampannavar et al., 2010).

3. Dairy Wastewater Treatment

Dairy industry is the most important industry in day to day life in India. After the white revolution majorly contributed by Amul, there has been a substantial increase in production as well as consumption of dairy products all over India. However dairy wastewater is the most polluting in nature among the food industry. It contains liquid waste from dairy processing as well as water used for cleaning and washing operations. Chemical basis of chemicals used for cleaning and washing operations decide the acidic or basic nature of effluents (Arvanitoyannis et al., 2006). A typical dairy wastewater has a temperature range between 17 and 32^0C with average COD of 2500 mgL^{-1} approximately (Buntner et al., 2013). It also varies according to type of equipment, unit process used and product obtained (Passeggi et al., 2012).

Traditionally dairy effluent is treated by anaerobic and facultative ponds where associated costs are relatively low. However, these treatments are relatively less efficient with large land requirements and uncontrollable actions (Martin-Rilo et al., 2014). Therefore, anaerobic treatment with production of methane as byproduct i.e. UASB is considered. Unlike its other applications, UASB has limiting success in treating dairy effluents. This is because of long hydrolysis time of organic material which later accumulates within the sludge blanket due to entrainment or adsorption. This results in dilution of biomass, poor contact and impaired sludge settling capacity (Passeggi et al., 2012). To avoid this pretreatment method such as dissolved air floatation (DAF) is used to separate fat (Puget et al., 2004; Ross and Valentine, 2008). Contact reactors van also be used for pretreatment methods (Hamilton et al., 2007).

4. Distillery Wastewater Treatment

Composition of distillery wastewater depends upon the raw material used. In most of the cases, cane molasses is used as a raw material. The raw molasses wastewater is typically moderately acidic with very high total chemical oxygen demand. It contains high concentration of mineral salts and has a bad smell and dark brown color. This dark color is very hazardous to aquatic life as it hinders photosynthesis by blocking sunlight. It also contains high concentration of nutrients in the form of nitrogen, phosphorous and potassium (Mahimairaja et al., 2004).

Alcohol distillery effluent is thermophilic (55^0C) in nature. It has large concentration of phenolic compounds which are poorly biodegradable and toxic. Conventionally these are treated by adjusting their temperature to mesophilic anaerobic process. But thermophilic sludge has much higher mehanogenic activity than mesophilic sludge which results in higher methane production. UASB is the only anaerobic reactor capable of thermophilic treatment. The HRT can be shortened by increasing volumetric organic loading rates.

5. Slaughterhouse Wastewater Treatment

Slaughterhouses in India generate large amount of wastewater. Consumption of water per animal varies with type of animal and the process employed. Most of this water is discarded as wastewater containing high amounts of biodegradable organic matter. The soluble fraction varies from 40% to 60%. Colloidal and suspended matter is in the form of fats, proteins and cellulose which has a very poor biodegradability [SL02]. Nitrate and sulfate are also present in considerable quantities in slaughterhouse wastewater. These have inhibitory effects on methanogenesis (Balderston et al., 1976).

For successful operation of UASB, an effective pretreatment like DAF can be used to remove fats and suspended solids. Also the upflow velocity needs to be maintained to avoid sludge washout. According to Lettinga, upflow velocity of 0.5 to 0.7 mh^{-1} gives the best results for UASB (Caixeta et al., 2002).

2.5 The Challenges and Limitations of UASB Reactor

UASB reactors are widely employed for most of the wastewaters containing high concentrations of soluble organic matter. However there are some limiting factors. Presence of certain components in the influent has inhibitory effect on the process. Excess of VFA which lacks in alkalinity in the influent leads to acidification of the reactor which causes reactor failure in case of high load reactors. This can be avoided by dilution of influent or by adding alkalinity. High concentration of suspended solids reduces settleability of sludge leading to biomass washout. For this upflow velocity needs to be monitored. All the limitations due to influent composition can be avoided by using suitable pretreatment methods.

There are some operational limitations like delay in startup and granule formation. Startup time decides the

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effectiveness and stability of UASB. This depends on characteristics of water, operating parameters and growth of microbial population in sludge. The reactor cannot be operated at full design organic loading rates before an acclimatization period to inoculate the seed sludge. This can be speeded up by using pretreated sludge inoculum. The choice of best inoculum source depends on toxicity and biodegradability test of wastewater (Ghangrekar et al., 1996; Sarria et al., 2003). Some nutrients can also be added in order to increase the stability of the reactor. Besides all this UASB alone cannot remove pathogens and coloring agents from the wastewater, hence significant post treatments are suggested for further treatment.

3. Performance Enhancement of UASB Reactor

UASB reactors are ideal for treatment of wastewater in tropical regions. However, recent studies have shown their suitability in subtropical regions as well. There are a number of studies which have suggested several modifications to achieve the optimal performance. Some of them are mentioned below.

3.1 By Modifying Configuration

Considering the strict restrictions for effluent quality, UASB alone is not sufficient to meet those norms. This can be achieved by applying some modifications to the design of reactor. Instead of conventional one step UASB, a two step UASB system is suggested at low temperatures. Here one acts as hydrolytic unit called as hydrolytic upflow sludge blanket (HUSB) reactor and the other acts as methanogenic unit i.e. UASB reactor (Chong et al., 2012).

