Chapter 5
Anaerobic Reactors Used for Waste Water Treatment

Abstract Different types of reactor configurations used for the anaerobic treatment of wastewaters are presented in this chapter. Anaerobic lagoon, anaerobic contact process, anaerobic filter, upflow anaerobic sludge blanket reactor, fluidized bed reactor, expanded granular sludge bed reactor, internal circulation reactor, anaerobic baffled reactor, membrane coupled high-rate and CSTR systems, anaerobic membrane bioreactors are being used.

Keywords Anaerobic reactors · Waste water treatment · Reactor configurations · Anaerobic lagoon · Anaerobic contact process · Anaerobic filter · Upflow anaerobic sludge blanket reactor · Fluidized bed reactor · Expanded granular sludge bed reactor · Internal circulation reactor · Anaerobic baffled reactor · Membrane coupled high-rate and CSTR system · Anaerobic membrane bioreactors

Many different types of reactor configurations, have been used for the anaerobic treatment of wastewaters (Allen and Liu 1998; Lee 1993; Speece 1983; Kosaric and Blaszczyk 1992; Lee et al. 1989). These are—anaerobic lagoon, anaerobic contact process, anaerobic filter, upflow anaerobic sludge blanket reactor, fluidized bed reactor, expanded granular sludge bed reactor, internal circulation reactor, anaerobic baffled reactor, membrane coupled high-rate and CSTR systems (anaerobic membrane bioreactors). Several variations in the basic designs have been proposed in the literature of which few made it to commercial scale application (McCarty 2001; Van Lier et al. 2015). Presently, the high-rate sludge bed reactors, i.e. UASB and EGSB reactors and their derivatives, are most widely used for the anaerobic treatment of industrial wastewater, having about 90% of the market share of all installed systems (van Lier et al. 2008). Their popularity for treating industrial wastewaters can be attributed to their ease of operation, compactness while using high VLRs at low HRTs (Rajeshwari et al. 2000; van Lier et al. 2008). Membrane coupled high-rate anaerobic reactor configurations are being studied in the recent years, because of the large amount of comparable knowledge from aerobic MBR operations and the application niche which exists for these systems (Dereli et al. 2012). Membrane assisted sludge retention ensures the accumulation of very slowly

P. Bajpai, *Anaerobic Technology in Pulp and Paper Industry*, SpringerBriefs in Applied Sciences and Technology, DOI 10.1007/978-981-10-4130-3_5

growing micro-organisms with inferior adherence properties, that are frequently required for the anaerobic treatment of toxic and recalcitrant wastewaters. Recently, van Lier et al. (2015), discussed the evolution of anaerobic sludge bed technology for the treatment of industrial wastewaters in the last forty years, focusing on granular sludge bed systems.

5.1 Anaerobic Lagoon or Covered Lagoon Reactor

Anaerobic lagoons are basically large unsophisticated, low-rate anaerobic reactors (Fig. 5.1). Anaerobic lagoon was first used in the food processing industry in Australia in the 1940s (Springer 1993; Simon and Ullman 1987; Lee 1993) and is the oldest low-rate anaerobic treatment process. It is not widely used in the pulp and paper industry. An anaerobic lagoon is a deep impoundment, essentially free of dissolved oxygen, which promotes anaerobic conditions. The process typically takes place in deep earthen basins, and such ponds are used as anaerobic pre-treatment systems. Anaerobic lagoons are not aerated, heated, or mixed (EPA 2006; Hamilton 2012; Saele 2004). The typical depth of an aerated lagoon is higher than eight feet, with higher depths preferred. Such depths reduce the effects of oxygen diffusion from the surface and allows anaerobic conditions to predominate. In this respect, anaerobic lagoons are different from shallower aerobic or facultative lagoons, making the process similar to that experienced with a single stage unheated anaerobic digester, except that anaerobic lagoons are in an open earthen basin. Furthermore, conventional digesters are typically used for sludge stabilization in a

