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# Sustainable Post Treatment Options of Anaerobic Effluent

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Additional information is available at the end of the chapter

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## 1. Introduction

The strategy of treating sewage by the common and known aerobic process has been shifted back to anaerobic processes in the recent years with the advent of high rate anaerobic systems such as up-flow anaerobic sludge blanket reactor (UASB), anaerobic contact process, anaerobic filter (AF) or fixed film reactors and fluidized bed reactors. The high rate anaerobic processes, like UASB have several advantages such as low capital, operation and maintenance costs, energy recovery in the form of biogas, operational simplicity, low energy consumption, and low production of digested sludge (van Haandel & Lettinga, 1994; Gomec, 2010; Khan et al., 2011a).

During early 1970s, due to the energy crisis and the above advantages, the UASB process was recognized as one of the most feasible method for the treatment of sewage in developing tropical and sub-tropical countries like India, Brazil and Colombia; where financial resources are generally scarce. However, the quality of UASB effluent rarely meet the discharge standards despite several modifications; such as settlers at the top of gas-liquid-solid-separator, addition of AF, two UASB reactors placed in series and even the incorporation of an external sludge digester (Lew et al., 2003; Khan et al., 2011a).

Since early 1980, the discussion on the applicability of UASB process for the treatment of sewage has been presented by Lettinga and co-researchers (Lettinga et al., 1980; Lettinga et al., 1993; Lettinga, 2008; Seghezzi et al., 2002; von Sperling and Chernicharo, 2005) and the results indicated that about 70% chemical oxygen demand (COD) removal can be achieved in warm climates countries (Schellinkhout and Collazos, 1992; Souza and Foresti, 1996; Khan et al., 2011a). Since its inception a lot of research has been done on this process and technology has

been given wider publicity. Presently about 30 UASB based sewage treatment plants (STPs) are in operation in India and more than 20 are under construction (MoEF, 2005 and 2006). In total, about 200 UASB reactors are used for municipal and industrial applications (Khan, 2012).

The UASB reactor treating domestic wastewater can produce two main valuable resources, which can be recovered and utilized: methane and the effluent. The methane gas, which is produced during the COD removal can be recovered (from 28% to 75%) and transformed into energy (Mendoza et al., 2009). In energy terms, 1m<sup>3</sup> of biogas with 75% methane content is equivalent to 1.4 kWh electricity. The biogas can be used to run dual fuel generators or street lighting (Arceivala and Asolkar, 2007). According to Arceivala and Asolkar (2007) approximately 23% methane gas was observed dissolved in UASB effluents, therefore, the recovery of dissolved methane gas is discretionary and may not be acceptable in case of sewage treatment due to high expenditure costs and complexity. However, the methane gas evolved to the headspace (gas phase) can be of much importance and easily collected. For high strength industrial wastewaters the recovery of dissolved methane gas is favoured in view of the global warming and its fuel value. Moreover, at high temperature the solubility of gaseous compounds decreases. Therefore, the issue of gas recovery especially dissolved methane gas must be carefully reviewed for each individual case in terms of economics and desirability.

The produced effluent can be used in agriculture irrigation or disposed. However, the inability of UASB process to meet international disposal standards, owing to its anaerobic nature has given enough impetus for the subsequent post treatment. Furthermore, the growing concern over the impact of sewage contamination on rivers and lakes and the increasing scarcity of water in the world along with rapid population increase in urban areas give reasons to consider appropriate technologies for the post treatment of anaerobic effluent in order to achieve the desired effluent quality and save receiving water bodies.

A variety of post treatment configurations based on various combinations with UASB have been studied, such as aerobic suspended growth, aerobic attached growth, combined suspended and attached growth aerobic processes, anaerobic processes, natural treatment processes, physical processes and physico - chemical processes. UASB followed by final polishing units (FPU) or polishing pond (PP) is a common process used at several STPs in India, Colombia and Brazil, since the technology is simple in operation (von Sperling and Mascarenhas, 2005; von Sperling et al., 2005; Chernicharo, 2006; Khan et al., 2011a). However, still the final effluent is generally devoid of dissolved oxygen (DO) and rich in nutrient. Moreover, polishing ponds operate at long hydraulic retention time (HRT), around 1 day, leading to a high land requirement (Khan, 2012).

Other post treatment options widely used in India are activated sludge process (ASP) and aeration-polishing pond. A demonstration scale Down-flow hanging sponge reactor is also in operation (Tandukar et al., 2005 and 2006). Several other options such as plain aeration i.e. without using biomass, are the next technology option for the post treatment of anaerobic effluents but, limited studies have been performed. A bench scale batch aeration investigated by Khan (2012) has demonstrated that aeration systems operating at 1 to 2 h HRT are able to reduce the BOD of UASB effluent to discharge standards but, unable to remove nutrient. In

the same study, continuous aeration of UASB effluent with and without activated sludge could remove nutrient.

Similarly, sequencing batch reactor (SBR), moving bed bio-film reactor, sand filtration, dissolved air flotation, rotating biological contactors (RBC), wetlands and others are still under investigations at bench and pilot scale. Results are promising; however, more studies are needed at pilot or demonstration level with actual environmental conditions in order to scale-up these technologies for best treatment concept. If stringent disposal standards need to follow, aeration with biomass can effectively reduce the organics, nutrients and odour causing substances like sulfides. Some of these processes are exclusively discussed in subsequent section.

Recently two different aerobic biomass based processes viz. continuous fill intermittent decant (CFID) type SBR and intermittent fill and intermittent decant type SBR were investigated by Khan (2012). Several researchers investigated the CFID and SBR and results revealed that the CFID can reduce the nitrogen to less than 10 mg/L as nitrogen. SBR is highly efficient to remove the nitrogen and phosphorous. Detailed studies were carried out on different aerobic treatment processes by Khan (2012).

Another latest concept of treatment is the 'Natural Biological Mineralization Route' (NBMR), which can be applied for the treatment of anaerobic effluents as suggested by Lettinga (2008) and elucidated in detail, by Khan (2012). This treatment concept enables conserving or recovery of useful by-products in the form of fertilizers, soil conditioners and renewable energy. The whole concept consists of treatment units of several micro aerobic and aerobic systems and dealt in subsequent section.

The objective of this chapter is to summarize different post treatment options for anaerobic effluent in general and specifically effluent of UASB reactor treating sewage. Natural biological mineralization route (NBMR) concept is also explained for an economical and efficient treatment.

## **2. Anaerobic effluent/ UASB effluent characteristics**

The effluent characteristics in terms of biological oxygen demand (BOD), COD, suspended solids (SS), nutrients (N & P), microbial pathogens and reduced species such as sulfides explained as follows:

### **2.1. Organics and suspended solids**

The BOD, COD and SS of various anaerobic treatment systems anaerobic ponds, UASB reactors, Imhoff tank and septic tanks treating sewage without any post treatment system has been reported to vary from 60 to 150; 100 to 200 and 50 to 100 mg/L, respectively (Chernicharo, 2006; Foresti et al., 2006). The process efficiency depends on different factors like strength and composition e.g. fraction of industrial wastewater infiltrated, temperature and diurnal fluctuations. The dissolved mineralized compounds such as ammonia, phosphate and sulfides in the

effluent also varied with these factors. The performance of these treatment systems highly depends on temperature and decreases with a decrease in temperature (Lew et al., 2003 and 2004; Elmitwalli et al., 2001). The performance of UASB reactors (COD, BOD and TSS influent, effluent and removal) treating sewage at different temperatures is summarized in Table 1.1.

## 2.2. Nutrients (N and P)

Insignificant or negligible removal of nutrient may be expected in anaerobic systems treating sewage (Foresti et al., 2006; Moawad et al., 2009). The primary reason of poor removal of nutrients in anaerobic process is organic nitrogen and phosphorous hydrolyzed to ammonia and phosphate, respectively, which are not removed by anaerobic processes and in consequence, their concentration increases in the liquid phase. The concentration of ammonia nitrogen and phosphorous in anaerobically treated sewage has been reported to be from 30-50 and 10-17 mg/L, respectively (Foresti et al., 2006).

## 2.3. Highly mineralized or reduced compounds

Sulfur compounds exist as sulfides in anaerobic systems effluent treating sewage. The effluent total sulfides concentration to the highest degree depends on concentration of sulfates in influent and sulfate reducing bacterial activity present in the reactor. Generally, sulfide concentrations around 7-20 mg/L have been observed in the UASB effluent treating sewage, which increases the effluent oxygen demand (Khan, 2012). Moreover, the chemical and biochemical oxidation also depends on sulfides concentration along with other reduced species such as  $\text{Fe}^{2+}$ , mercaptans etc. although low ferrous ion concentration has been observed in the anaerobic effluent of systems treating sewage. However, Vlyssides et al. (2007) investigated the effect of ferrous ions addition to influent to enhance COD removal. The addition of ferrous ion induces a stable and outstanding conversion rate of COD and was proved to enhance the biological activity of UASB reactor; otherwise ferrous ions results by reduced environment if sewage is treated by UASB reactor.

