Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.800809

52 (2014) 4122–4143
June

Taylor & Francis
Taylor & Francis Group

A review of the upflow anaerobic sludge blanket reactor

Chidozie Charles Nnaji

Department of Civil Engineering, University of Nigeria, Nsukka, Nigeria
Tel. +234 803 894 880 8; email: chidozie.nnaji@unn.edu.ng

Received 1 March 2013; Accepted 24 April 2013

ABSTRACT

The upflow anaerobic sludge blanket (UASB) reactor has found wide acceptance in the treatment of industrial wastewaters since its development in the Netherlands. It has been applied to a wide spectrum of wastewaters on both domestic and industrial scales. This acceptance stems from its simplicity, economy and the possibility of energy recovery. Studies focusing on UASB reactors are numerous; and though conflicting results have been observed, researchers are unanimous when it comes to the efficiency of the reactor in the treatment of high- to medium-strength wastewaters with easily hydrolysable substrate. It has also recorded a level of success in sewage treatment in tropical countries. As much, success has not been recorded in cold climates and in the treatment of wastewaters containing complex or toxic substance. The efforts of numerous researchers have given rise to many variants and modifications of the UASB reactor, which have widened the scope of applicability of this very important facility. This paper presents a concise but comprehensive review of the UASB reactor and studies focusing on it. Key operational issues such as granulation, methanogenesis, hydraulic retention time, efficiency, toxicity, modifications of UASB reactors and biogas recovery were considered using facts and data sieved from literature. This review shows that UASB reactors can be adapted for the treatment of almost any type of wastewater if modified accordingly.

Keywords: UASB; Granulation; Methanogenesis; Biogas; Sludge blanket; Bacteria

1. Introduction

The upflow anaerobic sludge blanket (UASB) reactor is a promising alternative for house-on-site treatment of domestic wastewater designed to overcome the inherent weaknesses of the conventional septic tank [1,2]. On an industrial scale, it has also found wide acceptance because of low sludge production, possibility of energy recovery, low hydraulic retention time (HRT) and high solids retention time. It is by far the most widely used anaerobic reactor for the treatment of industrial wastewater. In a worldwide survey of treatment facilities, UASB reactors constituted 739 (64.5%) of the 1,229 anaerobic treatment units [3]. It was found that Japan, Germany, Netherlands, USA and India were the leading countries in anaerobic wastewater treatment with 162, 115, 92, 83 and 79 anaerobic treatment facilities, respectively. The advantages of anaerobic digestion include low cost, operational simplicity, low sludge production and biogas production [4]. The operation and maintenance of a UASB reactor would require less than 1% of its capital cost per year [5]. Similarly, construction of a UASB reactor cost between 20 and 40 USD per capita as compared to 60 and 120 USD per capita for the conventional activated sludge system [6]; while operation and maintenance of a UASB reactor cost approximately 30% of that for an activated sludge reactor [5].

The UASB process does not require any packing media or support materials; however, it achieves high SS and chemical oxygen demand (COD) removal efficiency by means of highly settleable and active granular sludge layer. Unlike most other treatment units, UASB reactor is vertical flow, rather than the conventional horizontal flow (see Fig. 1). This type of operation improves the contact between anaerobic accumulated sludge and influent wastewater which, in turn, improves the removal of suspended solids due to entrapment of solid and of dissolved anaerobically biodegradable organic particles by the sludge blanket [7–9]. A three-phase (gas, solid and liquid) separator near the top of the reactor provides effective separation of biogas produced in the reactor, and also returns dispersed sludge to the sludge layer. The upward movement of gaseous products of anaerobic digestion generates enough turbulence to maintain the reactor content in a fluidized state. Though no external mixing is applied, the turbulence generated by the upward movement of gases makes the UASB reactor approach a completely mixed flow reactor [10]. However, this does not necessarily apply to UASB reactors treating low-strength wastewaters. Hence, internal mixing may not be optimal in reactors treating sewage when operated at low temperatures (<20˚C), partly due to high liquid viscosity at such temperatures [11] and poor biogas production. Singh et al. [12] observed that UASB reactors treating municipal wastewater at temperatures between 20 and 30˚C can be assumed to be completely mixed reactors with additional slow mixing; while those operating at much lower temperatures tend to posses plug flow hydraulics. Operational problems relating to poor mixing can also occur at the early stages of operation of UASB reactors due to inadequate gas production.

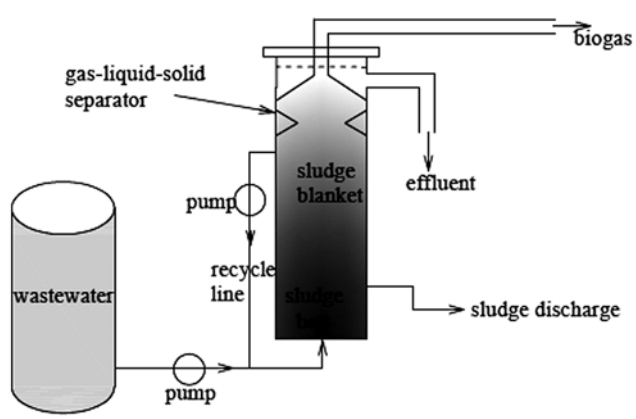

Fig. 1. Schematic of a UASB reactor.

Several reviews of anaerobic wastewater treatment exist in literature, the most recent of which are those of Chong et al. [13], Heffernan et al. [14] and Khan et al. [15]. The work of Chong et al. [13] was essentially an extensive comparison of various configurations, as well as the effects of certain additives on the performance of the UASB reactor. Khan et al. [15] did an extensive review and economic evaluation of a broad range of posttreatment options for effluents from UASB treating sewage. Heffernan et al. [14] studied 10 full-scale UASB reactors (seven in Brazil, two in India and one in the Middle East) treating sewage. However, this paper attempts to present a comprehensive review of several operational issues relating to UASB reactor process such as bacterial activities, granulation, treatment efficiency, inhibition/toxicity and biogas production, as well as variants of the UASB reactor available in the literature. Unlike those mentioned above, this review is not limited to sewage or domestic water treatment.

2. Bacterial activity in the USAB reactor

The efficiency of a UASB reactor is largely dependent on the health and activities of the microbial population in the reactor. The anaerobic stabilization of organic matter in a UASB reactor to form methane is a delicate and complex process involving hydrolytic, acidogenic, acetogenic, and methanogenic bacteria [16]. Hydrolysis is a rate-limiting stage which can be improved by mechanical, chemical and thermal pretreatments, and ozonation [17]. Hydrolysis is a temperature-dependent process which is favoured at thermophilic temperatures; while acidification is pH dependent, being favoured at an optimum pH of 6.0 and mesophilic temperatures between 34 and 36˚C [18,19]. The conditions such as short HRT and low pH that are favourable to the growth of acidogens are inhibitory to methanogens [19]. This observation does not hold for temperature, as it has also been found that activities of acidogenic and methanogenic bacteria under thermophilic (55˚C) conditions are about 1.8 and 1.6 times, respectively, as fast as under mesophilic (36˚C) conditions [20]. It was further observed that thermophilic digestion has the advantages of lower retention time, higher disinfection rate of pathogens and lower viscosity. However, the cost of maintaining UASB reactors at thermophilic temperatures should be critically weighed against the additional reactor efficiency. Most UASB reactors reviewed in the literature were operated at mesophilic temperatures, as can be observed from Table 2.

Methanogens are the only organisms that can metabolize acetate and hydrogen to gaseous end products [21]. They require a limited pH range of 6–8. The two classes of methanogens are those that metabolize methane from acetate, known as acetoclastic methanogens; and those that produce methane from hydrogen and carbon IV oxide, known as hydrogenotrophic methanogens [22]. Contrary to the observation of [16], it has been noted that organisms assumed to be acetoclastic are more abundant than organisms assumed to be hydrogenotrophic in most anaerobic systems [23]. These acetoclastic methanogens are in the order of *Methanosarcinales* (*Methanosaetaceae* and *Methanosarcinaceae*) while hydrogenotrophic methanogens are in the orders of *Methanobacteriales*, *Methanomicrobiales* and *Methanococcales* [11]. Table 1 shows the different species of methanogens found in UASB reactors by various researchers. *Methanosaeta* spp, utilize only acetate as substrate, have an optimum activity at a temperature of 37˚C and a pH of 7.8 and will show no activity at a pH below 6.8. On the other hand, *Methanosarcina* Spp form methane by utilizing different substrates in addition to acetate, and can tolerate a much wider range pH range of 5–8 and temperatures between 40 and 45˚C [24]. *Methanosaeta* Spp have an affinity to acetate which is 5–10 times higher than that of *Methanosarcina* Spp [25] and will, therefore, have higher growth rate at low acetate concentration. However, at high acetate concentration, *Methanosarcina* Spp will out-compete *Methanosaeta* Spp because of their higher pH tolerance in the acid range [16]. Hydrogenotrophic methanogens have been found to be more resistant to environmental changes, thriving at thermophilic conditions and high organic loading rate (OLR) or low HRT, and are more tolerant to acidic conditions than acetoclastic methanogens [26,27]. Acetoclastic methanogens are more sensitive to the presence of NH_3. It has been found that the specific growth rates of acetoclastic and hydrogenotrophic methanogens were halved at NH_3 concentrations of 4 g/L and 7.5 mg/L, respectively [28]. Hydrogenotrophic methanogens may have difficulty to compete with faster growing acetogens that also utilize hydrogen as substrate [29]. At low temperatures, homoacetogens out-compete hydrogenotrophic methanogens for hydrogen, forming acetate first, followed by methane production, as opposed to direct conversion from H_2/CO_2 to methane at high temperatures [13]. However, hydrogenotrophic methanogens have also been found to out-compete homoacetogens at low hydrogen concentrations [30]. Homoacetogens are strictly anerobic bacteria that catalyze the formation of acetate using H_2 and CO_2 as the sole source of energy. The environmental conditions favouring the predominance of certain species of methanogens over the others are varied, such that conditions favouring given species may be detrimental to some other species. Ordinarily, a competitive relationship exists between the different species of methanogens, hence any environmental imbalance will result in a competitive advantage of some species over some others. However, a balanced coexistence between acetoclastic and hydrogenotrophic methanogens is necessary for a successful operation of UASB reactors.

Table 1
Prevailing methanogens in UASB reactors

Type of wastewater	Prevailing methanogens	Ref.
Synthetic wastewater seeded with sludge from a UASB reactor	*Methanosarcina* sp., **Methanothrix* sp.	[31]
Landfill leachate	*Methanosaeta* sp.	[32]
Toluene	*Methanosaeta* sp. (dominant) *Methanosarcina*	[33]
Distillery wastewater	*Methanosaeta* sp. (dominant) *Methanobacteriales* sp. (subdued)	[25]
–	*Methanobacteriales* sp. (dominant) *Methanomicrobiales* sp. *Methanococcales* sp.	[34]
Synthetic wastewater with $AlCl_3$	*Methanosarcina* sp.	[35]
Synthetic wastewater seeded with sludge from anaerobic sewage digester	*Methanosarcina*	[36]
Starch, sucrose and fatty acid wastewaters	**Methanothrix* spp. (mostly)	[16]
Ethanol wastewaters	**Methanothrix* spp. *Methanosarcina* spp.	[16]
Synthetic wastewater with acetate, propionate, starch, sucrose, ethanol	**Methanothrix Soehngenii* (dominant) *Methanosarcina* sp.	[16]

Note: *The Methanothrix spp is now known as the Methanosaeta spp. [19].