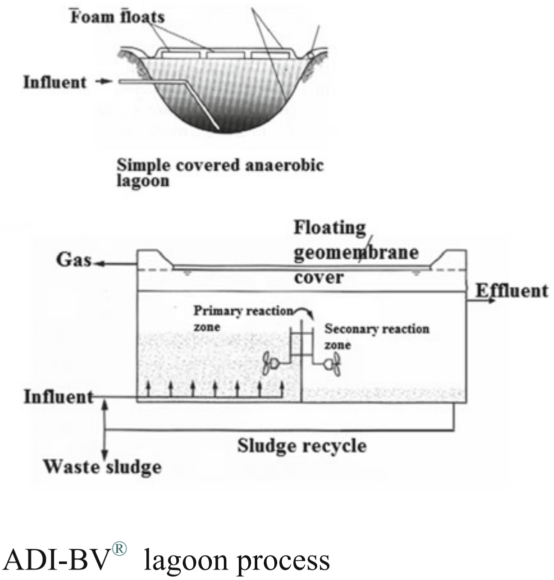

Fig. 5.1 Anaerobic lagoons. Based on mebig.marmara.edu.tr/Enve424/Chapter7.pdf

treatment process, whereas lagoons typically are used to pretreat raw wastewater. The operating cost is lower compared to other alternatives. It is also suitable for wastewaters that contain high levels of suspended solids or significant amounts of oil and grease. The accumulation of a settled biomass sludge results in a very long effective SRTs and maximizes the endogenous destruction of particulate to reduce the amount of sludge requiring disposal. Nutrients released from endogenous decay of the sludge become available for reuse by the active microorganisms. If the anaerobic treatment stage is followed by an aerobic treatment system, waste aerobic sludge can be returned to the covered lagoon for anaerobic digestion. Thus, the total quantity of biosludge requiring disposal from a compared anaerobic/aerobic treatment system is reduced. Periodically accumulated sludge may need to be removed from the process for final disposal. The in-ground construction and the insulated membrane cover allows long hydraulic retention times to be used in a covered lagoon system without greatly reducing process efficiencies due to heat loss. Typical HRTs in a covered lagoon may be between six and thirty days. Corresponding organic loading rates are usually less than 1 or 2 kg COD/m^3/day. The low-rate nature of the covered lagoon renders sludge settleability less important than in an anaerobic contact process. The large reactor volumes provide a good degree of equalization for toxics and organic shock loads. However, the process may suffer from mixing inefficiencies and non ideal contact between incoming wastewater and the anaerobic biomass. For many pulp and paper mill applications, minimum hydraulic retention times of 7–10 days would be required for achieving BOD_5 reductions in the range of 75–90%. Solid removal from the lagoon may be required at some time, depending upon the quantity of inorganic solids and the degradability of the suspended material in the influent. Table 5.1 shows the advantages and disadvantages of anaerobic lagoons.

5.2 Anaerobic Contact Reactor

The anaerobic contact process (ACP) was developed in 1950s and was first high rate anaerobic treatment system (Lee 1993). The first anaerobic contact process was reported for the treatment of dilute packing house waste having a COD of about 1300 mg/l (Schroepfer et al. 1955). The various versions of the first generation of these high-rate anaerobic contact process (ACP) systems for medium strength wastewaters were not much successful. The main difficulty was a poor separation of the sludge from the treated water in the secondary clarifier. Other problems were biogas formation and attachment in the settling tank (Rittmann and McCarty 2001). The poor sludge separation was attributed to the very rigorous agitation applied in the bioreactor, creating very small sludge particles having a poor settleability. In addition, super-saturation of solubilized gases resulted in buoyant upward forces in the clarifier. The idea of the very intensified mixing was to ensure optimized contact between the sludge and the wastewater. In the recent years, the ACP systems which have been developed use milder mixing conditions, whereas degasifying units are

Table 5.1 Advantages and disadvantages of anaerobic lagoons

Advantages
More effective for rapid stabilization of strong organic wastes, making higher influent organic loading possible
Produce methane, which can be used to heat buildings, run engines, or produce electricity, but methane collection increases operational problems
Produce less biomass per unit of organic material processed. This equates to savings in sludge handling and disposal costs
Do not require additional energy, because they are not aerated, heated, or mixed. Less expensive to construct and operate. Ponds can be operated in series
Disadvantages
Relatively large area of land is required
Undesirable odors are produced unless provisions are made to oxidize the escaping gases
Gas production should be minimized (sulfate concentration must be reduced to less than 100 mg/L) or mechanical aeration at the surface of the pond to oxidize the escaping gases is necessary
Aerators must be located for ensuring that anaerobic activity is not inhibited by introducing dissolved oxygen to depths below the top 0.6–0.9 m of the anaerobic lagoon. Another option is to locate the lagoon in a remote area
Relatively long detention time is required for organic stabilization due to the slow growth rate of the methane formers and sludge digestion
Seepage of wastewater into the groundwater may be a problem. This problem can be prevented by providing a liner for the lagoon
Environmental conditions directly affect operations so any variance limits the ability to control the process

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often equipped before the secondary clarification. The modern ACP systems are very effective for concentrated wastewaters with relatively high concentrations of suspended solids. According to van Lier et al. (2008), ACP have a consolidated market share within the full scale applied anaerobic high-rate systems. However, ACP effluents need a subsequent treatment step in order to comply with effluent restrictions.