## 2.4. Indicators of microbial pathogens

The reduction of fecal coliforms is around one order of magnitude (from around  $10^8$  to  $10^7$ ) in UASB systems although they are not designed for pathogenic removal, while helminth eggs removal efficiency has been reported to be 60–90% (Chernicharo et al., 2001; von Sperling et al., 2002; Chernicharo, 2006; von Sperling and Mascarenhas, 2005).

Hence, for ideal and sustainable treatment the high rate anaerobic treatment systems especially UASB reactor must be integrated with novel and innovative post treatment systems based on NMBR sequence. Numerous post treatment system or combination of anaerobic pre-treatment (i.e. UASB reactor) followed by aerobic systems were investigated at laboratory and pilot scale levels for the treatment of sewage. Most of these combinations were found viable option for the treatment of effluent of UASB reactor.

Country	Capacity	Temp. (°C)	HRT (h)	Influent (mg/L)			Effluent (mg/L)			Removal Efficiency (%)		
				COD	BOD	TSS	COD	BOD	TSS	COD	BOD	TSS
Japan	-	-	6	600	291	333	222	153	-	63	53	-
Japan	1148 L	-	6	532	240	-	197	79	-	63	67	-
India	5 MLD	25	10	590	167	-	201	60	-	66	64	-
-	-	-	8	463	214	174	125	39	47	73	82	73
India	5 MLD	20-31	6	560	210	420	140	53	105	74-78	75-85	75-89
Brazil	106 L	21-25	4.7	265	150	123	133	59	33	50	61	73
-	110 L	12-18	18	465	-	154	163	-	42	65	-	73
Colombia	35m <sup>3</sup>	23-24	5.2	430-520	-	200-250	170	-	65	66	80	69
-	3.7m <sup>3</sup>	24-26	10-18	660	300	-	178	66	-	73	78	-
Brazil	106 L	20	4	424	195	188	170	61	59	60	69	69
Netherlands	120 L	8-20	12	500	-	-	225	-	-	60-90	-	65-90
Netherlands	6 m <sup>3</sup>	20	18	550	-	-	165	-	-	70	-	-

**Table 1.** Treatment Performances of Lab and Full Scale UASB Reactors Treating Sewage (adopted from Khan et al., 2011a)

The discussion for the selection of the sustainable technology for the policymakers, engineers, contractors, consultants and authorities of the public sanitation (PuSan sector) has been presented in discussion/ summary part of this chapter.

In addition, more sustainability and treatment performance of these treatment system can be improved if these systems/ combinations were categorized based on their application to remove the suspended solids with or without chemical coagulants, soluble organic and inorganic matter, and removal of reduced compounds such as ferrous ions, sulfides etc. and recovery of methane.

The foremost categories are:

- i. Conventional settling systems and flotation methods with or without chemical coagulants for the removal of suspended solids and soluble organic and inorganic compounds like phosphate or termed as primary post treatment options;
- ii. Application of physical chemical methods to remove and recover dissolved methane from the effluent, which is very important issue for the researchers, engineers and scientists;
- iii. Biological micro-aerobic methods for the removal of highly reduced (malodours) compounds like sulfides and volatile organic S<sup>-</sup> compounds, Fe<sup>2+</sup> and colloidal matter;
- iv. High rate aerobic systems for nitrification, when combined with denitrification step;

- v. Polishing methods for high rate removals of pathogens and further polishing of the secondary treated effluent. The post treatment systems thus, categorized can either be used singly or sequentially.

### 3. Post treatment systems

#### 3.1. Low rate natural settling systems

The highly stabilized suspended matter present in the UASB effluent can be removed by micro-aeration and settling process. Therefore, proper methods of removal of suspended solids are needed. Currently, natural settling processes are widely used at full scale STPs. The natural settling method is often slow and inefficient and sometimes enhanced by addition of chemical which could easily remove the colloidal and finely dissolved solids, which are separated by physical aeration. Further, the recovery of resources in terms of phosphates and treated effluent, if used for irrigation purposes makes it ideal as a sustainable option.

##### 3.1.1. Overland Flow System (OFS)

Chernicharo et al. (2001) investigated extensively OFS operated in two phases in Brazil. This system is a classical example of a full scale natural system in use for UASB effluent post treatment and characterized by constant and transient hydraulic regime respectively. Three slopes (physically identical) for wastewater overland flow constituted the post-treatment system. A very common weed species named *Brachiaria humidicola* was used as vegetative cover on the slopes. This weed is known for its high rate of nutrient absorption and high resistance against flooding.

The good performance of OFS can be achieved at low flow rate application ranging from 0.4 - 0.5 m<sup>3</sup>/m.h. The final effluent concentration of the combined system (UASB followed by OFS) showed average values of BOD from 48 to 62 mg/L; COD from 98 to 119 mg/L and SS from 17 to 57 mg/L. The combined system removed 2 to 3 log-units of FC thereby reducing the residual FC of effluent to around  $8.4 \times 10^4$  to  $2.4 \times 10^5$  MPN/100mL. In addition, a significant removal of helminth eggs was observed with an average effluent concentration of 0.2 Egg/L. However, the final effluent quality of the overland flow system was interfered by the transient flow regime and the high concentrations of solids and organic matter in the UASB reactor effluent. For these situations, the length of the slope was suggested to be kept above 35 meters.

##### 3.1.2. Polishing Ponds (PP)

Cavalcanti et al. (2001) investigated the feasibility of a single flow-through PP for the post-treatment of effluent of UASB reactor in Brazil. The plug flow regime was maintained in pond in order to elevate the fecal coliform removal efficiency of the system. Two distinct HRT of 5d and 15d were maintained in the pond. At 5d HRT, the average BOD, COD and TSS values were reduced to 68, 188 and 68 mg/L, respectively. At HRT of 15d these concentrations lowered down to 24, 108 and 18 mg/L, respectively. Removal of pathogenic microbial indicators was

also encouraging, with the complete removal of helminth eggs at 5d HRT. Moreover, at 15d HRT the effluent FC concentration was very close to 1000 MPN/100mL, with conformity to the WHO guideline for unrestricted irrigation.

Again in Brazil, von Sperling and Mascarenhas (2005) investigated the performance of four shallow (0.40 m depth) PP in series for the treatment of UASB effluent at a total HRT of 7.4 d (1.4–2.5 days in each pond). Based on the results, the final effluent average concentration of BOD and COD were 44 and 170 mg/L, respectively. The mean overall FC removal efficiency was remarkably high, 6.42 log units, or 99.99996%. The high FC removal together with total nitrogen concentration of 10 mg/L in the effluent were found compatible with the discharge standards for urban wastewaters from the European Community, 15 mg/L (70% removal). The ammonia nitrogen concentration in effluent from combined system was 7.3 mg/L (67% removal). However, phosphorus removal was only 28% (effluent total phosphorus concentration of 2.8 mg/L). Others studies on integrated anaerobic-aerobic systems carried out in Brazil showed that shallow ponds in series, even at short HRT, are able to produce effluents complying with the WHO guidelines for unrestricted irrigation in respect to coliforms concentration (lower than 1000 MPN/100 mL). All polishing pond systems were able to produce effluents without helminth eggs, what is in compliance with the WHO guidelines for unrestricted and restricted irrigation ( $\leq 1$  egg/L, arithmetic mean).

Many UASB reactors combined with PP are located in India. Khan (2012) studied short HRT PP, 1d. The treatment performance was insignificant and merely running as settling tanks with a very limited algal activity. The BOD and TSS removal was generally found less than 50%. Due to very limited algal activity, coliform removal was also restricted to generally 1-2 log unit, however, helminth eggs were removed completely.

### 3.1.3. Constructed Wetland (CW)

The CW system for wastewater treatment is accepted as a technically and economically feasible alternative for small communities (Okurut et al., 1999). The systems used solid medium (sand, soil or gravel) to develop a natural processes under suitable environmental conditions that lead to the treatment of wastewaters. The plants are densely spaced and, together with the shallow water, provide habitats for animal, bird and insect communities. Vegetation in a wetland provides a substrate (roots, stems, and leaves) upon which microorganisms can grow as they break down organic materials. The most important functions of the plants are: (a) utilization of the nutrients and other constituents; (b) oxygen transfer to the solid medium; (c) support medium for bio-films on the roots and rhizomes (Sousa et al., 2001).

Sousa et al. (2001) investigated the demonstration scale wetland system for the treatment of effluent of UASB reactor for the removal of residual organic matter, suspended solids, nutrients (nitrogen and phosphorus) and fecal coliforms. The 1500 liter UASB reactor was operated at varied HRT (3h and 6h) while the effluent of the UASB reactor was treated in four units of CW, each 10 m long and 1.0 m wide, with coarse sand and operated in parallel under different hydraulic and organic loads. Macrophytes (*Juncus sp*) were planted in three CWs, whereas one CW was operated as a control unit without plants. The results revealed that the effluent COD from the four CW units had substantially constant concentration values,



indicating that there was no influence of varied hydraulic load applied and presence of plant in CWs on its removal efficiency.