Table 2
Studies on the performance of UASB reactors treating varieties of wastewater

Reference	Type of wastewater	Scale of UASBR	Inoculum	HRT (h)	pH	Temp (°C)	Max size of granules (mm)	OLR (kgCOD/m^3/d)	SMA or methane yield	Efficiency of removal (%)		Duration of study (days)	Start-up (days)
										COD	Others		
[31]	Synthetic ww	Lab scale	Anearobic sludge from a UASBR	36–12	8–8.4	27 ± 4	2.2–3.0	1.3–4 (stepped)	0.47–0.36 m^3CH_4/kg COD	97.4–98.1	–	≈125	–
[31]	1,1,2 trichloroethane	Lab scale	Anearobic sludge from a UASBR	36–12	8–8.4	27 ± 4	1.85–2.5	1.3–4 (stepped)	0.47–0.26 m^3CH_4/kg COD	84–96.6	–	≈125	–
[32]	Synthetic wastewater	Lab scale	Granules from a lab-scale UASBR	32	7.5–8.0	35	3.6	0.4–0.72	–	85.5–91.4	–	–	–
[88]	Molasses	Lab scale	Granular sludge stored at 4°C	23.7	7.6–7.8	35	–	3–30 (stepped)	0.88 gCH_4/gVSS.d (71.5%CH_4)	82–90	–	401	–
[89]	Azo dye ww	Lab scale	Sludge from lab-scale UASBR	24	4.8–6.3	35 ± 1	–	0.067–0.29	0.5–3.3 L/d	–	19–71	–	–
[90]	Brewery ww	Full scale	–	25	6.8–7	28–31	–	2.6	–	200	81–92	–	–
[91]	Domestic ww	Lab scale	Sludge from a UASBR	15	–	23.5 ± 0.51	–	2.7	–	32		33 months	7 months
[83]	ww containing sulphate	Lab scale	Sewage sludge from a UASBR	24	7.25	20	–	1.97	–	270	77	93.3 ± 1.5 (sulphate)	50
[62]	Latex ww	Lab scale	Non-granular sludge	96	6.8–7.2	30 ± 2	>0.8 (20%)	1	0.3 g COD/gVSS.d (3.34 L/d)	70	55	–	40
[62]	Latex ww	Lab scale	Granular sludge	96	6.8–7.2	30 ± 2	>0.8 (70%)	1	0.3 g COD/gVSS.d (2.4 L/d)	70	50	–	60
[62]	Latex ww	Lab scale	Non-granular sludge + $AlCl_3$	96	6.8–7.2	30 ± 2	>0.8 (47%)	1	0.3 gCOD/gVSS.d (2.65 L/d)	70	51	–	45
[84]	Poultry slaughter house	Lab scale	Non-granular sludge from poultry ww treatment plant	36–8	7.2–7.8	29–35	2.5	0.77–3.43 (stepped)	0.17 (gCH_4-COD/gVSS.d)	80	60–84 (TSS)	–	120
[76]	Domestic ww	Lab scale	Granulated sludge (source not specified)	7.3 (3.3)	7.4–8.1	–	–	≈0.4	1.8–7.1 L/d 62 ± 3% CH_4	76–86	70–92 (BOD, 30–35 (TS)	110	–
[25]	Distillery ww	Full scale	–	11.8d—2.5d	6.4–7.5	35–37	–	2.5–12 (stepped)	0.24–0.3 m^3CH_4/kgCOD	60–80	–	730	–
[67]	Wood fibre ww	Lab scale (100% UASBR)	Municipal activated sludge & manure	72–24	–	37	6.0	≈3–15 (stepped)	52% CH_4	58.5	–	6 months	–
[67]	Wood fibre ww	Lab scale (50% UASBR)	Municipal activated sludge & manure	72–24	–	37	6.0	≈3–15 (stepped)	48% CH_4	58.9	–	6 months	–

(*Continued*)

Table 2 (*Continued*)

Reference	Type of wastewater	Scale of UASBR	Inoculum	HRT (h)	pH	Temp (°C)	Max size of granules (mm)	OLR (kgCOD/m^3/d)	SMA or methane yield	Efficiency of removal (%)		Duration of study (days)	Start-up (days)
										COD	Others		
[87]	Distillery wastewater	Full scale	–	200	4.0–5.0	20–25	–	4–5.5	–	33–75	–	10 months	–
[21]	Synthetic ww + azo dye	Lab scale	Sludge from UASBR treating pulp ww	24	–	37 ± 2	–	1.8 ± 0.2	1.2 ± 0.1–1.31 ± 0.03 g/d (61%)	180	92 ± 3–67 ± 2	85–92 (colour)	50
[92]	Distillery ww	Full scale	–	–		–	–	6–11	0.15–0.3 m^3CH_4/kgCOD	>85	–	5yrs	–
[4]	Screened domestic ww	Lab scale	Not seeded	10–2	–	22–26	–	1.14–2.2 (stepped)	–	63	71 (BOD) 61 (TSS)	28wks	Not attained
[93]	Raw sewage	Lab scale	Seed from nitrifying plant	4	7.0–7.2	25	–	3.5	–	64	64 (TSS)	–	–
[94]	Congo red dye	Lab scale	Methanogenic sludge from Yeast Baker Factory	18.5–2.55	7	37	–	4.74–30 (stepped)	2–6 L/d	40–72	–	187	45
[85]	Synthetic ww	Lab scale	Non-granulated sludge from Yeast Baker Factory	2–0.25	7	35 ± 2	2.5	1.75–14 (stepped)	0.65–1.32 (gCH_4-COD/gTSS.d)	92	–	230	–
[82]	Acidified food waste	Lab scale	Sludge from a UASBR treating synthetic ww	2	5.5–6	35 ± 1	–	10	0.3 L/g.VS (68%CH_4)	74–93	77–99 (VFA)	16	Not attained
[36]	Syntheitic ww without $AlCl_3$	Lab scale	Sludge from anaerobic sewage digester	48–12	–	35	>4.0 (8%)	2–8 (stepped)	1.24 (gCH_4-COD/gVSS.d) (3.8 L/d)	>95	–	146	100
[36]	Syntheitic ww plus $AlCl_3$	Lab scale	Sludge from sewage anaerobic digester	48–12	–	35°C	>4.0 (11%)	2–8 (stepped)	1.1–3.4 (L/d)	>90	–	146	65
[43]	Synthetic ww	Lab scale	1/3 sewage, 2/3 industrial ww anaerobic digester sludge	–	6.9–7.5	35 ± 1	1.78	1–6 (stepped)	214–389 mL CH_4/gTSS /d	–	–	120	–
[57]	Synthetic ww	Lab scale	–	9.6	7	35 ± 2	–	11	0.33 L/d	67–97	–	400	–
[57]	Synthetic ww	Lab scale with modified settler	–	9.6	7	35 ± 2	0.7–4.8	11	0.25 L/d	81–97	–	400	–

(*Continued*)

Table 2 (*Continued*)

Reference	Type of wastewater	Scale of UASBR	Inoculum	HRT (h)	pH	Temp (℃)	Max size of granules (mm)	OLR (kgCOD/ m^3/d)	SMA or methane yield	Efficiency of removal (%)		Duration of study (days)	Start-up (days)
										COD	Others		
[95]	Synthetic ww + cyanide	Lab scale	Settled granular sludge from a UASBR	42.5 ± 8.8–11.8 ± 1.0	7	33	–	2.34–11.1	0.18–0.41 g CH_4/gVSS.d	283	10–85	–	83
[95]	Synthetic ww	Lab scale	Settled granular sludge from a UASBR	40.3 ± 7.9–12.8 ± 1.2	7	33	–	2.34–11.1	7–12 gCH_4/gVSS.d	283	50–95	–	83
[36]	Synthetic ww + $CaCl_2$	Lab scale	Sludge from a sewage anaerobic digester	48–12	6.8–7.5	35 ± 1	>4 (8%)	2–8	1.32–0.58 g COD/g. VSS.d	146	>90	–	45 ($CaCl_2$ > 300 mg/L) 80 ($CaCl_2$ < 300 mg/L)
[96]	Leachate from dead Birds	Lab scale	Sludge from brewery plant	–	7.5	35 ± 1	–	0.5–3	75% CH_4	–	–	–	–
[86]	Aircraft deicing fluid	Lab scale	Sludge from a winery ww UASBR reactor	72–12	–	35	–	1.7–38.7	0.66–15.1 L/d (70% CH_4)	75–98	–	90	–
[97]	Synthetic ww + heavy metals	Lab scale	Sludge from a winery UASBR	≈33	6.6–7	35 ± 1	2.3	–	–	3.2–40 mg CH_4/g VSS	–	–	–
[16]	Synthetic starch ww	Lab scale	Granular sludge from starch anerobic digester	10.9	6.9–7.3	37	>6	9	78.4 (%CH_4)	470	84	–	
[16]	Synthetic fatty acid (butyrate-propionate) ww	Lab scale	Granular sludge from starch anerobic digester	3.1	7.9–8.4	37	2	46	93.1 (%CH_4)	470	92.6	–	
[16]	Synthetic ethanol ww	Lab scale	Granular sludge from starch anerobic digester	4.3	6.5–7	37	≈4	36.5	89.1(%CH_4)	470	88	–	
[16]	Synthetic sucrose ww	Lab scale	Granular sludge from starch anerobic digester	7.1	7–7.3	37	≈6	12.2	81(%CH_4)	470	86.2	–	
[24]	Synthetic ww with acetate propionate	Lab scale	Municipal sewage sludge	–	7.5	30 ± 1	1.5	≈9	1.8 (g CH4-COD/gVSS.d)	>85	–	140	–
[24]	Synthetic ww with acetate propionate	Lab scale	Municipal sewage sludge	–	6	30 ± 1	1.0	≈8.5	1.3 (g CH4-COD/gVSS.d)	>85	–	140	–
[77]	Screened and clarified potato processing ww	Full scale	–	21.2	7.0	35	–	3.0	3,386,000 L/d	85	14 (TSS)	7wks	6 weeks

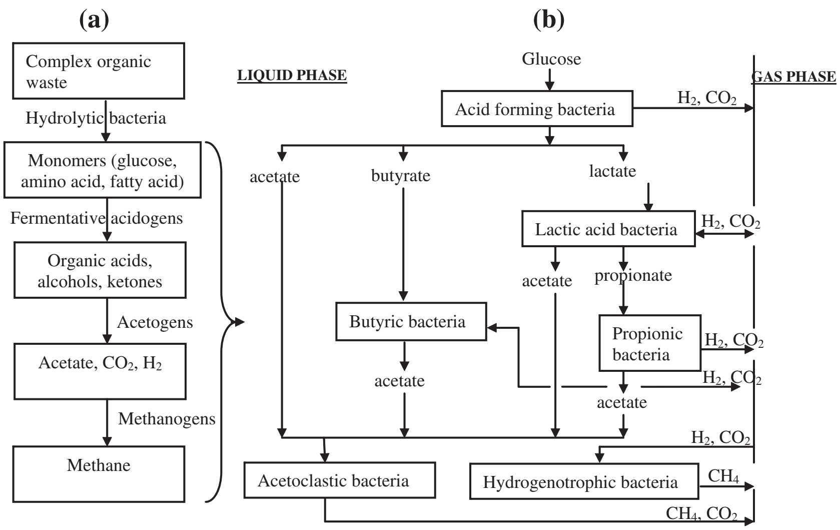

Fig. 2. (a) Simplified anaerobic process [39] and (b) Detailed processes in an anaerobic ecosystem [40].

The process of anaerobic digestion to produce methane is a multistage process in which various groups of organisms are involved. The stages and microbial groups involved in each stage have been illustrated as shown in Fig. 2(a). A more detailed anaerobic digestion pathway is shown in Fig. 2(b). Fig. 2(b) shows that anaerobic digestion in a UASB reactor is a very delicate and competitive process. Since there are several pathways for acetate metabolism, acetoclastic methanogens must keep pace with numerous populations of acidogens in order to maintain a balanced ecosystem and a stable reactor. Approximately, two-thirds of methane produced in an anaerobic reactor comes from acetate [29,37,38].

For an optimum performance of the UASB reactor, each stage of the process must progress uninhibited. Most hybrid UASB reactors are designed such that each stage of anaerobic digestion is optimized in a separate reactor. Higher efficiency of the anaerobic process can be achieved by separating the entire process into two or more stages [18]. The advantages of a multistage anaerobic digestion are: better stabilization of waste, lower reactor volume, higher biogas production, greater resistance to toxic shocks and higher disinfection ability [18]. One of the major concerns for UASB reactor performance is the excessive accumulation of volatile fatty acids (VFA) due to the inhibition of methanogens. VFAs (acetic acid, propionic acid and butyric acid) together with alcohols, hydrogen and CO_2 make up the intermediate products of anaerobic digestion. VFAs are partly responsible for unpleasant odour in anaerobic reactors [41]. The accumulation of VFA is a sign of incomplete digestion, possibly due to inadequate HRT for methanogens to metabolize soluble COD, low operating temperatures or organic overloading. VFA accumulation reflects a kinetic uncoupling between acid producers and consumers and is typical of a stress situation, leading to pH depression and subsequent inhibition of methanogenesis [42]. The most predominant VFAs in UASB reactors are acetate, propionate and butyrate [43]. Fig. 3 shows the inhibitory effect of these intermediate products on acetoclastic methanogens. The optimum concentrations are 4,000, 6,000 and 1,000 mg/L for acetate, butyrate and propionate, respectively. Below these concentrations, acetoclastic methanogens (and consequently specific methanogenic activity) increase, but above these concentrations, these properties decline. The accumulation of VFA in the form of propionate followed by acetate and then butyrate has the most inhibitory effect on the UASB process.