Anaerobic contract reactor is an outgrowth of the anaerobic lagoon and is similar to the activated sludge process. Separation of the sludge from the settling tank is the critical factor for maintaining high biomass concentration and for operating the contact process. It consists of fully mixed anaerobic reactor and sludge settling tank (Fig. 5.2). A portion of the sludge is returned to the contact reactor to maintain high biomass concentration (3000–10,000 mg/l) in the reactor. Due to the recycling of sludge, the SRT can be controlled to be much longer than the HRT. Separation of the sludge from the settling tank is the critical factor for maintaining high biomass concentration and for operating the contact process. This system is suitable for treating effluents containing a high concentration of suspended solids. It can be operated at an organic loading from 1 to 2 kg BOD/m^3/day.

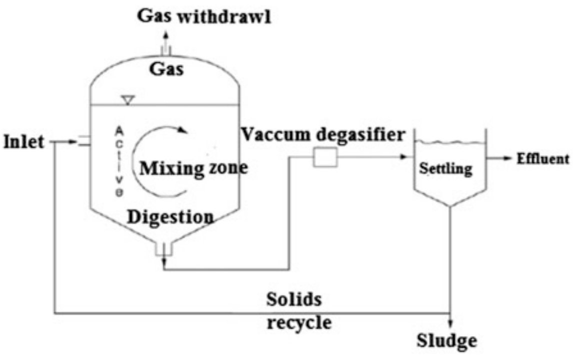

Fig. 5.2 Anaerobic contact process. Based on Agbalakwe (2011); mebig.marmara.edu.tr/Enve424/Chapter7.pdf

Anaerobic contact process can be applied to a wide range of wastewater concentrations. Although the lower economically practical limit of wastewater concentration is probably in the range of 1000–2000 mg COD/l, there is no well-established upper concentration limit. At very high wastewater concentrations, the completely mixed anaerobic reactor is the best alternative for efficient digestion while reducing internal reactor hydraulic inefficiencies. Wastewaters containing up to 100,000 mg COD/l can be treated in an anaerobic contact process as long as the anaerobic floc produced has satisfactory settling properties. In practice, the floc settleability can be diminished by the presence of high concentrations of dissolved solids. If the untreated wastewater contains significant concentrations of poorly biodegradable suspended solids, then a biomass recycle system can lead to the accumulation of inert solids in the reactor. Over long periods, the accumulation of inert material may cause the displacement of active anaerobic biomass from the process.

The treatment efficiency of an anaerobic contact process is usually much greater than that of a completely mixed digester. Total COD reductions of 90–95% are possible for highly biodegradable wastewaters with COD concentrations of 2–10 g/l. Typical organic loading rates in anaerobic contact systems are between 0.5 and 10 kg COD/m^3/day with HRT of 0.5–5 days.

5.3 Upflow Anaerobic Sludge Blanket Reactor

The upflow anaerobic sludge blanket (UASB) reactor was developed during the 1970s by Lettinga et al. (1976, 1979, 1980, 1987) in Netherlands. This is one of the most remarkable and significant developments in high-rate anaerobic treatment technology. It is basically a tank with a sludge bed (Fig. 5.3) (Gómez 2011; Lettinga et al. 1979). In this reactor, the mixing between sludge and the feedstock is obtained by an even flow distribution combined with a sufficiently high flow velocity and the agitation resulting from gas formation (Lettinga 1995; Duncan Mara 2003). The development of sludge into high-density granules results in the

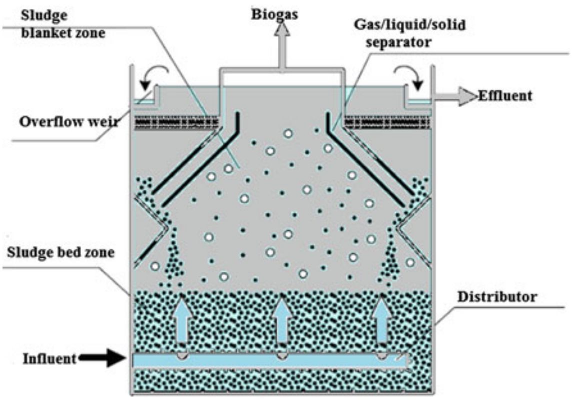

Fig. 5.3 UASB reactor. Based on Agbalakwe (2011)

formation a blanket or granular matrix, which is kept in suspension by controlled upflow velocity (Duncan Mara 2003).