Using a combined UASB reactor system is one of the most growing trends in the industry. UASB can be coupled with aerobic as well as anaerobic systems for pretreatment or post treatment or both. Various combinations have been used already. A COD removal of 86% was achieved when UASB was followed by two anaerobic packed bed filters operating in parallel (Goncalves et al., 1998). Sawajneh et al treated strong sludge at 15-21^{0}C by incorporating anaerobic filter reactor as a pretreatment unit to a UASB reactor. This AF+UASB system showed satisfactory COD removal in short period of time. Other combinations such as UASB – digester system, UASB – membrane system, UASB – biofilter are also incorporated by other researchers (Chong et al., 2012).

Design of UASB itself can also be modified. A recent study used vertical reticulates polyurethane foam (RPF) sheets on top of the gas – solid – liquid separator. This enhanced the entrapment of colloidal COD. Another modification suggested replacement of gas – solid – liquid separator by plastic filter rings. However this restricted the reactor to low temperatures only but the methane production increased significantly (Gao et al., 2011). Another study proposed a fixed bed model where randomly packed polyethylene ring shaped matrix pieces were fixed at the bottom half of UASB reactor. This increased the contact pattern between biomass and wastewater, lowering the temperature from mesophilic to psychrophilic.

3.2 By Changing OLR and HRT

Effective startup is achieved by using pretreated sludge inoculum. Then keeping influent flow rate fixed, OLR and HRT are manipulated to achieve maximum COD destruction. Substrate degradation rate was also evaluated to assess reactor performance. By gradually increasing the OLR and decreasing HRT at the same time, reactor startup was achieved rapidly. This may vary depending on the inoculum characteristics. If the influent is rich in sludge nutrients, visble granules are formed at much lower HRT. This allows us to operate UASB at high loading rates. In some cases like in dairy wastewater where VFA are more in the influent, OLR needs to be diluted to avoid excess acidic condition in the reactor which may cause reactor failure.

3.3 By Sludge Enhancement

Though UASB reactor can perform efficiently without granules, higher COD removal efficiency can be achieved by granule formation at the reactor startup. Formation of granules is a characteristic of sludge; however it depends greatly on composition of wastewater. Various nutrients can be added to influent or to sludge directly to speed up the granulation time. There are a lot of studies on theories and mechanisms of anaerobic granulation.

Initial development of granules can be divided into four steps (Schmidt et al., 1996): (1) Transport of cells to a substratum which is an uncolonized inert material; (2) Initial reversible adsorption to the substratum by physiochemical forces; (3) Irreversible adhesion of cells to the substratum by microbial appendages and/or polymers; (4) Multiplication of the cells and development of granules. Divalent and trivalent cations neutralize negative charges on bacterial surfaces and serves as cationic bridge between the bacteria. This exerts positive impact on granulation process (Liu et al., 2004). In addition to these, natural polymers such as water extract of Moringa Oleifera seeds, Reetha extract, charcoal; commercial and synthetic polymers such as commercial cationic polymer “AA 180H” and organic – inorganic hybrid polymers can also be added to enhance sludge granulation at the startup of reactor (Chong et al., 2012).

3.4 By Temperature Control

Based on the temperature anaerobic processes are divided into three types – Psychrophilic which is below 20^{0}C, Mesophilic which is between 20 to 50^{0}C and Thermophilic which is more than 50^{0}C. Some reactors can also be operated below 20^{0}C if a significant amount of methane is generated. Generation of methane i.e. methanogenesis step produces heat enabling mesophilic conditions inside the reactor. Research is being done in incorporating UASB process for thermophilic treatment as thermophilic conditions will allow us to remove pathogens effectively. Present studies have shown that when sucrose is used as substrate and cow manure as seed, thermophillic

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granulation of bacterial matter proceeds easily (Lettinga et al., 1984).

A hot water jacket can also be attached to the reactor at psychrophilic conditions to maintain mesophilic conditions in the reactor externally. This will help in higher COD removal rate at shorter HRT. The gas generated in the reactor can also be used to heat the jacketed water.

3.5 Potential of UASB Technology in Other Developing Countries

In the developing countries emphasis is given more to remove organic pollutants and pathogens to some extent only. Here low cost technologies such as UASB are more favorable as compared to other conventional technologies used in developed countries. Generation of energy in the form of methane is also a bonus. Besides this, the fact that anaerobic sludge can be sustained for a long time without any feed really helps when there is very less or no continuous supply of wastewater in summer season.

Recent studies have shown that UASB can be incorporated with other systems aerobic as well as anaerobic. This means there is no need to discard the previous plant entirely. Methane generated can also be used for lighting the streets as well.

4. Conclusions

Though UASB technology has far more advantages over other conventional wastewater treatment technologies, to meet the strict environmental norms a suitable pretreatment or post treatment or both need to be applied. Also efficient techniques need to be developed to recover essential nutrients like nitrogen, phosphorous, etc. from the treated effluent. Higher loading rates can be used to treat large amount of domestic wastewaters in all the major cities protecting the natural environmental habitat.

Based on the low capital and operational cost, it can be concluded that UASB in combination with adequate post treatment option still offers a best proposition compared to other treatment systems in India. Most of the developing countries have warm tropical and subtropical climates which will give better performance of UASB systems.

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