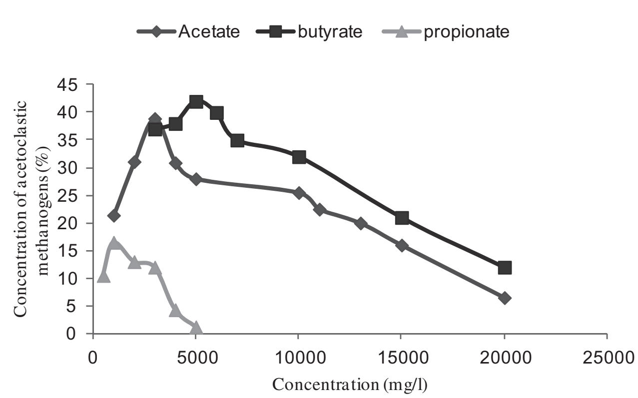

Fig. 3. The inhibitory effects of acetate, butyrate and propionate on methanogens (Illustrated with data from [43]).

Efficient conversion of VFA ensures that the pH of the reactor does not drop drastically. The predominant methanogen in a successful UASB reactor is the *Methanosaeta* spp because of the ability of these organisms to thrive at low acetate concentration. However, an accumulation of acetate will shift the predominant methanogens from *Methanosaeta* spp to *Methanosarcina* spp which are more tolerant to low pH [16]. The specific growth rate of *Methanosaeta* under thermophilic conditions is about 2.5 times that in the mesophilic range [44]. Specific methanogenic activity (SMA) in a UASB reactor is reduced by the formation of excessively large granules. Where granulation has been accelerated by the addition of Ca^{2+}, accumulation of calcium deposits in the core of granules can also reduce methanogenic activity [35,45]. High concentrations of calcium deposits in sludge granules reduce sludge activity by making granules more of inorganic entities than active organic biomass. It has been observed that calcium concentrations as great as 6700 mg/L accumulated in granules are formed by the addition of $CaCO_3$ [35]. Though granulation was enhanced by the addition of $CaCO_3$, there was reduced SMA in the long run. Hence, the efficiency of UASB reactors is dependent on the degree of completion of the different stages of anaerobic digestion by the respective micro-organisms.

3. Granulation

Granulation is the physicochemical aggregation of active biomass to form higher density and more settleable sludge. The performance of UASB reactors is heavily dependent upon the rate and degree of granulation. Sludge granules are dense, multispecies and microbial communities and none of the individual species in the granular ecosystem is capable of degrading complex organic waste [46]. The merits of granular sludge have been summarized by [47] as follows: reduced possibility of washout, accelerated start-up of UASB reactors [48], high settleability ranging from 2 to 90 m/h [49], high growth rate of methanogens accompanied by high SMA [50], reduced operating cost and reactor volume [51], low sensitivity to inhibitors [52] and increased tolerance to oxygen [53]. Several granulation models have been proposed by various researchers. However, these models do not contradict one another but rather highlight different granulation mechanisms which are favoured by different conditions. The process of granulation can be summarized as transport, adsorption, adhesion and multiplication [54]. However, the very first step towards granulation is acclimatization of inoculum, followed by multiplication. A typical granule is characterized by predominantly *Methanosaeta* Spp, extracellular polymers (ECP), inorganic deposits and high rate of methanogenic activity as well as protein, polysaccharide and nucleic acid [55,56]; with a chemical formula of $C_7H_{12}O_{4.6}N$ or $C_{5.4}H_{9.3}O_{4.2}N$ [57]. ECPs are secreted by hydrogenotrophs and help initiate granulation by imparting greater negative charges to bacterial cell and sustain granulation by forming irreversible ECP matrices [58,59]. A typical granule contains 28–32% calcium, 18–21% phosphorus, 3–4% magnesium, 2–3% sodium, 0.5–1% potassium and 0.4–0.6% trace elements (Fe, Ni and Co) [16]. It is widely believed that stratification occurs in sludge granules with filamentous *Methanosaeta* Spp forming the core of the granule [60]. This postulation has been further extended to imply that granulation is initiated by the *Methanosaeta* Spp. However, it was observed that the predominance of *Methanosaeta* Spp at the core of granules is favoured by low concentration of VFA while high concentration of VFA results in granular cores consisting of a diverse bacterial population [59]. Hulshoff Pol et al. [51] noted that UASB granules consisting predominantly of *Methanosarcina* Spp cause operational problems and, therefore, recommended that UASB reactors should be started up with low acetate concentration which favours the growth of *MethanosaetaI* Spp.

The rate of granulation in UASB reactors determines the length of start-up period and also prevents washout of sludge due to upflow current. Granulation and physicochemical properties of granules are dependent on temperature [61], inert nuclei [49], multivalent ions such as Ca^{2+}, Mg^{2+} and Al^{3+} [36,62,63], wastewater composition, nature of seed sludge, essential nutrients, pH, alkalinity and reactor control parameters [64], OLR [65] and HRT. For aerobic granules, the optimum OLR for balance between biomass retention and starvation condition for successful development of aerobic granular is 4 kg COD/m^3 d while 8 kg COD/m^3 d has been shown to be too high, leading to disintegration and subsequent washout of granules [65,66]. However, for anaerobic granulation, large granules have been found to develop at an OLR of 15 kg COD/m^3 d [67]. Granular sludge is characterized by good mechanical properties, good settling properties, high activity and ability to withstand high loading rates [68]. The settling properties of anaerobic granules depend on the presence of ECP and cell surface hydrophobicity [65]. The effect of storage temperature on granular sludge has been demonstrated [43]. It was found that granular sludge preserved at 4°C had more structural stability than that stored at 24 and 35°C. The reduction in average particle sizes was 26.7, 37.9 and 33.9% for granular sludge stored at 4, 24 and 35˚C, respectively. This inability of sludge granules to maintain their structure and size has been attributed to the inhibition of enzymes at low temperatures, and lack of substrate under mesophilic conditions [43]. Granules preserved at 4˚C also exhibited higher rate of granulation than those preserved at 35˚C after initial decrease in median particle size, when used as inoculum in a new UASB reactor. The usual sludge washout observed in new UASB reactors inoculated with granular sludge can be attributed to this structural instability of preserved sludge. On the other hand, sludge stored near room temperature maintained high methanogenic activity [61].

Complete granulation can be achieved after about 60 days for UASB reactors inoculated with granulated sludge, irrespective of storage temperature, while it takes about 100 days for granulation to be completed in an uninoculated UASB reactor at an OLR of 6 kg COD/m^3 d. Maximum granulation (6 mm) has been observed after six months at an OLR of 15 kg COD/m^3 d [66]. ECP prefer to bond divalent cations due to the presence of more complexes [69]. Granulation has been reportedly enhanced by the addition of $CaCl_2$ concentrations between 100 and 300 mg/L [36,70,71]. The addition of $CaCl_2{\cdot}2H_2O$ slightly enhances the UASB process at an optimum concentration of 300 mg/L, accompanied by maximum biogas production [36]. The effect of $CaCl_2{\cdot}2H_2O$ on granulation was only visible within the first 60 days. Granules ranging from 0.2 to 0.6 mm have been found to develop within 30 days in a UASB reactor inoculated with 300 mg/L of $AlCl_3$ [36]. It took 65 days for an identical UASB reactor without $AlCl_3$ to achieve the same result (Fig. 4). Accelerated rate of granulation is initially accompanied by a corresponding increase in COD removal. The presence of Al^{3+} and Ca^{2+} only accelerate UASB reactor start-up but have a negative effect by inhibiting methane production in the long run due to the formation of very large granules, as illustrated in Fig. 4. Fig. 4 shows that SMA begins to decline as average granule size approaches 2 mm.

Contrary to the findings of [35,36], it has been reported that $CaCl_2$ concentrations of 300 mg/L do not enhance granulation and might even have inhibitory effects when the concentration approaches 500 mg/L [72]. The addition of 150 and 300 mg/L of $AlCl_3$ resulted in the formation of 0.8 mm granules in 21 and 14 days, respectively, while the addition of 150 and 300 mg/L of $CaCl_2$ resulted in the formation of 0.8 mm granules in 21 and 28 days, respectively [62]. There is no consensus on the exact concentration of $CaCl^{2+}$ that is optimum for granulation, but it has been demonstrated that low concentrations (up to 300 mg/L) of Ca^{2+} enhance granulation while high Ca^{2+} concentrations (above 500 mg/L) inhibit granulation. The addition of large doses of $CaCl_2$ and $AlCl_3$ is expected to affect the pH of UASB reactors, thereby retarding wastewater treatment. However, in the two cases cited previously, calcium oxide and sodium bicarbonate were used as buffers. Hence, no substantial effect on pH was observed when $CaCl_2$ and $AlCl_3$ were added. Accelerated granulation is usually accompanied by enhanced sludge settleability. Calcium promotes granulation by forming precipitates that serve as inert nuclei for microbial adsorption. An additional envisaged advantage of calcium in the granulation process is in the preservation of granules. Deterioration in the structural characteristics of preserved uncatalyzed granular sludge has been

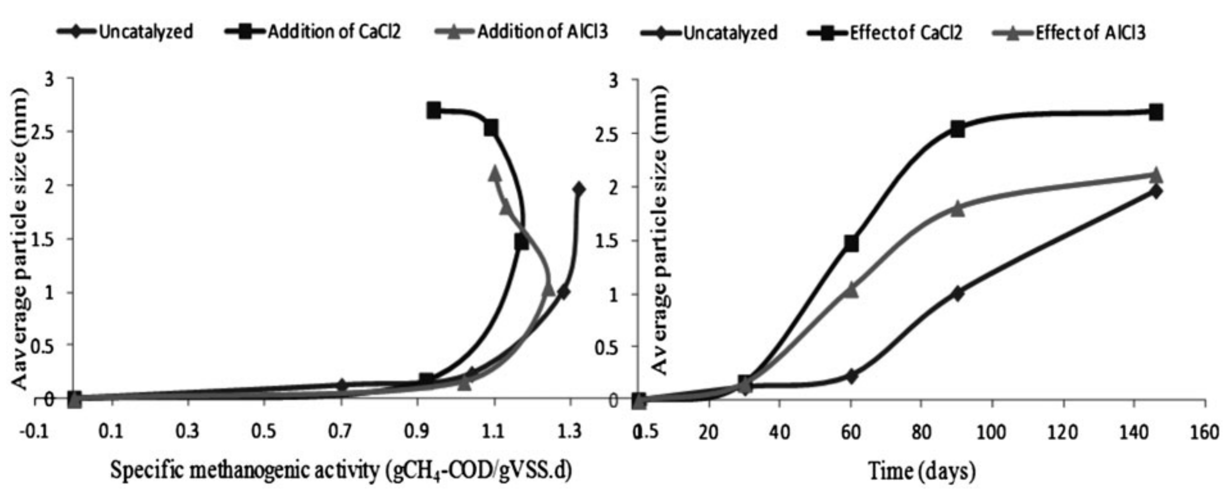

Fig. 4. The effects of 300 mg/L of $CaCl_2{\cdot}2H_2O$ and 300 mg/L of $AlCl_3$ on granulation and SMA (Illustrated with data from [35,36]).

reported [20]. The accumulation of calcium carbonate in granular sludge may help in preserving the structural integrity of granular sludges. Despite the gains of catalyzed granulation, the formation of excessively large granules can reduce COD removal efficiency and biogas production as well as give rise to sludge with poor settling characteristics, leading to sludge washout. Generally, SMA decreases in the long run where accelerated granulation is induced, due to the excessive sizes of granules which results in a reduction in the specific area of active biomass. The reduction in SMA (see Fig. 3) in the long run may result from the accumulation of inorganic substances in granules, thus reducing the concentration of active biomass. Lens et al. [73] demonstrated the abundance of inorganic precipitates in granules, mostly FeS, using back-scattering electron microscopy. They found a high concentration of FeS in the core of granules as well as randomly distributed small spots within the aggregates. Large granules also tend to possess a polymeric coat which traps evolved gases and thus make the granules fluffy [16]. The larger the granules, the more difficult it becomes for substrate to diffuse into the core of the granule, hence reducing the rate of bioconversion (see Fig. 5). Obviously, accelerated/catalyzed granulation has no long-term positive effect on the performance of UASB reactors. The belief that larger granules favour the performance of UASB reactors might have been based on studies of short durations. However, a contrary conclusion can be drawn from the work of [16] who operated four UASB reactors for 470 days. Fig. 5 shows inverse relationship between granule size on one hand, and methanogenesis and COD removal efficiency on the other hand. Fig. 5 in conjunction with Fig. 4 shows again that granule sizes above 2 mm result in reduced methane yield and COD removal efficiency. The reduced efficiency of the UASB process becomes more drastic as granule size approaches 6 mm. As granule size increases from 2 to 6.5 mm, COD removal efficiency drops by 9.3% while methane yield drops by 15.8%.