The sludge retention in such a reactor is based on the formation of well settleable sludge aggregates (flocs or granules), and on the application of a reverse funnel-shaped internal gas–liquid–solids separation device. Many successful performance results have been reported at laboratory and pilot-scale applications using anaerobic granular sludge bed processes, which resulted in the establishment of thousands of full-scale reactors worldwide (Nnaji 2013; Lim and Kim 2014; van Lier et al. 2008). Undoubtedly, anaerobic sludge bed reactors, are by far the most popular anaerobic wastewater treatment systems so far, having a wide application potential in industrial wastewater treatment. The first UASB reactors were installed for the treatment of food, beverage and agro-based wastewaters, rapidly followed by applications for paper and board mill effluents in 1983 (Habets and Knelissen 1985). Most of the full-scale reactors are used for treating agro-industrial wastewater, but the applications for the treatment of wastewaters from chemical industries are increasing (van Lier et al. 2008; Rajagopal et al. 2013). The wastewater moves in an upward flow through the UASB reactor. Good settle-ability, low HRTs, high biomass concentrations (up to 80 g l^{-1}), effective solids/liquid separation, and operation at high VLRs can be achieved by UASB reactor systems (Speece 1996). The design VLR is typically in the range of 4–15 kg COD m^{-3} day (Rittmann and McCarty 2001). One of the major limitations of this process is related to wastewaters having a high suspended solids content, which hampers the development of dense granular sludge (Alphenaar 1994).

UASB can treat various concentrations ranging from 250 to 24,000 mg/l COD of wastewaters including various pulp mill effluents. The high biomass concentration also renders UASB to be more tolerable to toxicants. Loading rates generally range from 3.5 to 5 kg BOD/m^3/day and can be up to 8 kg BOD/m^3/day. UASB has several advantages compared with other high-rate anaerobic systems (Table 5.2). The capital costs for the UASB reactor are comparatively lower than for other anaerobic systems. A high loading rate means reduced reactor volumes

Table 5.2 Advantages of UASB reactors

Availability of granular or flocculent sludge, thus no requirement of a support medium
High biomass content, enabling a wide range of loading rates and high COD removal efficiency
Blanketing of sludge, enabling short hydraulic retention time and high solids retention time
Rising gas bubbles produced, eliminating the need of mixing and thus lower energy demand
Long experience in practice

Weiland and Rozzi (1991), Zoutberg and de Been (1997), Hickey et al. (1991)

Table 5.3 Challenges of UASB reactors

Start-up is susceptible to temperature and organic shock loads
Difficulties in controlling the bed expansions, thus limiting the applicable organic loading rates
Wash-out, flotation and disintegration of granular sludge
Performance deteriorates at low temperatures
High sulphate concentration
Necessity of post-treatment to reach the discharge standards for organic matter, nutrients and pathogens
Purification of biogas

Weiland and Rozzi (1991), Lettinga and Hulshoff Pol (1991), Li et al. (2008), Lew et al. (2011), Heffernan et al. (2011), Mahmoud et al. (2008)

and the separation of gas, liquid and solid often only needs to take place in one tank. Also, no support medium is required for attachment of the biomass. The UASB reactor has comparatively low energy, chemical and labour requirements. If the reactor is seeded with adapted granular sludge from another full-scale plant treating a similar waste, start-up can be very rapid. The challenges of UASB reactors are presented in Table 5.3.

5.4 Anaerobic Filter Reactor

The anaerobic filter (AF) (Hamilton 2012) are also known as the fixed film digester or packed bed digester. These reactors were already applied in the nineteenth century (McCarty 2001) but the application for industrial wastewater treatment started in the 1960s in the United States (Young and McCarty 1969; Young 1991; Young and Yang 1989). Since 1981, about 130–140 full-scale upflow AF installations have been put in operation for the treatment of various types of wastewater, which is about 6% of the total amount of installed high-rate reactors. The experiences with the system certainly are rather satisfactory; applying modest to relatively high loading rates up to 10 kg COD m^{-3} day^{-1}. AF technology has been widely applied for treatment of wastewaters from the beverage, food-processing, pharmaceutical and chemical industries due to its high capability of biosolids retention (Ersahin et al. 2007). The AF system will remain attractive for treatment of mainly soluble types of wastewaters, particularly when the sludge granulation process cannot occur satisfactory. On the other hand, long-term problems related to system clogging and the stability of filter material caused a decline in the number of installed full-scale AF systems.