The phosphorous removal was very efficient during entire period of study. The phosphorous removal was mainly due to the utilization by plants and microorganisms as well as adsorption and precipitation. In the CW without plants, the removal was due to precipitation and adsorption as well as assimilation by the bio-film developed on sand grains. The results indicated that there was no adverse affect of varying hydraulic load or retention time on phosphorous removal efficiency.

The nitrogen removal in the four CW units was satisfactory under variable operation conditions. The total nitrogen removal efficiency varied from 59% to 87% in wetlands containing microphytes. The two basic factors for the removal of nitrogen in wetlands containing microphytes were observed to be assimilation by plants and microorganisms present in wetlands and; probably nitrification due to transport of oxygen from atmosphere by plants. The results indicated that the presence of microphytes enhance the nitrogen removal efficiency significantly. The highest removal efficiency occurred in the unit with lowest hydraulic load corresponding to HRT of 10 d. The removal efficiency of fecal coliforms was observed to be very high in wetlands with microphytes. The increase in hydraulic load reduced the removal efficiency.

#### 3.1.4. Duckweed Pond (DP)

The aquatic macrophyte based treatment systems such as DP can be used to recover the nutrient and transformed them into easily harvested protein-rich by-products. The UASB effluents are highly rich in nutrient which should not be removed but, recovered. DP are covered by floating mat of macrophytes, which prevents light penetration into the pond resulting in shading. The high growth rates of the macrophyte permits regular harvesting of the biomass and hence nutrients are removed from the system. The produced biomass has economic value, because it can be applied as fodder for poultry and fish.

El-Shafai et al. (2007) evaluated the performance of a combined UASB and DP system (3 ponds in series). The UASB reactor had a volume of 40 liter and run at 6 h HRT while each pond had 1 m<sup>2</sup> surface area and 0.48 m depth. The HRT in each pond was 5 d providing total HRT of 15 d in all ponds. The DP were inoculated with *L. gibba*, obtained from a local drain, containing 600 g fresh duckweed per m<sup>2</sup>. The system removed 93% COD, 96% BOD and 91% TSS during warm season. Residual values of ammonia, total nitrogen and total phosphorus were 0.41 mg N/L, 4.4 mg N/L and 1.1 mg P/L, with removal efficiencies of 98%, 85% and 78%, respectively. The system achieved 99.998% FC removal during the warm season with final effluent containing 4 × 10<sup>3</sup> cfu/100 mL. During the winters, the system efficiently removal for COD, BOD and TSS was the same, but not nutrients and fecal coliforms. The coliform count in the effluent was 4.7 × 10<sup>5</sup> cfu/100 mL. The authors reported that the FC removal in DP was affected by the decline in temperature, nutrient availabilities and duckweed harvesting rate.

### 3.2. High rate physical chemical methods

#### 3.2.1. Chemically Enhanced Primary Treatment (CEPT) & zeolite column (UASB post treatment)

Aiyuk et al. (2004) proposed an integrated Coagulation and Flocculation- UASB- Zeolite column concept for the low-cost treatment of domestic wastewater. In this integrated treatment system, domestic wastewater is initially treated with CEPT using  $\text{FeCl}_3$  as a coagulant and polymer to remove suspended material and phosphorus, followed by UASB treatment to remove soluble organics. The effluent of UASB reactor was treated by regenerable zeolites to remove total ammonia nitrogen. The CEPT pre-treatment on average removed 73% COD, 85% SS and 80%  $\text{PO}_4^{3-}$ . The coagulation/flocculation step of this integrated system produced a concentrated sludge (8.4% solids), which can be stabilized in a conventional anaerobic sludge digester and used as fertilizer for agricultural purposes. After coagulation/ flocculation step, UASB reactor consequently received an wastewater with low total COD, approximately 140 mg/L and it was operated with volumetric loading rate of 0.4 g COD/L.day (HRT of 10 h) and 0.7 g COD/L.day (HRT of 5h). For these conditions, the system removed about 55% COD, thus producing an effluent with a low COD of approximately 50 mg/L ( $53 \pm 28$  mg/L). The zeolite removed almost 100%  $\text{NH}_4^+$ . The integrated coagulation / flocculation–UASB-Zeolite system effectively decreased the TSS and COD upto 88% and more than 90%, respectively. The nitrogen and phosphorus were decreased by 99% and 94%, respectively. The column of zeolite proved most beneficial due to very high removal efficiency of ammonia and the oxidation of residual organic matter. Pathogenic indicators (FC) levels were reduced from  $10^7$  cfu/L to  $10^5$  cfu/L, indicating a removal of 99%. The final effluent from the system can be used for crop irrigation or be discharged in surface waters.

Percolation of the UASB effluent through the zeolite ion exchange column resulted in an improved effluent quality (average final effluent total COD of  $45 \pm 6$  mg/L). Still it is possible that the overall integrated system effluent characteristics do not meet desired standards. But, the system operates at low costs, making it suitable for developing countries and rural areas. The final effluent can be used at least for crop irrigation. The recycling/ reuse or disposal of the side streams generated should be explored further and evaluated in future research, together with the energy recovering potential of the CEPT sludge.

#### 3.2.2. Dissolved Air Flotation (DAF)

Based on the results observed from the use of physico-chemical processes for sewage treatment DAF stood up to be an attractive alternative for the post treatment of UASB effluent. DAF system clarifies wastewater by removing floating suspended matter such as oil, fats or solids. The removal is achieved by dissolving air in wastewater under pressure and then releasing the air at atmospheric pressure in a flotation tank. The released air forms tiny bubbles which adhere to the suspended matter causing the suspended matter to float to the surface of the wastewater and form a froth layer where it may then be removed by a skimming device. The feed water to the DAF float tank is often (but not always) dosed with a coagulant (such as ferric chloride or aluminum sulfate) to flocculate the suspended matter. Penetra et. al. (1999) studied a lab scale DAF with previously coagulated effluent from a pilot scale

UASB reactor. Ferric chloride ( $\text{FeCl}_3$ ) was used as coagulant and dosages ranged from 30 to 110 mg/L with pH in the range of 5.3 to 6.1, varified with addition of lime. Best results were achieved at a  $\text{FeCl}_3$  dose of 65 mg/L. The DAF system was found efficient to reduce COD up to 91%, total phosphate up to 96% TSS up to 94%, turbidity up to 97% and sulfides more than 96%. The combined UASB-DAF system was observed to reduce 98% COD, 98% TP, 98.4% TSS and 94% Turbidity.

### 3.2.3. Two Stage Flotation and UV disinfection (TSF-UV)

The  $\text{FeCl}_3$  coagulant and cationic polymer used in DAF systems presents a fairly good removal efficiency of the UASB effluent, but these processes resulted in a significant volume of sludge. Tessele et al. (2005) investigated a pilot scale UASB (50m<sup>3</sup>/d flow) reactor followed by conventional two stage flotation and UV disinfection system for nutrient recovery. The proposed two stage flotation unit brings the advantage of separating the biomass and sludge that contain the phosphate and hydroxide. The suspended solids were removed by first stage flotation-flocculation (FF) process referred as F1 followed by second stage DAF referred as F2. Phosphate ions were removed by precipitation and coagulation. The removal mechanism in FF was the formation of small bubble and entrapped in flocs and these flocs floats over the water surface. In second flotation stage, both flocs and fine solids were aimed to removed. The concentration of  $\text{Fe}^{+3}$  and flocculant varied from 0 to 25 mg/L and 0 to 15 mg/L, respectively. The air flow in FF process was 3.0 L/minutes while DAF air flow rate 0.9 to 1.2 L/minute. The hydraulic loading rate was kept around 49 m/h at an HRT of 2 minutes in DAF, which is higher than in conventional DAF (6-10 m/h). After F2, the effluent was disinfected with low pressure UV lamp operated at a theoretical value of 25 mJ/cm<sup>2</sup>. The results present that the combined UASB-TSF-UV process is more efficient than UASB-PP system. The final effluent contained low COD, phosphate ion concentration, turbidity and air/ water surface tension is as high as that of tap water while the ammonia removal was insignificant.

### 3.2.4. Coagulation-flocculation

Feasibility of coagulation and flocculation as a post treatment process for the effluent of UASB reactor treating domestic sewage were studied by Jaya Prakash et al. (2007). Commonly used coagulants (alum, polyaluminium chloride (PAC), ferric chloride, and ferric sulphate) were used in a series of jar tests to determine the optimum coagulant dose. The optimum chemical dosage was 20 mg/L (as Al) for alum, 24 mg/L (as Al) for PAC, 39.6 mg/L (as Fe) for  $\text{FeCl}_3$  and 17.6 mg/L (as Fe) for  $\text{FeSO}_4$ . All the tested coagulants were found to be effective in reducing the effluent BOD and SS to less than 20 mg/L and 50 mg/L, respectively. However, coagulation-flocculation alone was not found sufficient to reduce the FC concentration to a permissible limit (1000 MPN/100 mL) for unrestricted irrigation. The final concentration of fecal coliform of UASB reactor effluent was 2300 MPN/100 mL using alum and PAC optimum doses. Moreover, the investigators suggested that disinfection by a chlorine dose of 1-2 mg/L with contact time of 30 minutes could reduce the FC concentration to below 1000MPN/100 mL after treating UASB effluent by coagulation-flocculation process. Further, higher doses of chlorine i.e. 3 mg/L removed all the FC from the sample after coagulation together with the above

mentioned optimum alum and PAC doses. However, 4 mg/L of chlorine dose was needed after coagulation with iron coagulants to remove all the FC.