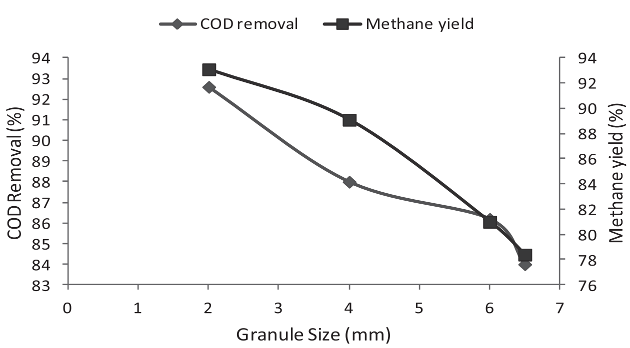

Fig. 5. Effect of large granules on COD removal and methane yield (Illustrated with data from [16]).

Early formation of granules shortens the length of time required for UASB reactors to start-up. While catalyzed granulation might accelerate UASB reactors start-up, formation of very large granules reduces the long-term efficiency of the reactor; hence, studies focusing on optimizing substrate diffusion have been conducted by researchers. However, such studies are not as abundant as studies focusing on the granulation process in UASB reactor. Van Lier et al. [74] observed that overall mass transfer can be increased by crushing the granules, leading to a decrease in the distance required for diffusion. Lens et al. [73] observed that heat exposure strongly increases (20–35% at 70°C) the self-diffusion coefficient of H_2O within methanogenic aggregates. However, Glutaraldehyde reduced self-diffusion of H_2O by 20%, whereas $HgCl_2$ did not alter the self-diffusion coefficient compared to untreated aggregates. They also observed that self-diffusion coefficient of H_2O was higher in the aggregates present at the bottom of a sludge bed, where substrate and nutrient-rich conditions prevail, than in the aggregates present at the top of a sludge bed, where lower substrate concentrations prevail. It has been postulated that in addition to catalyzing granulation, Fe^{2+} can as well enhance substrate diffusion into granules by condensing the diffusive double layers of granules, resulting in relatively strong effect of van der Waal forces [45]. Factors affecting the actual depth of substrate diffusion into granules can be summarized as: (i) substrate concentration in liquid phase, (ii) density and distribution of active biomass, (iii) porosity of granules, (iv) size and shape of granules, (v) temperature which determines the maximum activity of biomass, and ash content [45,73,74].

4. Treatment efficiency

The efficiency of a UASB reactor is measured in terms of COD removal. Factors affecting the efficiency of UASB reactors include but are not limited to temperature, reactor design wastewater composition/type, mixing, pH, OLR, toxicity, upflow velocity, size and composition of granules and bacterial activity [62,75,76]. The UASB process is favoured at mesophilic/thermopilic temperatures and a TSS concentration below 500 mg/L [77]; a limited pH range of 6.8–7.8 [78]; and a settling velocity above 50 m/h [54]. The recommended range of parameters for optimum performance of UASB reactor are: OLR of 15–20 Kg COD/m^3 d, a liquid velocity of 1.2–1.5 m/h, a reactor height less than 6 m, a superficial gas release range between 1 and 3–5 m^3/m^2 h feed inlet distribution area of 7–10 m^3/inlet, a wall settler inclined at 50° and an average flow through aperture between gas collector below 2 m/h [49,79]. Table 2 shows that UASB reactors have been successfully applied to the treatment of different kinds of wastewater. However, stronger wastewaters require lower OLR for efficient reactor performance. The two most important parameters affecting the performance of UASB reactors are sufficient upflow velocity and even distribution of influent across the reactor cross section [1,80]. The upflow velocity is a very important design parameter because only particles whose settling velocities exceed the upflow velocity will be retained in the reactor. Increasing the velocity of the influent into the UASB reactor can expand and disrupt the sludge bed in addition to suspension and subsequent washout of small solids and colloids [81]. Sludge washout occurs when upflow velocity exceeds 1 m/h [78]. However, the superficial liquid velocity can be made to reach 5–15 m/h by increasing the sludge loading rate and recycling the effluent using expanded granular sludge bed reactor.

Sixty-five per cent COD removal in a UASB reactor treating wood fibre wastewater at three days HRT and an OLR of 15 kg COD/m^3 d has been reported [68]. For UASB treating acidified food waste, up to 93% COD removal and 77–79% conversion of VFA have been recorded [82] As much as 93.3 ± 1.5% sulphate removal in a lab-scale UASB reactor at an optimum HRT between 20.4 and 21 h through the action of sulphate utilizing bacteria has also been achieved in a UASB [83]. Biological sulphate reduction was found to progress unhindered at low temperatures (20°C) and ensured that the pH of the reactor was maintained near neutral. UASB reactors have been found to be efficient in the treatment of very strong industrial wastewaters. It is worthy of note that most pilot and laboratory-scale UASB reactors reported in literature seem to have better efficiencies than full-scale UASB reactors, because pilot and laboratory-scale UASB reactors are operated at properly controlled conditions. Heffernan et al. [14] summarized the reasons for operational problems in some UASB reactors as: (i) improper design, (ii) poor operating procedures, (iii) insufficient maintenance and (iv) high concentration of sulphate.

5. Hydraulic retention time

HRT is one of the most critical design parameters in wastewater treatment facilities. HRT is the average time an influent particle spends in the reactor before it is discharged, with minimal short circuiting. Adequate HRT ensures enough time for micro-organisms to degrade organic matter. The HRT of UASB reactors can range from 2 to 200 h (see Table 2) depending on the type of wastewater being treated and the scale of the reactor. The start-up HRT of UASB reactors is normally longer than the steady-state HRT. This is to allow the reactor to acclimatize and to prevent sludge washout due to high upflow velocity. At the start of operation, the UASB reactor is more of a physical system for solids settling because of insufficient microbial population for effective biodegradation. Even with the introduction of sludge, poor performance is common because of structural instability associated with preserved sludge. Hence, a long initial retention time acts as a buffer for the start-up period. The usual starting HRT is 2 to 3 days for lab-scale UASB reactors [31,84]. As biological activities in the reactor progress, the HRT is then reduced by increasing the OLR in a stepped mode until steady state is reached. Various researchers use different HRTs to suit their objectives. However, a very long HRT will hamper reactor performance by starving the microbial population of substrate, while a very short HRT will reduce contact time between active biomass and substrate and also result in sludge wash-out. Reactor efficiency of 65% COD removal, 75% BOD removal and 73% TSS removal has been recorded at an HRT of 10 h [4]. However, an HRT of 6 h has been recommended since the additional 4 h HRT yielded no substantial improvement [4]. This recommendation was based on the findings that at mesophilic conditions, UASB reactor contents have a maximum adenosine triphosphate (ATP) content at 5 h HRT [36]. ATP is the complex chemical compound responsible for energy storage and release in living cells. Further support for high performance efficiency at low HRT can be seen in the work of [21] who found negligible difference in the performance efficiency of a UASB reactor treating synthetic wastewater inoculated with azo dyes at 8 and 24 h HRT. Several researchers achieved very high COD removal efficiency (70–90%) at HRT ranging between 8 and 12 h [4,31,35,36,57,84–86]. About 70 and 90% COD removal has been recorded in a hybrid UASB reactor at 8 and 10 h, respectively [84]. Hence, HRT determines the performance of UASB reactors. However, it is necessary to start with a low OLR, in order to minimize sludge wash-out, and then increase the OLR (decreasing the HRT) stepwise until an optimum state is reached. While pilot-scale UASB reactors can attain very high treatment efficiency at low HRT, full-scale UASB reactors may require longer HRTs depending on the characteristics of wastewater and operational conditions. The HRT can reach 8.3 or 11.8 days for a full-scale UASB reactor treating distillery wastewater [25,87].

The HRT of a UASB reactor should be selected such that a balance is struck between availability of substrate and substrate consumption by micro-organisms. A long HRT does not necessarily translate into better reactor performance, as this can lead to starvation of the microbial population, thereby necessitating predation and unhealthy competition for available substrate. Moreover, as HRT increases, the time required for the removal of additional units of COD increases, and so does the cost of operation. It is, therefore, necessary to reduce HRT gradually by increasing OLR until the reactor attains stability at start-up.

6. Effects of certain substances on the performance of UASB reactors

Despite the successes recorded in the application of UASB reactors to the treatment of a wide range of wastewaters, UASB reactors are known to be prone to instability due to toxicity and inhibition of acidogens and methanogens. This instability is partly due to the sensitivity of anaerobic organisms to external physicochemical factors. Effects of certain substances on the performance of UASB reactors as observed by some researchers have been highlighted on Table 3. Cyanide is one of the most toxic and inhibitory compounds encountered in wastewater. Toxicity of cyanide to both aerobic and anaerobic organisms has been reported [98,99]. The adverse effect of cyanide on the UASB process is due to the sensitivity of acetoclastic methanogens to cyanide [95,100]. It has been reported that methanogenesis has been inhibited at cyanide concentrations below 1 mg/L. However, methanogens can recover from a cyanide shock as they acclimatize to the toxin. Ten per cent reduction in COD removal efficiency of UASB reactors with about 70% reduction (from 11 to 3.3 L/d) in methane production upon the introduction of 5 mg/L of cyanide has been reported [100]. After the initial shock, COD removal efficiency and methane production fully recovered within four weeks, and methanogens were able to tolerate cyanide concentrations up to 125 mg/L with more than 90% cyanide removal at 12 h HRT. It was also observed that hydrogentrophic methanogens are less sensitive to cyanide than acetoclastic methanogens. The efficiency of UASB reactors has been found to reduce from $92 \pm 3\%$ at monoazo dye concentration of 60 mg/L to $67 \pm 2\%$ at a concentration of 300 mg/L [21]. Azo dye is a by-product of textile production which is stable and difficult to biodegrade. This change in efficiency can be attributed to the inability of organisms in the UASB reactor to metabolize the azo dye, rather than inhibition of their activities. The above inference was drawn because there was no effect on the removal of acetate-based COD as well as SMA and biogas production. However, about 30% reduction in COD removal and a reduction in pH from about 6.3 to 4.8 were recorded for an azo dye concentration above 200 mg/L [89]. The effects of heavy metals (Cu, Cr, Ni, Cd, Zn and Pb) on the performance of UASB reactors are well established. The relative toxicities of the metals on methane production of the bed and blanket zones, respectively, are as follows: $Cu >> Cr > Cd >> Zn > Ni > Pb$ and $Cu >> Cr > Zn > Ni > Pb$ [97]. Copper is the most toxic while lead is the least toxic, causing a 50% reduction in methane production at 210 and 2640 mg/L, respectively. Copper concentrations up to 0.9 mg/L and lead concentrations up to 12.5 mg/L can cause a 50% reduction in the activities of acidogens and methanogens, respectively [101,102]. The metallic toxicity-resistance of UASB biogranules is related to zones of sludge, kinds of heavy metal, types of individual VFA and HRT of a UASB system [97]. Not all metals have an inhibitory effect on the UASB process. It has been previously shown that the presence of multivalent cations such as Ca^{2+}, Al^{3+} and Fe^{2+} can enhance the performance of UASB reactors. Ca^{2+} and Al^{3+} enhance granulation while Fe^{2+} leads to increased methane yield [62,103].

Other substances such as sulphide [88], toluene [33] and trichloroethane [31,85]) cause reduced methanogenic activity which manifests in poor biogas yield. The presence of sulphide leads to competition between methanogens and sulphide reducing bacteria [106,107]. That any substance which inhibits or catalyzes the activities of UASB organisms is likely to have serious effects on the UASB process is obvious from Table 3 and other cases highlighted above. These effects include reduced or improved COD removal efficiency, reduced or improved biogas yield, accumulation of VFAs, reduced pH, accelerated rate of granulation, poor sludge characteristics and shift in dominant species of methanogens. When any of such substances are present in wastewater, steps should be taken to counter any of these possible effects. One of the most successful avenues of containing the effects of inhibitors is by the use of modified (high rate) UASB reactors.

7. Modifications and variants of the UASB reactor

Progressive improvements in reactor configurations and arrangements have given rise to very high rate UASB reactors with sludge recycle, biogas recovery and filtration. These modifications were imperative in the face of more stringent effluent standards and heavily polluted industrial wastewater.