This reactor relies upon a media substrate to retain the microorganisms within the reactor vessel, and the filter material is usually made from ceramics, glass, plastic, or wood (EPA 2006). As the growth of microorganisms requires relatively long periods of time to develop, their holding in the reactor by the media can facilitate the anaerobic digestion process (Gerardi 2003).

The AF has been developed as a biofilm system in which biomass is retained based on the attachment of a biofilm to the stationary carrier material; entrapment of sludge particles between the interstices of the packing material, and the sedimentation and formation of very well settling sludge aggregates (Fig. 5.4). AF technology can be applied in upflow and downflow reactors (Young and Yang 1989). Various types of synthetic packing materials, as well as natural packing materials, have been investigated in order to be used in AFs. These are gravel, coke and bamboo segments. Important aspects of the packing materials are shape, size, weight, specific surface area, and porosity. Also the surface adherence properties with regard to bacterial attachment are important. Applying proper support material, AF systems can be rapidly started, because of the efficient adherence of anaerobic organisms to the inert carrier. The ease of starting up the AFs was the main reason for its popularity in the eighties and nineties. Problems with AF systems generally occur during long-term operation. The major disadvantage of the AF concept is the

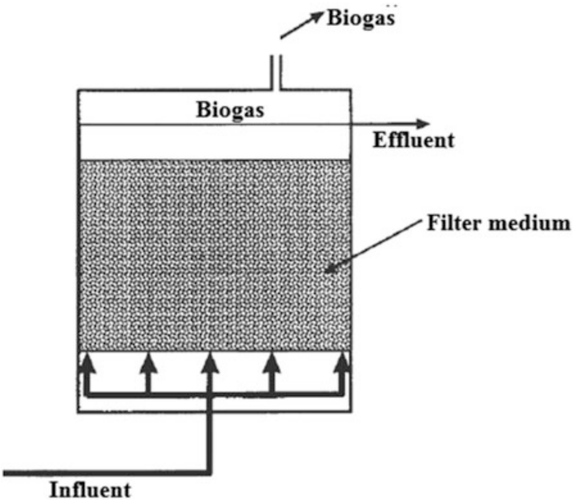

Fig. 5.4 Anaerobic filter. Based on Agbalakwe (2011); mebig.marmara.edu.tr/Enve424/Chapter7.pdf

difficulty to maintain the required contact between sludge and wastewater, because clogging of the "bed" easily occurs. This is particularly the case for partly soluble wastewaters. These clogging problems can be partly overcome by applying a primary settler and/or a pre-acidification step (Seyfried 1988). However, this would require the construction and operation of additional units. Moreover, apart from the higher costs, it would not completely eliminate the problem of short-circuiting (clogging of the bed), leading to disappointing treatment efficiencies.

5.5 Anaerobic Fluidized and Expanded Bed Systems

These reactors are regarded as the second generation of anaerobic sludge bed reactors which achieve very high VLRs. In the lab scale, 30–60 kg COD m^{-3} day^{-1} and at full scale: 20–40 kg COD m^{-3} day^{-1} have been obtained. The fluidized bed (FB) system can be regarded as an advanced anaerobic technology which may reach loading rates exceeding 40 kg COD m^{-3} day^{-1}, when operated under defined conditions (Moletta et al. 1994; Heijnen et al. 1990; Li and Sutton 1981). The FB process is based on the occurrence of bacterial attachment to non-fixed or mobile carrier particles, which consist, of fine sand, basalt, pumice, or plastic (Fig. 5.5). FB reactors are very efficient due to following reasons:

- Good mass transfer resulting from liquid turbulence and high flow rate around the particles
- Less short circuiting and less clogging due to the occurrence of large pores through bed expansion
- High specific surface area of the carriers make FB reactors highly efficient

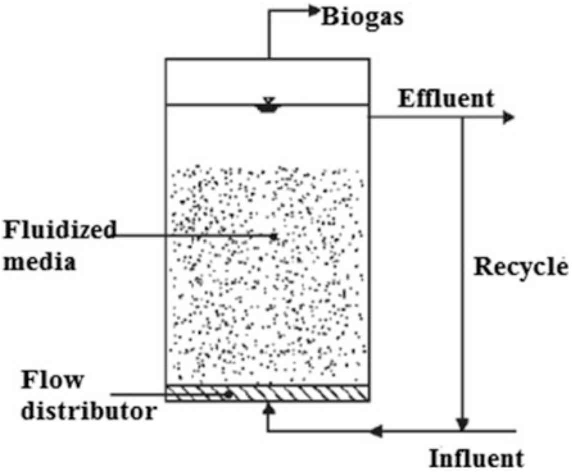

Fig. 5.5 Fluidized bed reactor. Based on Agbalakwe (2011); mebig.marmara.edu.tr/Enve424/Chapter7.pdf