### 3.3. Micro-aerobic methods (Including removal/ or recovery of dissolved gases)

The UASB effluent contains reduced organic and inorganic species and dissolved methane gas which can be removed by micro-aeration. Micro-aeration implies aeration of treated effluent for about 30 min. The role of micro-aeration is to strip off and to oxidize the reduced species such as sulfides, ferrous ions etc. which exert immediate oxygen demand and remaining easily biodegradable organic pollutants and to remove the dissolved methane gas. Generally, these systems have very short HRT and the amount of excess sludge generated is negligible. The simple physical micro-aeration can be sufficiently remove or strip off the dissolved sulfides or methane from the UASB effluent. However the removal of suspended solids is insignificant from this process.

#### 3.3.1. Down-flow Hanging Sponge (DHS)

DHS reactor was developed by Harada and his research group at Nagaoka University of Technology, Japan, for the aerobic post-treatment of the UASB effluent. In DHS, sponge cubes diagonally linked through nylon string have been used to provide a large surface area to accommodate microbial growth under non-submerged conditions. The wastewater trickled through the sponge cubes supplies nutrients to resident microorganisms. Oxygen is supplied through natural draught of air in the downstream without equipment. The system provides for dissolved methane gas to be recovered. Matsuura et al. (2010) investigated a two stage DHS system for the post treatment of UASB effluent in Nagaoka, Japan. Most of the dissolved methane (99%) was recovered by the two stage system, whereas about 76.8% of influent dissolved methane was recovered by the first stage operated at 2h HRT. The second DHS reactor was mainly used for oxidation of the residual methane and polishing of the remaining organic carbons. The removal of COD and BOD in the first stage was insignificant as there was no air supply; however, high removals were expected in the second stage due to sufficient supply of air, which is quickly oxidize the residual dissolve methane in the upper reactor portion before being emitted to the atmosphere as off-gas.

Agrawal et al. (1997) evaluated for the first time the performance of combined UASB reactor and DHS cube process. With post-denitrification and an external carbon source, 84% in average N ( $\text{NO}_3 + \text{NO}_2$ ) was removed with an HRT of less than 1 hour, for temperature range of 13 to 30 °C. The effluent contained a negligible amount of SS and total COD was only in the range of 10 to 25 mg/L. The DHS reactor was capable of stabilizing total nitrogen through nitrification, which ranged from 73-78%. In another study Machdar et al. (2000a & b) observed that the combined UASB+DHS system successfully achieved 96–98% of BOD removal, 91–98% of COD removal, and 93–96% of TSS removal, at an overall HRT of 8 h (6 h for UASB and 2 h for DHS unit). The complete system neither requires external aeration input nor withdrawal of excess sludge. The final BOD effluent concentration was 6- 9 mg/L. Similarly, FC removal was 3.5 log with a final count of  $10^3$  to  $10^4$  MPN/100mL in the effluent. Nitrification and denitrification in DHS accounted for 72% removal of total nitrogen (effluent concentration of 11 mg N/L) and

60% removal of ammonium nitrogen (effluent  $\text{NH}_4\text{-N}$  of 9 mg N/L) over the total operational period.

### 3.3.2. *Trickling Filter (TF)*

The TF consists of a fixed bed of rocks, gravel, slag, polyurethane, foam, sphagnum peat moss, or plastic media over which sewage or other wastewater flows downward promoted a layer or film of microbial slime to grow. Aerobic conditions are maintained by splashing, diffusion, and either by forced air flowing through the bed or natural convection of air if the filter medium is porous. The process mechanism involves sorption of organic pollutants by the layer of microbial slime. Diffusion of the wastewater over the media furnishes dissolved oxygen which the slime layer requires for the biochemical oxidation of the organic compounds and releases  $\text{CO}_2$  gas, water and other oxidized end products. Chernicharo and Nascimento (2001) studied the applicability of pilot level TF for polishing the effluent of UASB reactor. The volume of UASB reactor was 416 liter operated at an average HRT of 4h and the TF volume was 60 liters with blast furnace slag of 4 to 6 cm in size used as media. The operational conditions in the UASB reactor was kept constant throughout the study period while the TF was operated at three different phases, low, intermediate and high rate. The performance of UASB reactor was consistent, with removals above 70% in terms of BOD and COD. The final effluent quality was produced when the TF was operated as low and/or intermediate rate. Under these operational conditions the average COD, BOD and SS concentrations were 90, 30 and 30 mg/L, respectively and; hence, complying with the discharging standards. The system proved very efficient under low loading conditions. At high rate conditions the system was not efficient to remove the BOD, COD and SS. The results of this study showed that the TF can be used as the post treatment option for the treatment of UASB effluent for low organic and hydraulic rates in tropical countries.

### 3.3.3. *Micro aeration methods i.e. flash aeration*

For the last decade progress has been made on the use of high rate micro-aerobic methods for the removal or recovery of dissolved sulfides contained in anaerobic effluents. Besides, sulfide purging into the atmosphere, micro-aeration can also be utilized for biological oxidation of sulfides into elemental sulfur, which offers an excellent potential for reuse and it has been shown to be a cost effective alternative (Vallero et al., 2003; Chuang et al., 2005; Chen et al., 2010; Khan et al., 2011a and 2011c). The process is generally focused on the treatment of biogas, off-gas, natural gas or low strength wastewaters, like in the case of anaerobic effluents. In addition, micro-aeration of anaerobic system may be an option for increase hydrogen sulfide stripping and methane production (van der Zee et al., 2007). Buisman et al. (1990) developed a low-cost, high-rate biotechnological aerobic process for the oxidation of sulfide into elemental sulfur by a group of colorless sulfur bacteria, where the sulfide oxidation rate was dependent on the oxygen level. The biofilm on a reticulated polyurethane was more suitable to produce sulfate than a free cell suspension of biomass, for the same given oxygen and sulfide concentrations. For efficient achievement of elemental sulfur, high sulfide loads or low oxygen concentrations must be applied (Stefess et al., 1996). Vallero et al. (2003) utilized the micro-

aerated reactors for the oxidation of sulfides to elemental sulphur from the liquid phase of anaerobically treated sewage. The results were encouraging and partial conversion of soluble sulfides ( $\text{HS}^-$ ) into colloidal elemental sulphur was observed.

The produced element sulfur forms transparent globules of up to 1 micro-meter in diameter, which is deposited inside or outside the bacteria. An important issue is the recovery of the colloidal sulfur particles. Janssen et al. (1999) studied the properties of the colloidal sulfur particles and developed an up-side down cone expanded-bed bioreactor for spatially separation of the aeration and oxidation phases. After 50 days of operation 90% of the sludge settled at a velocity greater than 25 m/h and could be easily removed. Although the results are very encouraging, more studies on the application of high micro-aerobic systems for colloidal matter removal are necessary. One of the most promising technologies for sulfide removal from biogases is a two-step process where gaseous sulfide is dissolved into the liquid in the first step, followed by sulfide oxidation to elemental sulfur. Although little research has been conducted on the subject Chuang et al. (2005) treated a sulfate-rich wastewater in a UASB followed by a floated bed micro-aerated reactor. The floated bed was operated at short HRT (2.8 hours) and during long-term steady state operation results showed that almost all sulfides (>96%) was oxidized to elemental sulfur and sulfate. Annachatre and Suktrakoolvait (2001) observed a sulfide conversion higher than 90% at sulfide loading rates of 0.13-1.6 kg S/m<sup>3</sup>/d and at DOs lower than 0.1 mg/L sulfur was the major end product.

The simplest method of sulfide oxidation is the introduction of micro-aerobic conditions in the anaerobic reactor. Despite the toxicity exerted by oxygen against obligatory anaerobes, its moderate introduction is not expected to have a harmful impact to the biomass, mainly to the limited penetration depth of oxygen in biofilm. Van der Zee et al. (2007) determined the air injected to sulfide ratio to be 8-10:1 ( $\text{O}_2$ : S in mol units), which was sufficient to reduce the biogas  $\text{H}_2\text{S}$  content to undetectable levels. Element sulfur and sulfate were the main products.