Table 3
Observed effects of certain substances on UASB reactors

Chemical	Effect	Reference
$AlCl_3$ (300 mg/L)	• Improved rate of granulation • Improved SVI, MLVSS and SMA • Improved COD removal efficiency • No effect on CH_4 yield	[62]
$AlCl_3$ (150–300 mg/L)	• Improved sludge settleability • Accelerated granulation and start-up • Reduced long term SMA	[36]
Azo dye	• Improved CH_4 yield • Drastic reduction in pH • Reduced COD removal efficiency	[89]
$CaCl_2$ (150 mg/L)	• Improved rate of granulation and larger granules • Reduced SVI • Increased MLVSS • No effect on CH_4 yield	[62]
Calcium carbonate	• Reduced SMA and biomass activity • Formation of larger granules • Cementation of sludge to bed • Reduced COD removal	[35]
Chitosan and Reetha extract	• Enhanced formation of large granules • Enhanced COD removal • Enhanced biogas production	[13]
Commercial cationic polymer AA180H	• Shortening of start-up period • Strengthening of granules • Improved settleability of granules at all OLR studied (2–40 kg COD/m^3/d) • Increased organic removal efficiency	[13]
Congo red dye	• Increased CH_4 yield • Low COD removal	[94]
Cyanide (>125 mg/L)	• Reduced CH_4 production • Reduced COD removal efficiency (<10%)	[95]
Fe^{2+} <500 mg/L; Fe^{2+} 300–400 mg/L; Fe^{2+} <150 mg/L	• Increase in CH_4 production • Enhanced granulation • Accumulation of Fe^{2+} in granules • Reduction in water content of granule • No substantial effect	[103]; [45]; [45]
$FeCl_3$	• Shift in dominant methanogens from *Methanosarcina barkeri* to *Methanosaeta soehngenii*	[104]

(*Continued*)

Table 3 (*Continued*)

Chemical	Effect	Reference
Heavy metals	• Reduced granules size from 2–3 to 1.5–2 mm • Reduced pH from 6.6 ± 0.2–7 ± 0.2 to 6 ± 0.5–6.5 ± 0.5 • Inhibition of CH_4 and VFA production	[97]
Metals	• Reduction in total bacterial activity • Reduction in VFA production • Blanket sludge more vulnerable than bed sludge	[105]
Organic-inorganic hybrid polymers	• Formation of granules within 5 min • 90% COD removal efficiency even at 18 kg COD/m^3/d OLR	[13]
Polyethylene (PE) cubes	• Increased size of granules • Low loss of sludge • High and stable COD removal over an OLR range of 1.4–15.4 kg COD/m^3/d	[13]
Polyvinyl alcohol (PVA)-gel beads	• Higher biomass attachment • Dominance of *Methanosarcina* Spp in granules	[13]
Sulphide	• Inhibition of methanogens due to competition from SRB	[88]
Toluene	• Loss in potential acetoclastic methanogenic activity	[33]
TCE	• Inhibition of methanogenesis • Reduced SMA • Reduction in effluent quality	[85]
WEMOS	• Improved granulation by enhancing the aggregation of coccoid-like bacteria and growth of filamentous cells • Increased biogas production by 1.6-fold	[13]
1,1,2trichloroethane	• Reduced COD removal • Reduced biogas yield	[31]

One variant of the UASB reactor is the upflow anaerobic fixed film reactor or UAFF [67,108–111]. This is simply a UASB reactor with fixed film media in the upper part (Fig. 6(a)). It offers the dual benefit of being both a suspended and an attached biomass reactor. The benefits of hybrid UASB reactors include: higher efficiency; reduced HRT which translates to smaller reactor volume; improved stability and shock resistance; improved methane production; and reduction of complex compounds. This hybrid UASB reactor has been successfully applied to a wide range of industrial effluents including abattoirs, dairies, distilleries, soft beverages, petrochemical plants, pharmaceuticals, textiles, pulp and paper, vegetable and fruit processors, tanneries as well as fish and other food processing units [67]. More than 80% total COD removal efficiency has been observed in a UAFF reactor treating poultry wastewater at an OLR of 2.27 kg COD/m^3 d and an HRT of 10 h [84]. The anaerobic filter helps to prevent sludge washout even at early stages of operation. A modification of the UASB reactor closely resembling the UAFF reactor is the UASB-anaerobic filter reactor (UASB-AF) which consists of a serial arrangement of a UASB reactor followed by an anaerobic filter (Fig. 6(b)). A UASB-AF reactor has been successfully used for the treatment of

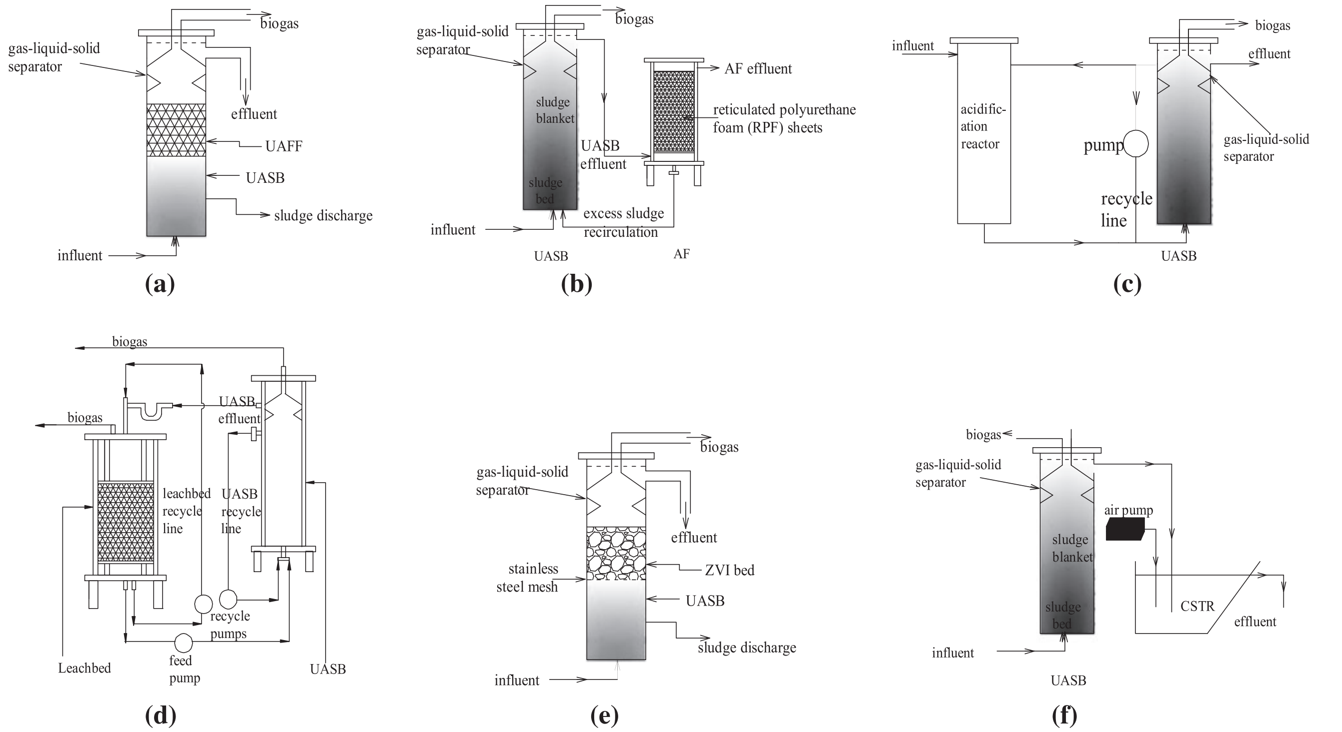

Fig. 6. (a) UAFF reactor [67], (b) UASB-AF reactor [91], (c) acidification-UASB reactor [82], (d) LB-UASB reactor [96], (e) UASB-ZVI [89] and (f) UASB-CSTR [94].

concentrated domestic wastewater having COD concentrations greater than 1500 mg/L at an OLR of 6.3 kg COD/m^3 d and an HRT of 4 h [91]. The total COD removal efficiency was 65%, together with a 17% reactor volume reduction compared to a single UASB reactor. In the treatment of wastewaters, where VFA could be a limiting substrate, it has been demonstrated that methane yield can be improved by first acidifying the waste in an acidification reactor to enhance VFA production [82]. A hybrid UASB reactor involving an acidification reactor interconnected with a UASB reactor with recirculation (Fig. 6(c)) has been used to treat food waste with over 90% COD removal efficiency and 77–99% VFA conversion [82]. The acidification phase ensures maximum production of VFA for the methanogenic population in the UASB reactor. The VFA-rich waste is then degraded by acetoclastic methanogens in the UASB reactor. The observed methane yield was 0.31 L/g.VSS (68% CH_4). A combination of the leachbed and UASB reactor (LB-UASB) can also be used to enhance treatment efficiency. A LB-UASB reactor (Fig. 6(d)) has been used to treat leachate from dead birds with the leachbed serving as the hydrolysis/acidification stage whereas the UASB reactor served as the methanogenic phase [96]. A UASB reactor packed with zero valent iron (ZVI) has been applied to the treatment of azo dye wastewater with more than 90% removal of colour and about 50% COD removal with increased population of methanogens compared to 20% COD removal and 60% colour removal for an identical UASB reactor without ZVI [89]. The ZVI-UASB hybrid reactor (Fig. 6(e)) maintained a stable pH at higher concentrations of azo dye while the pH of the UASB reactor without ZVI deteriorated drastically giving rise to acidic condition which could hamper the activities of methanogens. The ZVI bed consists of a stainless steel mesh packed with waste scrap iron. ZVI provides a buffer against pH fluctuation at higher concentrations of azo dye, hence giving rise to a stable performance [89]. ZVI can also synergize with anaerobic sludge to degrade nitrobenzene with the resultant Fe^{2+}/Fe^{3+} catalyzing the growth of anaerobic micro-organisms. The mode of catalyzation of organic matter degradation by ZVI is as follows [103]:

- lowering of the oxidation-reduction potential thereby facilitating anaerobic metabolism;
- production of micro-nutrients (Fe^{2+}/Fe^{3+}) for anaerobic micro-organism;
- formation of stable granules by the attachment of electronegative anaerobic bacteria to iron particles; and

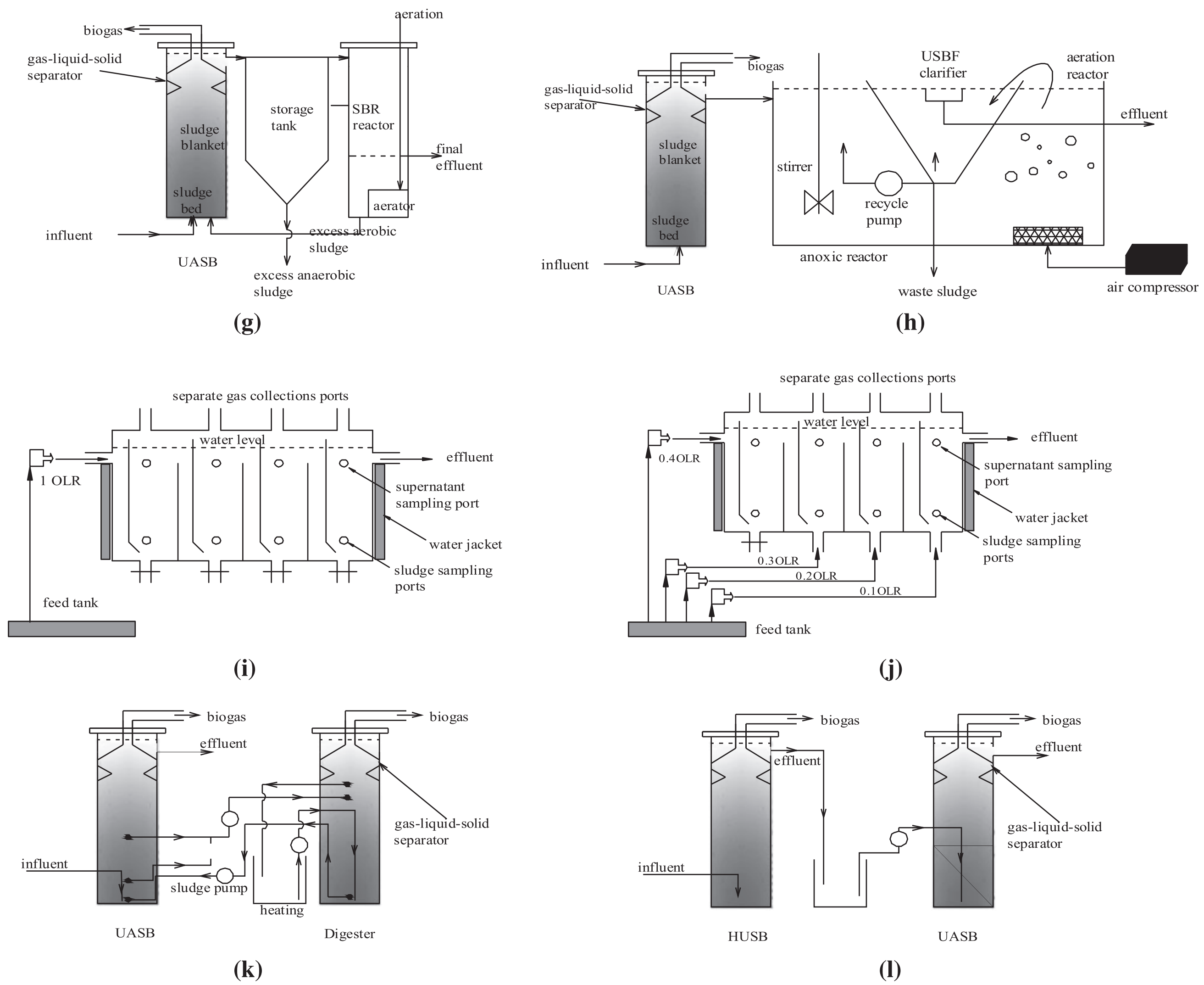

Fig. 6. (g) UASB-SBR [93], (h) UASB-USBF [112], (i) ABR [59], (j) ABR with split/stepped feeding [59], (k) UASB-digester reactor [117,118] and (l) HUSB-UASB reactor [119].