Long-term stable operation however, appears to be problematic. The system depends on the formation of a more or less uniform attached biofilm and/or particles. Ehlinger (1994) has reported that to maintain a stable situation with respect to the biofilm development, pre-acidification is important and dispersed matter should be absent in the feed. Inspite of that, an even film thickness is very difficult to control and in many cases segregation of different types of biofilms over the height of the reactor occurs. In case of full-scale reactors, bare carrier particles may separate from the biofilms leading to operational problems. In order to sustain the biofilm particles in the reactor, adjustments of the flow are required, after which the support material will start to collect in the lower part of the reactor as a kind of stationary bed, while in contrast light fluffy aggregates will be present in the upper part of the reactor. Retention of these fluffy aggregates can only be performed when the superficial velocity remains relatively low, which is not the aim of an FB system.

Modern FB reactors like the Anaflux system depend on bed expansion instead of bed fluidization (Holst et al. 1997). The bed expansion allows a much wider distribution of prevailing biofilms therefore, the system is easy to operate. An inert porous carrier material is used for bacterial attachment in the Anaflux system. The reactor uses a triple phase separator at top of the reactor which is almost similar to the Gas liquid solids separator device in UASB reactors. When the biofilm layer attached to the media becomes excessively over-developed and the concerning aggregates subsequently collect in the separator device, the material is extracted from the reactor periodically by an external pump, in which it is subjected to enough shear to remove part of the biofilm. Then, both the media and detached biomass are returned to the reactor; the free biomass is then allowed to get washed out from the system. The density of the media is controlled in this way and a more homogeneous reactor bed is created. Up to 30–90 kg volatile suspended solids m^{-3}, reactor can be retained in this way and because of the applied high liquid upflow velocities, i.e. up to 10 m h^{-1}, an excellent liquid-biomass contact is achieved. The system can be applied to wastewaters with a suspended solids concentration of <500 mg/l. Most of the full-scale anaerobic FB reactors are installed as Anaflux processes. Nevertheless, at present, the EGSB reactors are much more of commercial interest for full scale applications than the more expensive FB systems (Driessen and Vereijken 2003). EGSB reactors can be defined as a modification of the UASB reactor in which the granules are partially fluidized by effluent recycle at a liquid upflow velocity of 5–6 m/h (Frankin and Zoutberg 1996). This reactor shows better mass transfer characteristics over the UASB reactor (Fig. 5.6) (Mutombo 2004).

A special version of the EGSB concept is the Internal Circulation reactor (IC) (Vellinga et al. 1986) (Fig. 5.7). The biogas produced is separated from the liquid halfway the reactor by gas/liquid separator device and conveyed upwards through a pipe to a degasifier unit. The separated gas is removed from the reactor and the sludge-liquid mixture drops back to the bottom of the reactor through a different pipe. This gas lift transport results to an improved contact between the sludge and wastewater (Vellinga et al. 1986; Pereboom and Vereijken 1994; Habets et al. 1997). The IC reactor can be considered as two anaerobic treatment compartments (like UASB) on top of each other, one highly loaded and the other with

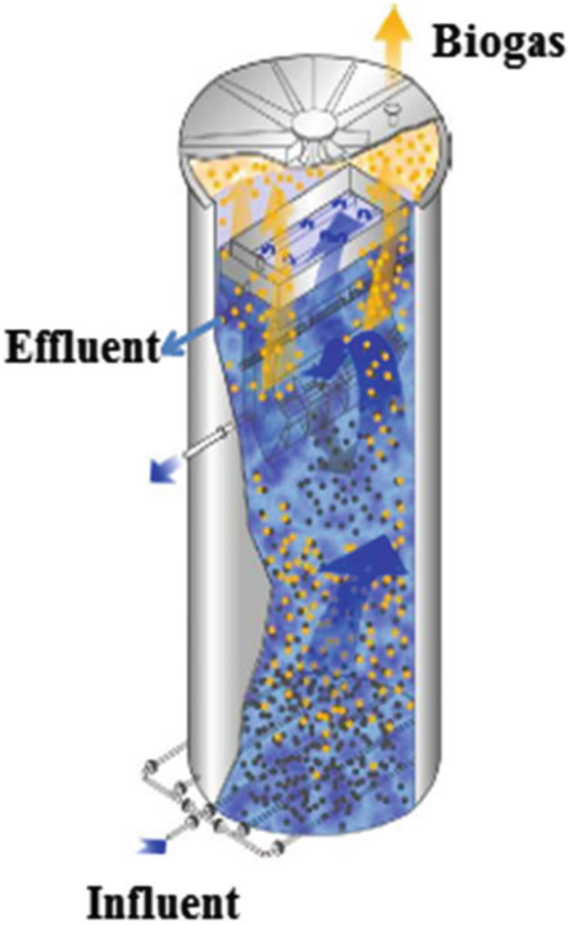

Fig. 5.6 EGSB reactor. Based on Wilson (2014)