#### 3.3.4. Continuous Diffused Aeration (CDA)

CDA system was investigated to treat the effluent of UASB reactor in India by several authors (Walia, 2007; Khan et al., 2011b; Khan, 2012). The treatment of sewage in a 60 L pilot scale UASB reactor followed by a CDA system and a full scale plant (111MLD capacity; UASB +Aeration+FPU) were investigated by Khan et al. (2011a). The HRT of CDA system was maintained at 15, 30 and 60 min HRT. During aeration at each HRT bulk liquid DO of 5-6 (high) and 1-2 (low) mg/L were maintained. The final COD, BOD and TSS effluent concentrations were 40-60, 25-35, 30- 40 mg/L, respectively, for operating under high DO (5-6 mg/L) and 30 minutes HRT and 30- 50, 18-30, 20-30 mg/L, respectively, at 60 minutes HRT. The combined reduction efficiency of the integrated UASB-CDA system at HRT of 30 and 60 min ranged from 80 to 85% COD, 85 to 90% BOD, 65-75% TSS. A conceptual model was developed wherein it demonstrated that the aerobic nature of the effluent depends on dissolved oxygen (DO), ORP and BOD. Anaerobic UASB effluent becomes aerobic if its BOD is reduced to less than 30 mg/L and minimum values of DO and ORP are observed, 4-5 mg/L and 120-135mV, respectively. Based on experimental results empirical correlations between BOD, ORP and DO have been developed and the results indicated a 50% reduction in BOD of the UASB

effluent at HRT of ~100 min. The removal of  $\text{NH}_4\text{-N}$  and total-P was insignificant at any of the maintained HRT. The Integrated UASB-CDA for sewage treatment could be recognized as a sustainable and cost effective option as the combined HRT of the system is still short (8 h for UASB + 0.25-1.0h for aeration, with a total HRT of 8.25-9.0 h). Existing UASB based STPs can be upgraded by installing continuous aeration system through fine pore diffuser and the energy produced by UASB reactor in terms of biogas could be used to operate the aeration system.

### 3.4. High rate aerobic methods (Including nitrification-denitrification steps)

The poorly biodegradable soluble matter, hazardous compounds or micro pollutants including ammonia-nitrogen and phosphorous present in the UASB effluent sometimes are difficult to be remove by micro-aerobic or simple settling. Therefore, secondary post treatment is required, following the micro-aerobic or settling treatment methods. A number of secondary post treatment processes have been categorized into methods responsible for the removal of (i) poorly biodegradable soluble matter including micro pollutant and hazardous material, (ii) finely dispersed organic matter i.e. colloidal and pathogens removal and (iii) ammonia-N and phosphorous. The removal of residual biodegradable carbon, ammonia nitrogen and phosphorous can also be achieved if the effluent of UASB is treated by high rate aerobic biological treatment methods.

#### 3.4.1. Sequential Batch Reactor (SBR)

The SBR is a fill and draw type modified activated sludge process, where four basic steps of fill, aeration, settle and decant take place sequentially in a single batch reactor. The operation of SBR can be adjusted to obtain aerobic, anoxic and anaerobic phases inside the standard cycles (Droste and Masse, 1995; Surampalli et al., 1997). Sousa and Foresti (1996) proposed a combined system composed of anaerobic-aerobic processes consisting a UASB reactor followed by a SBR. The system performance was evaluated through a bench scale set-up comprising of a 4 litre volume UASB reactor followed by two SBRs of 3.6 litres each. The UASB reactor was fed with partially mixed synthetic substrate in sewage while the SBR received effluent of UASB reactor. The HRT of 4h in UASB was maintained constant throughout the study while the 4h cycles in the following sequence of fill (0.10h), reaction (1.9h), sedimentation (1.6h), discharge (0.25h); idle (0.15h) were maintained in SBR. The combined system removed ~85% total nitrogen through nitrification. The COD removal in UASB reactor was around 86% while in SBR around 65% of the remaining, thus, combined systems removed 95% (residual effluent COD of 20 mg/L). The performance of combined system was 96% in terms of TSS removal (residual effluent TSS of 9 mg/L) and 98% in terms of BOD removal (residual effluent BOD of 6 mg/L).

Torres and Foresti (2001) studied the effect of aeration on the performance of SBR treating UASB effluent. The UASB reactor was operated at a constant HRT of 6 h while the SBR performance was monitored at four different duration cycles (24, 12, 6 and 4 h) corresponding to aeration times (AT) of 22, 10, 4 and 2 h, respectively. The overall removal efficiencies of COD and TSS were 91% and 84%, respectively and observed independent of aeration time given in the SBR. However, the nutrients removal was found to be dependent on aeration time. Total

nitrogen removal of approximately 90% was achieved for AT longer than 10 h; complete nitrification occurred for AT longer than 4 h; significant phosphate removal (72%) occurred only at the AT of 2 h. Moawad et al. (2009) also investigated the performance of the combined UASB-SBR system under different operating conditions for the treatment of domestic wastewater. The retention time in the UASB was changed from 4 h to 3 h and the aeration time in the SBR cycle varied from 2 to 5h, and then to 9 h. The observed average percentage removal for the three runs for COD, BOD and TSS was 94%, 97% and 98%, respectively. The residual COD, BOD, and TSS were 26, 5.8 and 5.0 mg/L, respectively. Complete nitrification of ammonia was achieved after 5 h aeration in the SBR. The average percentage removal of phosphorus reached up to 65%. Increasing the HRT in the SBR from 2 to 9 h caused a significant improvement in FC removal as the geometric count of FC was reduced to  $7.5 \times 10^2$  MPN/100mL in the effluent of the 3rd run (HRT 9 h).

Khan et al. (2011a) investigated the performance of a pilot scale integrated UASB-SBR system for treatment of sewage. Two different variant of SBR Process were investigated: a Continuous Flow-Intermittent Decant Sequencing Batch Reactor (CFID) and Intermittent Fill- Intermittent Decant Sequencing Batch Reactor (IFID) for about 18 months in conjunction with UASB reactor at ambient environment. Initially, the UASB-CFID system was operated at an HRT of 8h in the UASB reactor while it varied in CFID ( 20, 8 and 6 h), which also had different DO regimes, 4.0 to 5.0 and < 0.5 mg/L, 2.5-3.5 and < 0.5 mg/L and 2.5 to 3.5 and <0.5 mg/L, for the respectively HRT. The BOD and TSS removal efficiency of combined UASB-CFID system was up to 90%. The FC reduction was more than 99%. It was observed that average reactor MLVSS concentration reduced to around 30% at DO of 2.5-3.5 mg/L showing high degree of mineralization. Later, an integrated UASB followed by IFID system for the treatment of sewage was evaluated for the removal of organics and nutrient for more than six months at ambient conditions. The HRT in UASB reactor was maintained constant at 8 h. The IFID was operated at 6h HRT at DO concentration ranged between 2.5 to 3.5 mg/L. Results revealed that the removal of BOD, COD and TSS were 90, 95 and 90%, respectively in IFID. During higher organic loading conditions and low SRT, the removal of phosphorous was significantly higher than that of lower organic loadings and higher SRT. The suitable COD: P ratio of 105~160 helped for the effectively removal of phosphate. The total nitrogen removal was sufficiently good ranged from 80 to 95%.

#### 3.4.2. Activated Sludge Process (ASP)

Activated sludge process is the most widely used process for the treatment of sewage and industrial wastewaters. Atmospheric air is bubbled through wastewater combined with organisms to develop biological flocs which reduce the organic content of the sewage. The combination of wastewater and biological mass is commonly known as Mixed Liquor. von Sperling et al. (2001) monitored a pilot-scale plant comprising of an UASB reactor followed by an activated sludge system treating actual municipal wastewater from a large city in Brazil. The UASB reactor removed 69-84% COD, while ASP only removed remaining COD ranging from 43% to 56%, resulting in 85% to 93% removal achieved through the overall system (residual effluent COD of 50 mg/L avg.). The final effluent SS concentration was 13 - 18 mg/L. Therefore, UASB and ASP configuration was suggested to be a better alternative for warm-



climate countries than the conventional activated sludge system alone, considering the total low hydraulic detention time of 7.9h (4.0 h UASB; 2.8 h aerobic reactor; 1.1 h final clarifier), offering the advantages in terms of savings in energy consumption, absence of primary sludge and possibility of thickening and digesting the aerobic excess sludge in the UASB reactor itself.

### 3.4.3. Rotating Biological Contactors (RBC)

A RBC consists of a series of closely spaced circular disks of plastic material such as polystyrene mounted on a shaft that are partially submerged (typically 40%) in wastewater. The microorganisms grow on the surface of circular disks which breakdown and stabilize organic pollutants in presence of oxygen obtained from the atmosphere as the disks rotate. The development of excessive biofilm growth and sloughing problems besides odor and poor performance occurs when oxygen demand has exceeded the oxygen transfer capabilities and is the major drawback of this technology. These rotating biological contactors offer many advantages like the capability of handling a wide range of flows, low power requirements, low sludge production and excellent process control.

Tawfik et al. (2003) examined the removal of organic matter, nitrification and *E. coli* by UASB-RBC system at different operational temperature (11, 20 and 30°C) and at different organic loading rates with constant HRT of 2.5 h in the RBC. The results showed good performance of the system when operated at lower OLRs of 27, 20 and 14.5 g COD/m<sup>2</sup>/day at 11, 20 and 30°C, respectively. The residual COD values were 100, 85 and 72 mg/L for the respectively temperatures. Moreover, a high ammonia removal and low residual values of *E. coli* were found for the RBC at operational temperature of 30°C as compared to the situation for treatment of domestic wastewater and UASB effluent at lower temperatures of 11°C and 20°C. The effluent however, did not comply with WHO guidelines for unrestricted irrigation.