- facilitation of electron transfer, mass transfer and transformation of organic matter.

At acidic conditions, Fe^{2+}/Fe^{3+} concentrations of less than 150mg/L inhibited degradation while concentrations of between 100 and 200 mg/L promoted degradation. The situation was reversed for alkaline conditions. As much as 88% COD removal and 100% colour removal from Congo red dye has been achieved using a UASB reactor in series with a continuously stirred tank reactor (UASB-CSTR) shown in Fig. 6(f) [94]. A UASB reactor in series with a sequencing batch-activated sludge reactor (UASB-SBR) has been found to be very effective in COD and BOD removal (79%) and nitrification, in the treatment of domestic wastewater (Fig. 6(g)) [93]. The upflow sludge blanket filtration (USBF) unit is an aerobic/anaerobic treatment unit which involves an anoxic zone for mixing influent wastewater, an aeration unit and an upflow sludge blanket unit for clarification [112]. The USBF (Fig. 6(h)) has been successfully applied to over 80% removal of nitrogen at an HRT of 6 h [113]. However, the same success has not been recorded with phosphorus removal. Better phosphorus removal and an amazing 99% nitrogen removal at an optimum COD/N/P of 100:50:1 was achieved by an anaerobic/USBF reactor in which the USBF is preceded by an upflow anaerobic reactor [112,114]. A modified version of the UASB reactor which has been found very efficient in onsite treatment of domestic wastewater is the anaerobic baffled reactor (ABR). ABR has been described as a number of UASB units in series [115]; but the performance of the ABR in comparison with the UASB reactor is low, particularly at high OLR [47]. However, the performance of the ABR (Fig. 6(i) and (j)) can be substantially improved by stepped or split-feeding [59]. Split-feeding involves splitting the influent such that a fraction enters the reactor from the first compartment while the remaining fraction is fed to the other compartments from the bottom with subsequent compartments receiving a smaller fraction. Though the performance of the ABR is below that of UASB reactors, it is a substantial improvement over septic tanks. As much as 84% COD removal, 81% BOD removal and 89% TSS removal at an HRT of 20 h has been achieved in a two compartment upflow septic tank in series with an ABR (USBR) treating domestic wastewater [116]. The possibility of treating dilute domestic wastewater in colder climate using a modified UASB reactor (UASB-completely mixed digester: UASB-CMD) has been explored by Alvarez et al. [117] and Mahmoud et al. [118]. The performance of the single-stage UASB reactor in cold climates has been far from satisfactory due to the accumulation of undigested solids and subsequent deterioration of methanogenesis. At low temperatures, hydrolysis becomes the limiting phase, resulting in rapid sludge accumulation and poor performance. Rapid solids accumulation inhibits the formation of granules, thereby giving rise to an unstable and inefficient reactor. The UASB-CMD (see Fig. 6(k)) arrangement consists of a UASB reactor followed by a digester maintained at about 35˚C by means of a heater. Sludge is pumped from the upper sludge layer of the UASB reactor to the digester, while stabilized sludge is pumped from the bottom of the digester to the bottom of the UASB in order to enhance methanogenesis. After start-up, the UASB-CMD reactor attained a steady-state performance of 79% TSS removal as well as 52 and 60% removal of total COD and BOD_5, respectively [117]. The digester serves to enhance the stabilization of accumulated solids, thereby improving methanogenesis. Closely resembling the UASB-CMD reactor is the UASB reactor in series with a hydrolytic upflow sludge blanket (HUSB-UASB) reactor employed by Álvarez et al. [119] in the treatment of domestic wastewater at low temperatures (14–21˚C). The HUSB-UASB hybrid reactor (see Fig. 6(l)) achieved removal efficiencies of 89, 65 and 77% for total suspended solids, total COD and BOD, respectively. Ligero et al. [120] summarized the advantages of hydrolytic pretreatment of wastewater as follows:

- It removes an elevated percentage of suspended solids compared to a primary settler of a similar HRT.
- It stabilizes the sludge, totally or partially.
- It increases the biodegradability of the remaining COD.
- Favours the subsequent biological elimination of nutrients (N, P).

High-rate UASB reactors are usually obtained by using substances or reactor configurations that optimize the different stages of anaerobic digestion and influence key operational parameters such as pH, sludge characteristics, granulation, VFA production and biogas production. For instance, prefitting UASB reactors with anaerobic filters minimize sludge washout during the initial stages of operation. Pretreatment of influent wastewater in an acidification reactor produces sufficient VFAs for conversion by methanogens; while ZVI and other multivalent cations catalyze granulation, and also serve as pH buffers. Regardless of the modification applied to the UASB reactor in an attempt to achieve better performance, the most common and the most important attribute of UASB reactors is the forced contact between active biomass and wastewater necessitated by an upward flow of influent.

8. Energy recovery through biogas production

One of the main attractions of the UASB process is the possibility of energy recovery in the form of biogas. The production of biogas signals the completion of anaerobic digestion in UASB reactors. This final step of anaerobic digestion is performed by acetoclastic and hydrogenotrophic methanogens. Approximately, 70% of methane in biogas produced during anaerobic digestion is derived from acetate by the acetoclastic methanogens from the *Methanosarcina* and *Methanosaeta* genera [42]. For every kilogram of COD digested at 35˚C, 0.39 m^3 of methane is produced, which amounts to 13.5 MJ of methane energy [121]. Greater quantity of biogas is usually obtained at thermophilic temperature (45˚C) than at mesophilic temperature (30˚C) [62]. This shows that biogas production is a temperature-dependent process. The composition and quantity of biogas produced also depends on other operational conditions such as OLR, pH, influent wastewater, inhibition and degree of granulation. A biogas production rate of 0.15 m^3/kg of COD removed has been recorded at an OLR of 1 kg COD/m^3 d and 0.4 m^3/kg of COD removed at an OLR of 2.1 kg COD/m^3 d, in a UASB reactor treating paper mill wastewater [122]. The biogas produced comprised of 69% CH_4, 27% CO_2 and 1–1.5% H_2S. A detailed summary of biogas composition and production rate at different operational conditions has been provided in Table 2. In addition to OLR, biogas production is influenced by the characteristics of influent wastewater and the presence of inhibitors. The presence of heavy metals (Cu, Cr, Ni, Cd, Zn and Pb) has been found to inhibit methanogenesis, with copper being the most toxic to methanogens [97]. A cyanide concentration of 5 mg/L can cause a sharp inhibition of methanogenesis [95]. At a concentration of 125 mg/L, methane production is further reduced to a meagre 5.7%. Other substances such as trichloroethane [31,85] and sulphide [88] also cause severe inhibition of methanogenesis. The presences of sulphides favour the growth of sulphide reducing bacteria which inhibit the activities of methanogens.

Energy recovered from UASB reactors can compensate for the operational and maintenance costs of the reactors. Besides serving as a source of energy, biogas production in UASB reactors helps in enhancing reactor performance. Biogas production is one of the key parameters indicating the health of UASB reactors [122]. During the initial stages of operating a UASB reactor, a low OLR is maintained in order to allow for the establishment of a dense sludge layer and the acclimatization of inoculum. However, OLR is raised intermittently (stepped) in order to maintain an adequate F/M ratio, until start-up is attained. As the OLR is raised, the biogas production rate increases correspondingly. The upward flow of biogas produced generates turbulence which helps in mixing the reactor content [66]. In fact, gas production will contribute more to reactor content mixing than upflow velocity of influent wastewater [66]. However, excessive biogas production can result in the suspension and subsequent washout of biomass, thereby reducing the efficiency of the reactor.

The quantity and composition of biogas produced in a UASB reactor depends on operational conditions. Biogas produced during anaerobic digestion in UASB reactors could provide a substantial renewable energy potential. Replacement of fossil fuel with biogas will reduce the rate of global climatic changes and the rate of depletion of natural resources.

9. Conclusion

UASB reactors have been successfully applied to a wide spectrum of wastewaters on both domestic and industrial scales. The high efficiency of UASB reactors can help ensure that effluent qualities meet stipulated standards for effluent discharge. The efficiency of UASB reactors is largely dependent on the activities of micro-organisms involved in anaerobic digestion of wastes. Early formation of granules shortens the length of time required for the start-up of UASB reactors. However, formation of very large granules reduces the long-term efficiency of the reactor. Long HRTs do not necessarily translate into better reactor performance as this can lead to starvation of the microbial population, thereby necessitating predation. Moreover, as the HRT increases, the time required for the removal of additional unit of COD increases, and so does the cost of operation. The HRT of a UASB reactor should be selected such that a balance is struck between availability of substrate and substrate consumption by micro-organisms. High-rate UASB reactors are usually obtained by using substances or reactor configurations that influence key operational parameters such as pH, sludge characteristics, granulation, VFA production and biogas production. The quantity and composition of biogas produced in a UASB reactor depends on operational conditions. Biogas produced during anaerobic digestion in UASB reactors habours an enormous renewable energy potential.

Nomenclature

ABR	—	anaerobic baffled reactor
AF	—	anaerobic filter
ATP	—	adenosine triphosphate
COD	—	chemical oxygen demand
CSTR	—	continuosly stirred tank reactor
LB	—	leachbed
ECP	—	extracellular polymer
F/M ratio	—	food to micro-organism ratio
HRT	—	hydraulic retention time
HUSB	—	hydrolytic upflow sludge blanket
MLVSS	—	mixed liquor volatile suspended solids
OLR	—	organic loading rate
SBR	—	sequencing batch reactor
SMA	—	specific methanogenic activity
SRB	—	sulphate reducing bacteria
SVI	—	sludge volume index
TCE	—	trichloroethane
UAFF	—	upflow anaerobic fixed film
UASB	—	upflow anaerobic sludge blanket
UASBR	—	upflow anaerobic sludge blanket reactor
USBF	—	upflow sludge blanket filtration
TSS	—	total suspended solids
VFA	—	volatile fatty acid
VS	—	volatile solids
VSS	—	volatile suspended solids
WEMOS	—	water extract of *Moringa Oleifera* seed
WW	—	wastewater
ZVI	—	zero valent iron