low loading (Mutombo 2004). A special feature associated with the IC reactor is related to its highly efficient multi-level circulation system. The IC technology is based on the proven UASB process (Habets 2005). Typically, the loading rate of the IC reactor can be higher as compared to that of the UASB reactor (Driessen and Vereijken 2003).

5.6 Anaerobic Baffled Reactor

Anaerobic baffled reactor (ABR) is a high rate bioreactor (Fig. 5.8). It was developed by McCarty and co-workers at Stanford University. It is described as a series of upflow anaerobic sludge blanket reactors because it is divided into several compartments (Bachmann et al. 1985; Barber and Stuckey 1999; Zhu et al. 2015).

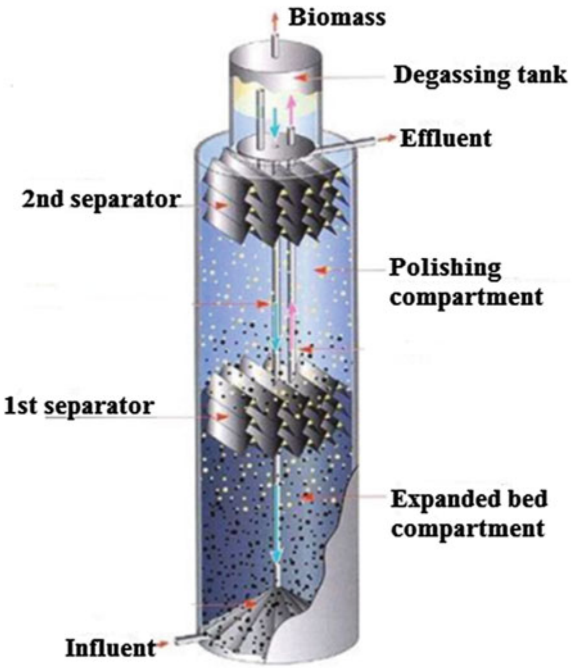

Fig. 5.7 IC reactor. Based on Wilson (2014)

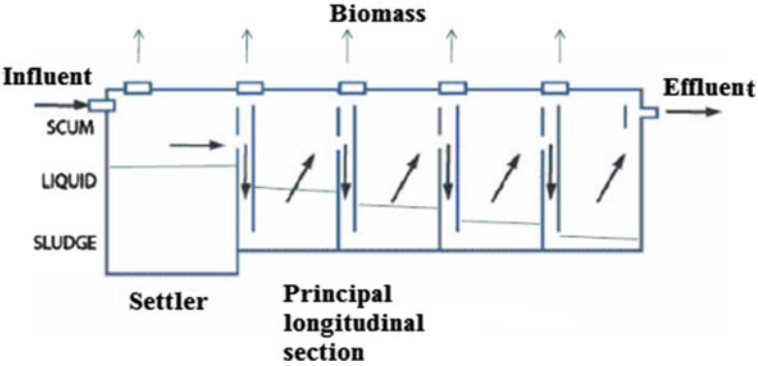

Fig. 5.8 Anaerobic baffled reactor. Based on Agbalakwe (2011)

A typical ABR consists of a series of vertical baffles which direct the wastewater under and over the baffles as it passes from the inlet to the outlet. The washout of bacteria is reduced. This enables the ABR to retain active biological mass without the use of any fixed media. The bacteria within the reactor rise and settle with gas production in each compartment, but they move down the reactor horizontally at a relatively slow rate, giving rise to a SRT of 100 days at a HRT of 20 h. The slow movement in horizontal direction allows wastewater to come into intimate contact with the active biomass as it passes through the ABR with short HRTs of 6–20 h (Bachmann et al. 1985; Barber and Stuckey 1999; Zhu et al. 2015). ABR has a simple design and does not require special gas or sludge separation equipment. This reactor can be used for almost all soluble organic wastewater from low to high strength wastewaters. It could be considered a potential reactor system for treating municipal wastewater in tropical and sub-tropical areas of developing countries considering its simple structure and operation.