Tawfik et al. (2005) investigated the performance of a combined single stage RBC, two stage RBC and an anoxic up-flow submerged bio-filter followed by a segmental two stage aerobic RBC system. This study was carried out in order to assess the impact of biodegradable COD in an UASB effluent applied to the systems on the removal efficiency of different COD fractions, *E. coli*, ammonia and partial nitrate removal. The two (single stage) RBCs were operated at a constant HRT of 2.5 h and temperature of 21 °C but at different OLRs, 10 and 14 g biodegradable COD/m<sup>2</sup>/day due to varied UASB effluent qualities. The results clearly show that the residual values of COD, ammonia and *E. coli* in the final effluent are significantly lower at the lower OLR of 10 g biodegradable COD/m<sup>2</sup>/day. In view of the results it is recommend to use a single stage RBC system at OLR of 10 g biodegradable COD/m<sup>2</sup>/day and at HRT of 2.5 h for post-treatment of the effluent of UASB reactor operated at high temperature of 30 °C, as it generally prevails in tropical countries.

The performance of a single stage versus two stage RBC system for post-treatment of the effluent of an UASB reactor operated at a low temperature of 12 °C was also evaluated. Both systems were operated at the same OLR of 18 g biodegradable COD/m<sup>2</sup>/day and at HRT of 2.5 h. The results demonstrated that the COD fractions, ammonia and *E. coli* content in the final effluent of a two stage RBC system were significantly lower than the effluent of the single stage RBC system. Accordingly, results envisaged a two stage RBC system at an HRT of 2.5 h and

OLR of 18 g biodegradable COD/m<sup>2</sup>/day for post-treatment of the effluent of a conventional UASB reactor operating at a low temperature of 12 °C.

The nitrogen removal from the nitrified effluent was investigated using a biofilm system consisting of three stages, namely an anoxic up-flow submerged bio-filter followed by a segmental two stage aerobic RBC. The nitrified effluent of the second stage RBC was recycled to the anoxic up-flow submerged bio-filter reactor. The results obtained reveal that the introduction of an anoxic reactor as a first stage combined with recirculation of the nitrified effluent of the second stage RBC was accompanied with a conversion of nitrate into ammonia, at least in case the content of biodegradable COD in the UASB effluent was low. In such a situation the ammonia needs to be nitrified two times, which obviously should be avoided. Therefore in such situations of a too high quality anaerobic effluent in terms of biodegradable COD content, the introduction of a separate anoxic reactor for denitrification as final post-treatment step cannot be recommended.

#### 3.4.4. Aerated Fixed Bed Reactor (AFBR)

A sequence of denitrification reactor (DN), UASB, AFB and settling units treating sewage was evaluated by Sumino et al. (2007). The DN and AFB reactors contained sponge sheets media fixed to both the surfaces of the boards oriented vertically. The air was supplied to the AFB reactor from the bottom of the tank. Granular sludge obtained from food waste treatment plant was used as the inoculum sludge in the UASB reactor and activated sludge from a sewage treatment plant was used as the inoculum sludge in the AFB reactor. The SS recirculation from settling tank was made to the denitrification tank and the poly aluminium chloride PAC was injected to ABF for phosphorous removal. The whole system was studied for more than 300 days under constant HRT of 24 h in three different seasons, summer, autumn and winter. The performance of the combined system was satisfactory with final mean effluent values of soluble COD of 54, 66 and 65 mg/L in the summer, autumn and winter, respectively, while the mean total soluble BOD were 11, 18 and 25 mg/L for the corresponding periods. The information on nitrogen and phosphorous removal and indicators of pathogens was not discussed in this study.

#### 3.4.5. Submerged Aerated Bio-Filter (SABF)

The SABF system is composed of floating porous media through which wastewater and air flows from the bottom of the reactor. The airflow in the SABF system is always in upflow mode, while the liquid flow can be in upflow or downflow mode. These biofilters backwashed routinely at least once in 3 days. The development of thin, homogeneous and active biofilm layer is the main mechanism of biofilters to remove the soluble organic compound and suspended solids from the wastewater. Besides serving as support medium for microorganisms, the granular material also works as an effective filter (von Sperling and Chernicharo, 2005). Gonclaves et al. (1998) investigated an UASB reactor (46 L) followed by a SABF (6.3 L) for domestic sewage treatment. The floating and totally submerged granular medium in the SABF was made of S5 type polystyrene spheres with 3 mm diameter, 1200 m<sup>2</sup>/m<sup>3</sup> specific

surface area, 0.04 density and 0.50 m height. The air was injected in the SABF bottom, wastewater co-current through an air compressor.

In the study, the UASB reactor was initially operated at 8h hydraulic retention time and subsequently reduced to 6h and 4h. The 4h HRT in UASB reactor was maintained to investigate the performance of reactor under breakdown situation. Several authors recommended that the HRT in the UASB to be shorter than 5h in order to keep an adequate mechanization activity in UASB reactor (Vieira and Garcia Jr., 1992; van Haandel and Lettinga, 1994). However, the performance of the UASB reactor was stable and similar at all HRTs studied. The final mean removal efficiency of the combined system in terms of SS, BOD and COD were 94%, 96% and 91% respectively, which amounts to the final effluent concentration of 10 mg/L, 49 mg/L and 10 mg/L respectively.

Goncalves et al. (1999) studied the combined UASB-SABF system and observed similar results. The experiments were conducted with UASB reactor operated at HRT of 6 h without sludge recirculation and the bio-filter at HRT of 0.5 h. The average removal efficiencies of SS, BOD and COD were 95%, 95% and 88%, respectively, with final effluent quality of 10, 10 and 50 mg/L, respectively. Although the efficiency of the UASB-SABF system was satisfactory in terms of organic matter removal, the removal of the pathogenic microorganisms was very low.

Keller et al. (2004) investigated the combined UASB-SABF system followed by conventional and UV system to enhance the efficiency of the system to remove the pathogenic microorganisms. The results revealed that the 84% of COD (residual effluent COD of 78 mg/L), 86 % of BOD (residual effluent BOD of 26 mg/L) and 86% of TSS (residual effluent TSS of 23 mg/L) removal was achieved. The concentration of *E.coli*, *salmonellae* and *colliphages* were reduced to very low in the final effluent of the system. The association of UASB-SABF confirms the viability of the system with excellent final effluent quality of the system.

#### 3.4.6. Moving Bed Bio-film Reactor (MBBR)

Tawfik et al. (2010) investigated a laboratory-scale integrated UASB reactor followed by a MBBR for sewage treatment at three different combined HRTs, 13.3 (8+5.3), 10 (6+4) and 5.0 h (3+2) under temperature range of 22–35 °C for a period of 290d in Egypt. The working volumes of UASB reactor and MBBR were 10 and 8.0 L respectively. A cylindrical carrier media of 1.85 cm diameter and 1.8 cm long made of polyethylene was used in MBBR. Its specific gravity and effective specific surface area were 0.95 and 363 m<sup>2</sup>/m<sup>3</sup> respectively. The dissolved oxygen was maintained at 2.0 mg/L throughout the experiment. The performance of the integrated UASB-MBBR system was monitored in terms of COD fractions and FC. At the HRT of 5-10 h an overall reduction of 80–86% for total COD; 51–73% for colloidal COD and 20–55% for soluble COD was achieved. The removal efficiencies were increased up to 92, 89 and 80%, for total, colloidal and soluble COD respectively by increasing the HRT to 13.3 h. However, the removal efficiency of suspended COD in the combined system remained unaffected when increasing the total HRT from 5 to 10 h and from 10 to 13.3 h. This indicated that the removal of suspended COD was independent of the HRT. Final effluent total COD at three different HRTs were 54, 95 and 142 mg/L respectively. The final average FC counts were 8.9× 10<sup>4</sup>, 4.9×10<sup>5</sup> and 9.4×10<sup>5</sup> MPN/100 mL, corresponding to overall log reduction of 2.3, 1.4 and 0.7 respectively. The main

mechanisms observed for the removal of FC were adsorption into the media and predation by higher microbes such as protozoa and metazoa.

The removal of ammonia nitrogen was also investigated in MBBR. The results revealed that the removal of ammonia nitrogen greatly depends on organic loading rate. About 62% of ammonia nitrogen was removed at OLR of 4.6g COD/m<sup>2</sup>/day but the removal efficiency decreased by 34 and 43% at the higher OLRs of 7.4 and 17.8g COD/m<sup>2</sup>/day, respectively. Nitrogen was mainly reduced by assimilation into biomass and denitrification in anoxic zone in the biofilm. The sludge produced by MBBR showed poor settleability, however, the combined system still produced less sludge compared to conventional ASP. The authors reported that the integrated UASB-MBBR system at an HRT of 8 and 5.3 h are technically feasible for sewage treatment.