References

[1] G. Lettinga, A. De Man, A.R.M. Van Der Last, W. Wiegant, K. Van Knippenberg, J. Frijns, J.C.L. Van Buuren, Anaerobic treatment of domestic sewage and wastewater, Water Sci. Technol. 27 (1993) 67–73.
[2] G. Zeeman, K. Kujawa-Roeleveld, G. Lettinga, Anaerobic Treatment Systems for High-Strength Domestic Waste (Water) Streams, In: P. Lens, G. Zeeman, G. Lettinga (Eds), Decentralized Sanitation and Reuse, IWA, London, 2001, 218–234.
[3] L. Hulshoff Pol, H. Euler, S. Schroth, T. Wittur, D. Grohganz, GTZ sectoral project, “promotion of anaerobic technology for the treatment of municipal and industrial wastes and wastewaters”, in: Proceedings of the 5th Latin-American Workshop – Seminar “Wastewater anaerobic treatment”, Vina del Mar, October 27–30, 1998.
[4] A. Azimi, M. Zamanzadeh, Determination of design criteria for UASB reactors as a wastewater pretreatment system in tropical small communities, Int. J. Environ. Sci. Technol. 1 (2004) 51–57.
[5] N. Khalil, R. Sinhab, K. Raghava, K. Mittal, UASB technology for sewage treatment in India: Experience, economic evaluation and its potential in other developing countries, in: Proceedings of the Twelfth International Water Technology Conference, IWCT 12, Alexandria, 2008, pp. 1411–1427.
[6] M. Sperling, Comparison among the most frequently used systems for wastewater treatment in developing countries, Water Sci. Technol. 33 (1996) 59–72.
[7] G. Zeeman, G. Lettinga, The role of anaerobic digestion of domestic sewage in closing the water and nutrient cycle at community level, Water Sci. Technol. 39 (1999) 187–194.
[8] S. Luostarinen, J. Rintala, Anaerobic on-site treatment of black water and dairy parlour wastewater in UASB-septic tanks at low temperatures, Water Res. 39 (2005) 436–448.
[9] S. Luostarinen, W. Sanders, K. Kujawa-Roeleveld, G. Zeeman, Effect of temperature on anaerobic treatment of black water in UASB-septic tank system, Bioresour. Technol. 98 (2007) 980–986.
[10] A.S. Bal, N.N. Dhagat, Upflow anaerobic sludge blanket reactor – a review, Indian J. Environ. Health 43 (2001) 1–82.
[11] C.Y. Gomec, High-rate anaerobic treatment of domestic wastewater at ambient operating temperatures: A review on benefits and drawbacks, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 45 (2010) 1169–1184.
[12] K.S. Singh, T. Viraraghavan, D. Bhattacharyya, Sludge blanket height and flow pattern in UASB reactors: Temperature effects, J. Environ. Eng. 132 (2006) 895–900.
[13] S. Chong, K.S. Tushar, A. Kayaalp, H.M. Ang, The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment, Water Res. 46 (2012) 3434–3470.
[14] B. Heffernan, J.B. Van Lier, J. Van der Lubbe, Performance review of large scale up-flow anaerobic sludge blanket sewage treatment plants, Water Sci. Technol. 63 (2011) 100–107.
[15] A.A. Khan, R.Z. Gaur, V.K. Tyagi, A. Khursheed, B. Lew, I. Mehrotra, A.A. Kazmi, Sustainable options of post treatment of UASB effluent treating sewage: A review, Resour. Conserv. Recycl. 55 (2011) 1232–1251.
[16] S. Fukuzaki, N. Nish, S. Naga, High rate performance and characterization of granular methanogenic sludges in upflow anaerobic sludge blanket reactors fed with various defined substrates, J. Ferment. Bioeng. 79 (1995) 354–359.
[17] T. Kobayashi, Y. Li, H. Harada, H. Yasui, T. Noike, Upgrading of the anaerobic digestion of waste activated sludge by combining temperature-phased anaerobic digestion and intermediate ozonation, Water Sci. Technol. 85 (2009) 185–193.
[18] N. Dichtl, Thermohpilic and mesophilic (two-stage) anaerobic digestion, Water Environ. J. 11 (1997) 98–104.
[19] O. Ince, Performance of a two-phase anaerobic digestion system when treating dairy wastewater, Water Res. 32 (1998) 2707–2713.
[20] Y. Kiyohara, T. Miyahara, O. Mizuno, T. Noike, K. Ono, A comparative study of thermophilic and mesophilic sludge digestion, Water Environ. J. 14 (2000) 150–154.
[21] R. Brás, A. Gomes, M. Ferra, H. Pinheiro, I. Gonçalvesa, Monoazo and diazo dye decolourisation studies in a methanogenic UASB reactor, J. Biotechnol. 115 (2005) 57–66.
[22] P.A. Sam-Soon, R.E. Loewenthal, M.C. Wentzel, G. Marais, Growth of biopellets on glucose in upflow anaerobic sludge bed (UASB) systems, Water SA 16 (1990) 151–164.
[23] D. Karakashev, D.J. Batstone, I. Angelidaki, Influence of environmental conditions on methanogenic compositions in anaerobic biogas reactors, Appl. Environ. Microbiol. 71 (2005) 331–338.
[24] E.T. Brummeler, L.W. Hulshoff Pol, J. Dolfing, G. Lettinga, A. Zehnder, Methanogenesis in an upflow anaerobic sludge blanket reactor at pH 6 on an acetate-propionate mixture, Appl. Environ. Microbiol. 49 (1985) 1472–1477.
[25] M. Kolukirik, O. Ince, B. Ince, Methanogenic community change in a full-scale UASB reactor operated at a low F/M ratio, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 42 (2007) 903–910.
[26] B. Demirel, P. Schreor, The roles of acetogenic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: A review, Rev. Environ. Sci. Biotechnol. 7 (2008) 173–190.
[27] T. Amani, M. Mostari, S.M. Mousavi, R.K. Kermanshahi, Study of syntrophic anaerobic digestion of volatile fatty acid using enriched cultures at mesophilic conditions, Int. J. Environ. Sci. Technol. 8 (2011) 83–96.
[28] R. Borja, E. Sánchez, P. Weiland, Infuence of ammonia concentration on thermophilic anerobic digestion of cattle manure in upflow anaerobic sludge blanket (UASB) reactors, Process Biochem. 31 (1996) 477–483.
[29] M. Keyser, R.C. Witthuhn, C. Lamprecht, M.P.A. Coetzee, T.J. Britz, PCR-based DGGE fingerprinting and identification of methanogens detected in three different types of UASB granules, Syst. Appl. Microbiol. 29 (2006) 77–84.
[30] O. Kotsyurbenko, M. Glagolev, A. Nozhevnikova, R. Conrad, Competition between homoacetogenic bacteria and methanogenic archaea for hydrogen at low temperature, Microbiol. Ecol. 38 (2001) 153–159.
[31] D. Basu, S. Asolekar, Performance of UASB reactor in the biotreatment of 1,1,2-Trichloroethane, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 47 (2012) 267–273.
[32] B. Calli, B. Mertoglu, K. Roest, B. Inanc, Comparison of long-term performances and final microbial compositions of anaerobic reactors treating landfill leachate, Bioresour. Technol. 97 (2006) 641–647.
[33] O. Ince, M. Kolukirik, Z. Cetecioglu, O. Eyice, O. Inceoglu, B. Ince, Toluene inhibition on an anaerobic reactor sludge in terms of potential activity and composition of acetoclastic methanogens, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 44 (2009) 1551–1556.
[34] J. Hofman-Bang, D. Zheng, P. Westermann, B. Ahring, L. Raskin, Molecular ecology of anaerobic reactor systems, Adv. Biochem. Eng./Biotechnol. 81 (2003) 151–203.
[35] H. Yu, J. Tay, H. Fang, The roles of calcium in sludge granulation during UASB reactor start-up, Water Res. 35 (2001) 1052–1060.
[36] H. Yu, J. Tay, H. Fang, Enhanced granulation in uplow anaerobic sludge blanket (UASB) reactor by aluminum chloride, Chemosphere 44 (2001) 31–46.
[37] S. Zinder, Physiological Ecology of Methanogens, In: J.G. Ferry (Ed), Methanogenesis: Ecology, Physiology, Biochemistry and Genetics, Chapman & Hall, New York, pp. 128–206, 1993.

[38] K. Ma, X. Liu, X. Dong, *Methanosaeta harundinacea* sp. nov., a novel acetate-scavenging methanogen isolated from a UASB reactor, Int. J. Syst. Evol. Microbiol. 56 (2006) 127–131.
[39] G. Bitton, Anaerobic Digestion of Wastewater Sludge, In: R. Mitchel (Ed), Wastewater Microbiology, Willey series in Ecological and Applied Microbiology, Willey, New York, p. 349, 1994.
[40] D.J. Costello, P.F. Greenfield, P.L. Lee, Dynamic modeling of a single-stage high-rate anaerobic reactor—I. Model derivation, Water Res. 25 (1991) 847–858.
[41] E.M. Siedlecka, J. Kumirska, T. Ossowski, P. Glamowski, M. Golebiowski, J. Gajdus, Z. Kaczynski, P. Stepnowski, Determination of volatile fatty acids in environmental aqueous samples, Pol. J. Environ. Stud. 17 (2008) 351–356.
[42] M. Shoen, D. Sperl, M. Gadermaier, M. Goberna, I. Franke-Whittle, I. Insam, J. Ablinger, Population dynamics at digester overload conditions, Bioresour. Technol. 100 (2009) 5648–5655.
[43] H. Xu, J. Tay, Preserved granular sludge for inoculation of new UASB reactors, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 36 (2001) 1747–1756.
[44] W.M. Wiegant, G. Lettinga, Thermophilic anaerobic digestion of sugars in upflow anaerobic sludge blanket reactors, Biotechnol. Bioeng. 27 (1985) 1603–1607.
[45] H.Q. Yu, H.H.P. Fang, J.H. Tay, Effects of Fe^{2+} on sludge granulation in upflow anaerobic sludge blanket reactors, Water Sci. Technol. 41 (2000) 199–205.
[46] Y. Liu, H. Xu, S. Yang, J. Tay, Mechanisms and models for anaerobic granulation in upflow anaerobic sludge blanket reactor, Water Res. 37 (2003) 661–673.
[47] M.I. Baloch, Methanogenic granular sludge as seed in an anaerobic baffled reactor, J. Water Environ. 25 (2009) 171–180.
[48] G. Lettinga, J.H Vinken, Feasibility of the upflow anaerobic sludge blanket (UASB) process for the treatment of low-strength wastes, in: Proceedings of the 35th Industrial Waste Conference, Purdue University, LaFayette, IN, 1980.
[49] G. Lettinga, R. Roersma, P. Grin, Anaerobic treatment of raw domestic sewage at ambient temperature using a granular bed UASB reactor, Biotechnol. Bioeng. 25 (1993) 1701–1723.
[50] D.J. Wijbenga, H.T.P. Bos, Physical and biological factors influencing the growth of anaerobic granular sludge, in: G. Lettinga, A.J.B. Zehnder, J.T.C. Grotenhuis, L.W. Hulshoff Pol (Eds.), Proceedings of the GASMAT Workshop: Granular Anaerobic Sludge, Microbiol. Technol. October 25–27, 1988, Pudoc, Wageningen, pp. 229–234.
[51] L.W. Hulshoff Pol, S.I. De Castro Lopes, G. Lettinga, P.N.L. Lens, Anaerobic sludge granulation, Water Res. 38 (2004) 1376–1389.
[52] L. Morvai, P. Miháltz, L. Czakó, The kinetic basis of a new start-up method for ensure the rapid granulation of anaerobic sludge, Water Sci. Technol. 25 (1992) 113–122.
[53] C.F. Shen, S.R. Guiot, Long-term impact of dissolved o_2 on the activity of anaerobic granules, Biotechnol. Bioeng. 49 (1996) 611–620.
[54] C.L. Schmidt, B.K. Ahring, Granular sludge formation in upflow anaerobic sludge blanket (UASB), Biotechnol. Bioeng. 49 (1996) 229–246.
[55] S. Fukuzaki, N. Nishio, H. Sakurai, S. Nagai, Characteristics of methanogenic granules grown on propionate in an upflow anaerobic sludge blanket (UASB) reactor, J. Ferment. Bioeng. 71 (1991) 50–57.
[56] S. Fukuzaki, N. Nishio, H. Sakurai, S. Nagai, Chemical composition and kinetic properties of granular methanogenic sludge grown on propionate, J. Ferment. Technol. 72 (1991) 405–407.
[57] Y. Ahn, K. Min, Z. Yun, Enhancement of reactor performance and pelletization by reactor modification in UASB system, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 35 (2000) 1719–1733.
[58] Y. Ahn, Physicochemical and microbial aspects of anaerobic granular biopellets, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 35 (2000) 1617–1735.
[59] S. Uyanik, Granule development in anaerobic baffled reactor, Turkish J. Eng. Environ. Sci. 27 (2003) 131–144.
[60] F.A. Macleod, S.R. Guiot, J.W. Costerton, Layered structure of bacterial aggregates produced in an upflow anaerobic sludge bed and filter reactor, Appl. Environ. Microbiol. 56 (1990) 1598–1607.
[61] M.A. Yükselen, Preservation characteristics of UASB sludges, J. Environ. Sci. Health. Part A Environ. Sci. Health Part A Environ. Sci. Eng. Toxicol. 32 (1997) 2069–2076.
[62] P. Boonsawang, S. Laeh, N. Intrasungkha, Enhancement of sludge granulation in anaerobic treatment of concentrated latex wastewater, Songklanakarin J. Sci. Technol. 30 (2008) 111–119.
[63] K.C. Teo, L. Xu, J.H. Tay, Molecular mechanism of granulation—II: Proton translocating activity, J. Environ. Eng. 126 (2000) 411–418.
[64] J.H. Tay, Y.G. Yan, Influence of substrate concentration on microbial selection and granulation during start-up of upflow anaerobic sludge blanket Reactors, Water Environ. Res. 68 (1996) 1140–1150.
[65] J.H. Tay, S. Pan, Y. He, S.T. Tay, Effects of organic loading rate on aerobic granulation I & II: Reactor performance, J. Environ. Eng. 130 (2004) 1094–1109.
[66] L. Korsak, Anaerobic treatment of wastewater in a UASB reactor. [A Licentiate thesis submitted to the Department of Chemical Engineering and Technology], Royal Institute of Technology, Stockholm, 2008.
[67] B. Ayati, H. Ganjidoust, Comparing the efficiency of UAFF and UASB with hybrid reactor in treating wood fiber wastewater, Iran. J. Environ. Health Sci. Eng. 3 (2006) 39–44.
[68] Y. Yoon, J.R. Park, I. Kim, The monitoring of anaerobic floc-like sludge influenced by calcium ions, Environ. Eng. Res. 11 (2006) 127–133.
[69] T. Rudd, R.M. Sterritt, J.N. Lester, Complexation of heavy metals by extracellular polymers in the activated sludge process, Water Pollut. Control Fed. 56 (1984) 1260–1268.
[70] R.G. Cail, J.P. Barford, The development of granulation in an upflow floc digester and an upflow anaerobic sludge blanket digester treating cane juice stillage, Biotechnol. Lett. 7 (1985) 493–498.
[71] E.M. Mahoney, L.K. Varangu, W.L. Cairns, N. Kosaric, R.G. Murray, The effects of calcium on kicrobial aggregation during UASB reactor start-up, Water Sci. Technol. 19 (1987) 249–260.
[72] K.R.K. Alibhai, C.F. Forter, An Examination of the granulation process in UASB reactors, Environ. Technol. 7 (1986) 193–200.
[73] P.N.L. Lens, R. Gastesi, F. Vergeldt, A.C. van Aelst, A.G. Pisabarro, H.V. As, Diffusional properties of methanogenic granular sludge: ^1H NMR characterization, Appl. Environ. Microbiol. 69 (2003) 6644–6649.
[74] J.B. Van Lier, J.L.S. Martin, G. Lettinga, Effects of temperature on the anaerobic thermophilic conversion of volatile fatty acids by dispersed and granular sludge, Water Res. 30 (1996) 199–207.
[75] G. Lettinga, L.W. Hulshoff, UASB process design for various type of wastewater, Water Sci. Technol. 24 (1991) 87–107.
[76] J.R. Banu, S. Kaliappan, I.T. Yeom, Treatment of domestic wastewater using upflow anaerobic sludge blanket reactor, Int. J. Environ. Sci. Technol. 4 (2007) 363–370.
[77] D.R. Christensen, J.R. Gerick, J.E. Eblen, Design and operation of an upflow anaerobic sludge blanket reactor, Water Pollut. Control Fed. 56 (1984) 1059–1062.
[78] P.L. McCarty, The development of anaerobic treatment and its future, Water Sci. Technol. 44 (2001) 149–156.
[79] M.E. Souza, Criteria for utilization, design and operation of UASB reactors, Water Sci. Technol. 18 (1986) 55–69.
[80] N. Mahmoud, G. Zeeman, H. Gijzen, G. Lettinga, Solids removal in up flow anaerobic reactors, a review, Bioresour. Technol. 90 (2003) 1–9.