5.7 Anaerobic Membrane Reactor

In the recent years a lot of research is being conducted on anaerobic membrane bioreactors (Fig. 5.9). Membrane technology is an interesting option in those areas where established technologies may not succeed. In Anaerobic Membrane Reactor (AMR), the size of reactor is reduced and organic loadings are increased due to higher biomass concentrations. Almost complete capturing of solids (much longer SRT) occurs which result in maximum removal of volatile fatty acids and degradable soluble organics resulting in better quality effluent. The greatest challenge in AMR is the organic fouling. This is typically caused by accumulation of colloidal materials and bacteria on the membrane surface. High liquid velocities across the membrane and gas agitation systems can be used to reduce membrane fouling. High pumping flow rates across the membrane may result in the loss of bacteria due to cell lysis. Developments in membrane design in the recent years and fouling control measures could make AMR a viable technology in future. Currently, only a few full scale AMR systems are in operation. But an increase in this emerging technology is expected considering the sharp drop in membrane prices (Henze 2008; Calli 2010).

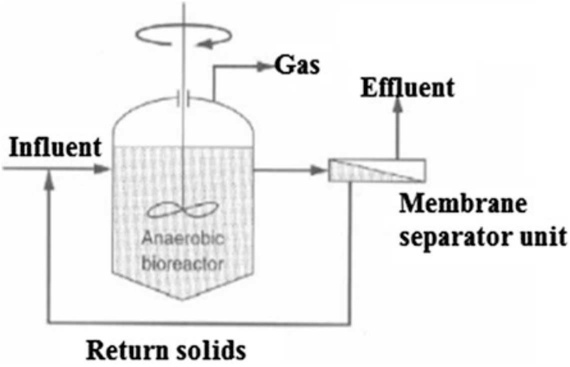

Fig. 5.9 Anaerobic membrane bioreactor. Based on Agbalakwe (2011); mebig.marmara.edu.tr/Enve424/Chapter7.pdf

5.8 Hybrid Upflow Anaerobic Sludge Blanket/Anaerobic Filter

Hybrid systems are designed to take advantage of special features of two or more process concepts (Fig. 5.10). Several hybrid reactor configurations which combine UASB/fixed media systems have been developed and evaluated in pilot plants or at full-scale (Lee 1993; Lee et al. 1989). As an example, where adapted granular sludge is not available, the UASB/fixed film hybrid may offer a faster startup than UASB alone. Development and entrapment of a flocculant anaerobic biomass, as well as growth of a fixed biofilm, normally proceed more rapidly than development and growth of granular sludge from an initial flocculant seed. Other features of the UASB/fixed film hybrid anaerobic reactor are—High overall reactor biomass concentrations than UASB alone, resulting in a small reactor volume; greater resistance to toxicity shock loads by having both a granular and a fixed film biomass; where biomass support media cost is high, the combination of processes may offer a capital cost advantage over an anaerobic filter alone, sized to achieve a similar treatment efficiency. The primary disadvantage may be eventual plugging of the fixed media operating in an upflow mode and the potential difficulty of optimizing two processes physically housed in a single vessel for a wide range of flow and loading conditions. Separation of the acid-forming and methane-forming phases into two stages, at least in theory, allows the design and operation of each phase to be optimized independently of each other. The facultative acid-forming bacteria in the first stage can provide significant protection to the more sensitive methanogenic strict anaerobes. This is particularly the case when the oxidants such as hydrogen peroxide are present in the wastewater.

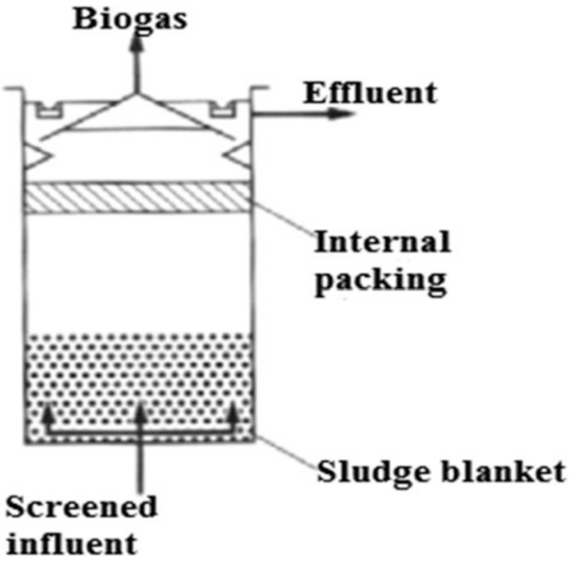

Fig. 5.10 Hybrid reactor. Based on Agbalakwe (2011); mebig.marmara.edu.tr/Enve424/Chapter7.pdf

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