### 3.5. Final polishing techniques

To achieve nearly complete removal of pathogens, color and hazardous compounds the UASB effluent needs to be polished after the micro aeration first step or secondary post treatment such as high rate aerobic treatment before reusing for intended purpose or discharging it into receiving water bodies.

#### 3.5.1. Membrane technology

Recently large number of membrane technologies was investigated for secondary and tertiary treatment of sewage. Therefore, in order to achieve the quality of treated effluent up to reuse standard from UASB reactor, YingYu et al. (2009) evaluated the pilot scale cross flow membrane filtration system for polishing the UASB effluent treating low strength sewage in Singapore. A pilot scale UASB reactor (34 litres) was coupled with a side stream membrane module having a centrifugal pump to feed the effluent of UASB reactor into the membrane filtration unit. The HRT of UASB reactor was reduced from initial 10h to 5.5h after 119 days of operation and kept constant throughout the study period. The precise and constant holding tank was used prior to membrane filtration module unit in order to feed constant permeate flow rate. Results clearly showed high performance of UASB reactor for total solids removal at HRT of 10h which, however, significantly were reduced from 91.1 to 83.6% at HRT of 5.5h. At steady state conditions in the UASB reactor, the average TOC removal efficiency was 65% (10 h HRT), which increased to 81% by treating the effluent of UASB reactor through membrane filtration. But, the performance of this system in terms of TOC removal further increased to 73 and 85%, respectively at the HRT of 5.5h. This might be due to the increased up-flow velocity which provides better contact and distribution of wastewater with membrane. But fouling of membrane limits its use for the stated purpose. Therefore, extensive studies were required regarding it controlling factors such as membrane tube diameter and cross flow velocity etc.

YingYu et al. (2010) also proposed membrane filtration for the post-treatment of the effluent of UASB reactor in Singapore. The system comprised of UASB reactor and membrane filtration. The UASB reactor with working volume of 30 liter divided into two parts i.e. a sludge zone and a membrane zone. A gas/liquid separator was installed at the top of the sludge zone to

separate the biogas from the liquid suspension. Two flat-sheet membrane modules (0.22  $\mu\text{m}$ , PVDF, 0.1  $\text{m}^2$ ) were directly submerged into the upper membrane zone of the reactor above gas/liquid separator. The modules of flat sheet membrane were submerged into the UASB reactor to as a barrier to retain the suspended solids present in the effluent of UASB reactor at intermittent permeation and air sparging operating conditions. The whole system was operated at a constant HRT of 12 h at a temperature of 35 °C and no sludge was removed from the reactor, except for sampling. The experimental study was conducted in two phases with varied flux. In phase I, Intermittent permeation was studied at three different flux of 15, 20 and 25  $\text{L}/\text{m}^2/\text{h}$  with varied suction pressure while in phase II, air sparging was investigated at four different air flow rates of 0, 1, 2 and 4  $\text{L}/\text{h}$  with constant flux of 25  $\text{L}/\text{m}^2/\text{h}$ .

The average supernatant TOC was 10.88  $\text{mg}/\text{L}$  with fairly stable TOC removal efficiencies of over 89% during the whole operation. Finally this study influence that intermittent permeation was more effective for membrane fouling control compared with air sparging.

The coupling of membrane filtration with UASB represented as an efficient treatment technology for raw municipal wastewater at the ambient temperature. But limited studied are available on this system therefore, detailed investigations on demonstration scale.

### 3.5.2. Slow Sand Filtration (SSF) system

Various researchers investigated effect of hydraulic loading and sand size on the effectiveness of SSF for tertiary treatment of sewage at laboratory and pilot scale level and found that the SSF was capable of removing BOD, SS, turbidity and total coliforms up to 86%, 68%, 88% and over 99%, respectively (Ellis, 1987; Suhail, 1987; Sawaf, 1986, Adham, 1989; Gersberg, et al., 1989). However, limited data is available on the applicability of SSF on UASB effluent. Recently, Tyagi et al. (2009) studied the applicability of slow sand filter at lab scale as a post treatment option for the treatment of effluent of UASB reactor. The sand filter column operated at hydraulic loading rate of 0.14  $\text{m}/\text{h}$  was found to be most effective in removing turbidity (91.6%), TSS (89.1%), COD (77%), BOD (85%), TC (99.95%) and FC (99.99%). The average values of COD, BOD and SS in SSF effluent were 27  $\text{mg}/\text{L}$ , 12  $\text{mg}/\text{L}$  and 20  $\text{mg}/\text{L}$ , respectively. The FC concentration was found below the standards set by WHO 1989 (1000 MPN/100 mL). It was concluded that slow sand filters can be effectively runs upto 7 days at a hydraulic load of 0.14  $\text{m}/\text{h}$  as compared to the common hydraulic load of 0.19  $\text{m}/\text{h}$  and 0.26  $\text{m}/\text{h}$ . Hence, slow sand filtration could also be an effective technology for the post treatment of UASB reactor effluent, where treated effluent can be reuse safely for irrigation and other non-potable reuse purposes. However, the major drawback of SSF system was the frequent cleaning and maintenance requirement.

## 4. Discussion

The installation of post-treatment system to treat the effluent of UASB reactor treating sewage is a challenging task as to find a proper, reliable and efficient system, that is easy in operation and maintenance; technically feasible, and economically viable (Chernicharo, 2006). Amongst

all post treatment systems, four natural wastewater treatment systems were extensively investigated as the post treatment units. The effluent quality of the polishing ponds in series satisfies the effluent pathogen disposal standards, but it has few disadvantages such as large land requirement, poor nutrient removal, odor related problems and occasionally high BOD and TSS concentrations in the effluent. The combination of polishing pond and duckweed pond, duckweed and algae pond system was reported to be very efficient but, large area requirement, low pathogens removal and high TSS concentration in the effluent were the main drawbacks of this system. The combination of polishing pond and coarse rock filter system give an effluent with high FC and occasionally high in BOD. In overland flow system for the treatment of effluent of UASB reactor under low organic loading rate, the performance was observed to be satisfactory, with low solids and organic matter concentration in the final effluent. However, helminthes eggs removal was insignificant.

The duckweed pond and constructed wetland system are also observed to be satisfactory in their respective performances but these systems are dependent on the temperature, hydraulic load, harvesting of plants, etc. Despite their good nutrient removal efficiencies these systems thought to be unable to bring down the effluent quality below discharging standards.

Four high rate physico-chemical processes were presented including CEPT- Zeolite Column system, DAF, TSF-UV and chemical coagulation-flocculation. These processes are capable to reduce organic pollutants and turbidity of UASB reactor effluent up to the level required to meet the reuse standards, but not the fecal coliforms. The other major drawbacks of these processes are high dose and cost of chemicals used, and large sludge volume generation. Further, these systems have only been evaluated on lab-scale models and no scaling up has been investigated so far.

The post-treatment of anaerobic effluents can be carried out by micro-aerobic processes such as flash aeration, trickling filters and DHS, where sulfides are oxidize back to sulfate, specially at low sulfide concentrations. The partial sulfides oxidation to elemental sulfur was observed from the application of these technologies for the anaerobic effluents containing low sulfides. However, the aeration has not been optimized.

Two broad categories of biological wastewater treatment systems were categorised under a high rate aerobic systems and extensive discussed, suspended and attached growth systems. Almost all suspended growth processes were found to be very promising. The SBR was found as one of the most suitable technology for the treatment of UASB effluent due to its high effluent quality with effluent BOD and SS concentrations lower than 10 mg/L. The nutrient removal was also efficient; besides the low energy consumption for aeration and low excess sludge production are other major advantages as compared to other aerobic suspended growth system. In the activated sludge process the final effluent quality follows the discharging standards but, the system requires relatively high energy and land area and, with no nutrient removal capabilities. The continuous aeration system for the treatment of UASB effluent would be able to reduce the BOD of UASB effluent to 50%, but rarely satisfies the effluent discharge standards.

Few attached growth biological treatment processes were also summarized. Among them DHS was reported as a promising technology which reduces the BOD and coliforms well below the effluent discharging standards. However, this process requires high initial investment (sponge cost), it clogs often and no nitrogen and phosphorous removal are observed. Another important attached growth process, RBC was extensively investigated at pilot scale level. The RBC was studied under different combinations, such as one, two, three stage RBC and combination of one, two stage RBC and anoxic biofilter followed by two stage RBC. The best performance was achieved by the post treatment of UASB effluent by a combined one stage RBC, two stage RBC and anoxic biofilter followed by two stage RBC system. The RBC is not very commonly used due to its wear and tear of mechanical moving parts. Additional pre-anoxic unit is required for nitrogen removal. Similarly submerged aerated biofilter systems were evaluated for the post treatment of UASB effluent resulting in high BOD and SS removal but, with no nutrient removal capabilities. Another attached growth process, trickling filter was also evaluated for the UASB reactor effluent. This system was able to maintain the effluent BOD, COD and TSS concentration in the permissible range, however, only under low loading conditions.