[81] G. Moussavi, F. Kazembeigi, M. Farzadkia, Performance of a pilot scale up flow septic tank for on-site decentralized treatment of residential wastewater, Process Saf. Environ. Prot. 88 (2010) 47–52.
[82] H. Xu, J. Wang, H. Zhang, J. Tay, Feasibility study on the operation of UASB reactor treating acidified food waste, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 37 (2002) 1757–1764.
[83] J. Poinapen, G.A. Ekama, M.C. Wentzel, Biological sulphate reduction with primary sewage sludge in an upflow anaerobic sludge bed (UASB) reactor—Part 3: Performance at 20˚C and 35˚C, Water SA 35 (2009) 543–552.
[84] R. Rajakumar, T. Meenambal, Comparative study on start—up performance of HUASB and AF reactors treating poultry slaughterhouse wastewater, Int. J. Environ. Res. 2 (2008) 401–410.
[85] D.T. Sponza, Tetrachloroethylene (TCE) removal during anaerobic granulation in an upflow anaerobic sludge blanket (UASB) reactor, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 37 (2002) 213–236.
[86] C. Darlington, K. Kennedy, Biodegradation of aircraft deicing fluid in an upflow anaerobic sludge blanket (UASB) reactor, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 33 (1998) 339–351.
[87] A. Mirsepasi, H. Honary, A. Mesdaghinia, A. Mahvi, H. Vahid, H. Karyab, Performance evaluation of full scale UASB reactor in treating stillage wastewater, Iran. J. Environ. Health Sci. Eng. 3 (2006) 79–84.
[88] T. Onodera, S. Sase, P. Choeisai, W. Yoochatchaval, H. Sumino, T. Yamaguchi, Y. Ebie, K. Xu, N. Tomioka, K. Syutsubo, High-rate treatment of molasses wastewater by combination of an acidification reactor and a USSB reactor, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 46 (2011) 1721–1731.
[89] Y.B. Zhang, Y.W. Liu, Y.W. Jing, Z.Q. Zhao, X. Quan, Steady performance of a zero valent iron packed anaerobic reactor for azo dye wastewater treatment under variable influent quality, J. Environ. Sci. 24 (2012) 720–727.
[90] C. Díaz, S. Baena, B. Patel, M. Fardeau, Peptidolytic microbial community of methanogenic reactors from two modified UASBs of brewery industries, Braz. J. Microbiol. 41 (2010) 707–717.
[91] M. Halalsheh, Z. Rumman, J. Field, Anaerobic wastewater treatment of concentrated sewage using a two-stage upflow anaerobic sludge blanket – anaerobic filter system, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 45 (2010) 383–338.
[92] T. Dogan, O. Ince, N. Oz, B. Ince, Inhibition of volatile fatty acid production in granular sludge from a UASB Reactor, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 40 (2005) 633–644.
[93] P. Guimarães, H. Melo, P. Cavalcanti, A. van Haandel, Anaerobic–aerobic sewage treatment using the combination UASB-SBR activated sludge, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 38 (2003) 2633–2641.
[94] M. Işik, D. Sponza, Aromatic amine degradation in a UASB/CSTR sequential system treating congo red dye, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 38 (2003) 2301–2315.
[95] H. Gijzen, M. Bernal, H. Ferrer, Cyanide toxicity and cyanide degradation in anaerobic wastewater treatment, Water Res. 34 (2000) 2447–2454.
[96] T. Chen, Anaerobic treatment of poultry mortalities in a modified LB-UASB system, J. Environ. Sci. Health, Part B 34 (1999) 527–547.
[97] C. Lin, M. Lin, Effect of heavy metals on the upflow anaerobic sludge blanket process, J. Environ. Sci. Health, Part A Environ. Sci. Eng. Toxicol. 32 (1997) 1933–1944.
[98] L.P. Solomonson, Cyanide as a Metabolic Inhibitor, In: B. Vennesland, E.E. Conn, C.J. Knowless, J. Westley, F. Wissing (Eds), Cyanide in Biology, Academic Press, New York, pp. 11–28, 1981.
[99] M.R. Smith, J.L. Lequerica, M.R. Hart, Inhibition of methanogenesis and carbon metabolism in *Methanosarcina* sp. by cyanide, J. Bacteriol. 162 (1985) 67–71.
[100] B. Eikmanns, R.K. Thauer, Catalysis of an isotopic exchange between CO_2 and the carboxyl group of acetate by *Methanosarcina barkeri* grown on acetate, Arch. Microbiol. 138 (1984) 365–370.
[101] C.Y. Lin, Effect of heavy metals on volatile fatty acid degradation in anaerobic digestion, Water Res. 26 (1992) 177–183.
[102] C.Y. Lin, Effect of heavy metals on acidogenesis in anaerobic digestion, Water Res. 27 (1993) 147–152.
[103] W. Zhang, L. Chen, H. Chen, S. Xia, The effect of Fe^0/Fe^2+/Fe^3+ on nitrobenzene degradation in the anaerobic sludge, J. Hazard. Mater. 143 (2007) 57–64.
[104] M. Takashima, R.E. Speece, Mineral nutrient requirements for high-rate methane fermentation of acetate at low SRT, Water Pollut. Control Fed. 61 (1989) 1645–1650.
[105] C. Lin, C. Chen, Characteristics of metallic toxicity-resistance between bed and blanket sludges in UASB systems, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng. 34 (1999) 1503–1516.
[106] Y. Chen, J. Cheng, K. Creamer, Inhibition of anaerobic digestion process: A review, Bioresour. Technol. 99 (2008) 4044–4064.
[107] C.J.S. Lozano, M.V. Mendoza, M.C. de Arango, E.F.C. Monroy, Microbiological characterization and specific methanogenic activity of anaerobe sludges used in urban solid waste treatment, Waste Manage. 29 (2009) 704–711.
[108] E. Ozturki, A. Asturk, Sludge utilization and reduction experience in pulp and paper industry, Water Sci. Technol. 26 (1992) 2105–2108.
[109] R. Lepisto, J. Rintala, The removal of chlorinated phenolic compounds from chlorine bleaching effluent using thermophilic anaerobic process, Water Sci. Technol. 29 (1994) 373–380.
[110] A. Broch Due, R. Anderson, O. Kristoffersen, Pilot plants experience with aerobic moving bed bio-film reactor for treatment of NSSC wastewater, Water Sci. Technol. 29 (1994) 283–294.
[111] C. Shivayogimath, T. Ramamujan, Treatment of distillery spent wash by hybrid UASB reactor, Bioprocess Eng. 21 (1999) 255–259.
[112] H. Khorsandi, H. Movahedyan, B. Bina, H. Farrokhzadeh, Innovative anaerobic upflow sludge blanket filtration combined bioreactor for nitrogen removal from municipal wastewater, Int. J. Environ. Sci. Technol. 8 (2011) 417–424.
[113] A.H. Mahvi, R. Nabizadeh, M.H. Pishrafti, Th. Zarei, Evaluation of single stage USBF in removal of nitrogen and phosphorus from wastewater, Eur. J. Sci. Res. 23 (2008) 204–211.
[114] L.K. Wang, N.K. Shammas, Y.T. Hung, Advanced biological treatment processes, Humana Press, New York, pp. 365–408, 2008.
[115] R. Boopathy, V.F. Larsen, E. Senior, Performance of anaerobic baffled reactor (ABR) in treating distillery wastewater from a Scotch whisky wastewater, Biomass 16 (1988) 133–143.
[116] T. Sabry, Evaluation of decentralized treatment of sewage employing upflow septic tank/baffled reactor (USBR) in developing countries, J. Hazard. Mater. 174 (2010) 500–505.
[117] J.A. Álvarez, E. Armstrong, J. Presas, M. Gómez, M. Soto, Performance of a UASB-digester system treating domestic wastewater, Environ. Technol. 25 (2004) 1189–1199.
[118] N. Mahmoud, G. Zeeman, H. Gijzen, G. Lettinga, Anaerobic sewage treatment in a one-stage and a combined UASB-digester system, Water Res. 38 (2004) 2348–2358.
[119] J.A. Álvarez, E. Armstrong, M. Gómez, M. Soto, Anaerobic treatment of low-strength municipal wastewater by a two-stage pilot plant under psychrophilic conditions, Bioresour. Technol. 99 (2008) 7051–7062.

[120] P. Ligero, A. Vega, M. Soto, Pretreatment of urban wastewaters in a hydrolytic upflow digester, Water SA 27 (2001) 399–404.
[121] C. Lamprecht, UASB granulation enhancement by microbial inoculums selection and process induction, [PhD thesis submitted to the Department of Food Sciences], Stellenbosch University, Matieland, 2009.
[122] M. Mahadevaswamy, B.M. Sadashiva, A.R. Girijama, Performance evaluation of up-flow anaerobic sludge blanket (UASB) reactor for treatment of paper mill wastewater, J. Environ. Sci. 16 (2004) 194–198.