The most common physical process, slow sand filtration and membrane filtration as a post treatment unit were also discussed. The systems are able to reduce the physical, chemical and microbiological pollutants not only to the desired standards but, also to satisfy wastewater reuse criteria. However, there are few drawbacks, such as frequent clogging of the filter and membranes.

The performance and effluent concentration of different parameters of various combinations are summarized in Table 2.

Among all discussed post treatment systems few of the alternatives produce final effluent with low COD, BOD and SS concentrations. Between all aerobic post treatment systems presented the SBR was found to be the most compact method and it allows for the removal of nutrient along with residual COD. Scantly information is available in literature on coupling of the SBR with UASB. The major advantage of SBR over other aerobic systems is the system flexibility for BOD and nutrient removal.

Low cost sewage treatment technologies are generally preferred for developing countries. Therefore, it is most important to evaluate the treatment sequence keeping in view of total investment including capital cost, operation and maintenance cost and land requirement. A comparison has been made among UASB reactors and its few post treatment systems with conventional ASP system based on energy requirement and generation from UASB reactor i.e. energy audit of UASB reactor per MLD:

*The basis of energy audit of a MLD UASB:*

- Negligible energy requirement ~6 kW-h/MLD (only for initial pumping) (Tassou, 1988).
- Energy production in the form of Biogas (60-70% methane) - 50 m<sup>3</sup> biogas/MLD sewage treated (Arceivala, 1998).

Integrated systems	Effluent Concentration*						
	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	NH <sub>4</sub> -N (mg/L)	TN (mg/L)	TP (mg/L)	FC (MPN/100mL)
CEPT+UASB+Zeolite	32 (85)	45 (91)	24 (88)	0.3 (99)	0.5 (99)	0.5 (94)	1.0×10 <sup>5</sup> (99)
UASB+DAF	-	17 (98)	4 (98.4)	-	-	0.6 (98)	-
UASB+ Coagulation-flocculation	>20 (91)	>50 (87)	>30 (82)	-	-	-	4.3×10 <sup>3</sup> (99.9)
UASB+SSF	12 (92.6)	27 (91)	20 (91)	-	-	-	1.0×10 <sup>3</sup> (99.995)
UASB+ Polishing Ponds	24 (92)	108 (79)	18 (96)	20 (50)	25 (55)	-	5.8×10 <sup>2</sup> (99.999)
UASB+Constructed Wetlands	-	52 (82)	174 (65)	14 (70)	17.5 (70)	0.74 (89)	1.0×10 <sup>3</sup> (99.99)
UASB+ Duckweed ponds	14 (96)	49 (93)	32 (91)	0.41 (98)	4.4 (85)	1.1 (78)	4.0×10 <sup>3</sup> (99.998)
UASB+DHS	2 (99)	40 (94)	0 (100)	6 (80)	6 (89)	-	-
	9 (96)	46 (91)	17 (93)	18 (28)	28 (40)	-	3.4×10 <sup>4</sup> (99.95)
UASB+SBR	5.8 (97)	26 (94)	5.0 (98)	0 (100)	12.6 (77)	1.2 (65)	7.5×10 <sup>2</sup>
UASB+ RBC	-	43	-	2.2 (92)	-	-	9.8×10 <sup>2</sup> (99.9)
UASB+ Aerated fixed bed reactor	11 (93)	54 (83)	10 (94)	-	30 (21)	3 (40)	-
UASB+ Submerged aerated bio-filter	9.4 (96)	37.8 (92)	9.8 (94)	-	27 (36)	-	-
	26 (86)	78 (84)	23 (86)	-	-	-	4.1×10 <sup>5</sup> (99)
UASB+ Trickling Filter	17-57 (80-94)	60-120 (74-88)	<30 (73-89)	-	-	-	-
UASB+ Anaerobic Filters	<40 (85-95)	60-90 (85-95)	<25 (77-94)	-	-	-	-
UASB+ Overland Flow System	48-62 (53-83)	98-119 (77-83)	17-57	14-18	-	-	8.4×10 <sup>4</sup> - 2.4×10 <sup>5</sup> (99-99.9)
UASB+ ASP	-	50 (85-93)	13-18 (82)	-	-	-	-
UASB+ Flash Aeration System	22 (89)	57 (86)	47 (83)	-	-	-	5.0×10 <sup>3</sup> (99)

\*% removal efficiency in parentheses.

**Table 2.** Treatment Performance of various Integrated UASB Post treatment systems Treating Sewage (adopted from Khan et al. 2011a)

- The electricity produced from 1.0 m<sup>3</sup> of methane gas generated by UASB is 36,846 kJ at standard condition and approx.7.0 kW-h under field conditions, since 3600kJ is approximately 1 kW-h (Arceivala, 1998; Metcalf and Eddy, 2003).



- Energy saving through reduced diesel consumption by more than 70% by feeding methane gas into the Dual-Fuel Mode Diesel Engine (Arceivala, 1998).

*The basis of energy audit of a MLD aerobic post treatment system:*

- Energy requirement of Aerobic Process as the sole wastewater treatment process, including initial pumping is approximately 195 kW-h/MLD (Tassou, 1988).
- *Salient features of comparative energy consumption:*
- Energy requirement of post treatment aerobic system treating only 35% BOD (as 65% BOD removal takes place in anaerobic system) is  $195 \text{ kW-h/MLD} \times 0.35 = 68.25 \text{ kW-h/MLD}$
- Hence Total Energy Consumption of integrated UASB-Aerobic Process is  $(6 + 68.25) \text{ kW-h/MLD} = 74.25 \text{ kW-h/MLD}$  compared to 195 kW-h/MLD for the aerobic process only.

Based on existing waste and wastewater treatment technologies Lettinga (2008) suggested (i) a Natural Biological Mineralization Route followed by physico-chemical methods for achieving the quality of treated wastewater for reuse/ or intended purpose such as for irrigation, industrial reuse etc. and, (ii) decentralization of the sanitation and resource recovery and reuse, that is, a concept which incorporates environmental protection where the waste and wastewater transportation is kept at minimum level and where pollutants are brought to an acceptable value at the location.

#### **4.1. Solutions for sustainability treatment options**

Sustainable technologies must be needed in order to make sustainable lifestyle of the society and to protect environment. It is difficult to understand and to implement it due to lack of proper parameters which leads to ambiguously the targets or proposed actions taken by politicians and/ or policy makers. Moreover, the quantification of sustainability is vague. For instance, if government implementing extremely stringent standards for protecting the aquatic environment from pollution many question arises, like why a single country or region pursuing a paradisiacal natural environment while at the same time little if any money or technology is made available to contribute to the highly needed environmental improvement in less prosperous countries. These potential combinations can be considered as sustainable solutions if adopted based on NBMR (Khan et al., 2011a).

#### **4.2. Sustainable technology concept**

The superiority of sequential anaerobic – aerobic treatment systems over conventional aerobic is more profound with increase in sewage concentration. In countries of limited per capita share of water, like in Africa, Middle East and India the treatment of concentrated sewage via conventional aerobic system is highly expensive, especially with respect to operational costs (Khan et al., 2011a).

The advantages of introducing UASB reactor ahead of aerobic system is obvious, mainly in terms of sludge production and energy consumption. In view of the fact that aeration costs increase linearly with increasing organic loads, adopting the activated sludge system for

polishing of anaerobic effluents may not be the most sustainable option for concentrated sewage. Other aerobic systems, such as DHS, SBR and CFID type SBR for UASB effluents post treatment reviewed in this paper are promising options for sewage management at low cost, low land requirement and low sludge production. Moreover, the potential of nutrients recovery and pathogens removal in an aerobic post-treatment for UASB effluents is considerable and the effluent discharge standards established by various national and international environmental agencies can be achieved.

## 5. Conclusions

Numerous anaerobic/ aerobic treatment concepts were evaluated in this chapter. The best option observed for the sewage treatment was integrated UASB-SBR system. The organics, nutrients and pathogenic pollutant removal efficiency of the integrated treatment approach was capable to achieve the effluent with low BOD ( $\approx 5$  mg/L; 98 % removal), COD ( $< 25$  mg/L; up to 95% removal) and TSS ( $< 10$  mg/L; up to 98% removal) and nutrients (TN=4 mg/L; NH<sub>4</sub>-N=Nil; P=1 mg/L). Ammonium nitrogen and phosphorus levels were decreased up to 98% and 90%, respectively. Fecal coliforms levels fell to  $< 1000$  MPN/100 mL, indicating a significant removal of pathogenic indicators. Thus the final effluent from the integrated UASB-SBR system can be reused for unrestricted irrigation or be discharged safely into the surface waters. However, no information is available regarding the efficacy of integrated UASB-SBR system at full scale level for sewage treatment. The performance of existing UASB based STPs can be improved by installing any of the post treatment system demonstrated in this chapter. The energy conservation, resources recovery and carbon credit were the gaps that still need to be explored for the above suggested post treatment options so that a natural biological mineralization route or sequence can be utilized to make the integrated system a viable sustainable option for treatment of sewage and anaerobically treated effluents.

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