LITERATURE REVIEW
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INTRODUCTION

The upflow anerobic sludge blanket (UASB) is a single tank reactor that treats wastewater. The general process is completed by having sludge enter the reactor from the bottom. Light and dispersed particles are washed out of the process, while heavier particles collect and retain within the system. These heavier particles then form flocs consisting of inorganic and organic matter (Hulshoff Pol et al. 2003). After a start-up period, a dense sludge blanket consisting of flocs develops creating an environment for biological reactions to take place. As flow passes upward through the sludge blanket, the soluble organic compounds in the influent convert to biogas.

The UASB reactor is an increasingly common method of wastewater treatment because it has a high reduction of biochemical oxygen demand (BOD), low sludge production, high organic and hydraulic loading rate tolerance, and biogas production (UASB|SSWM). However, although the UASB reactor can handle high organic and hydraulic loading rates, if variable, treatment may also be unstable. Furthermore, most UASB reactors require a constant source or electricity. The effluent and sludge from the reactor require further treatment and appropriate discharge (UASB|SSWM).

This literature review will focus on the review by Chong et al. (2012) and complementing research papers. It will discuss UASB start-up, post-treatment options, and use of resulting biogas.

START-UP

Before direct treatment of wastewater, the UASB reactor needs a start-up period using selected nutrients as substrate. This start-up is a strong determinant of the effectiveness and stability of the reactor, determined by many physical, chemical, and biological parameters (Ghangrekar et al., 1996). Municipal wastewater takes two-eight months on average to achieve full efficiency (Chong et al., 2012, Lettinga et al., 1993, Vlyssides et al., 2008). To shorten this period, the standard procedure is to inoculate the reactor with active microorganisms or granules (Bhatti 2014).

This procedure to develop granules can be split into four steps (Schmidt 1996, Escudie et al. 2011):

1. Transport of cells to a substratum
2. Initial reversible adsorption to the substratum by physicochemical forces
3. Irreversible adhesion of cells to the substratum by microbial appendages and/or polymer
4. Multiplication of the cells and development of granules

Ghangrekar et al. (1996) observed that COD removal efficiency is greatly influenced by start-up and sludge loading rates (SLR). For example, a reactor which started with 0.6 kg COD/kg VSS/d resulted in ~50% COD removal at steady state, and it did not improve through operation time. However, a reactor which started with 0-0.3 kg COD/kg VSS/d resulted in a better performance with more than 90% COD removal at steady state. This study also suggests that organic loading rates and SLR are determiners in how much time is required for a reactor to reach steady state.

Furthermore, other additives can be incorporated to increase the start-up time. See Table 3 in the Appendix for the results of recent studies on theses additives.

POST-TREATMENT

A UASB reactor has an inability to meet all disposal standards for degraded soluble matter, colloidal, nutrients, and pathogens. Therefore, in order to meet present standards, a secondary treatment, also known as post-treatment or polishing process, is required (Khan 2011).

Options

There are seven common post-treatment options for the UASB reactor. See Table 1 for a summary of the advantages and disadvantages of the options below.

1. *Activated Sludge (AS)*
   AS uses microorganisms to feed on organic components in the wastewater to improve effluent. In general, the microorganisms grow to form floc (particles which bind together) from the organic material and suspended solids. The floc settles which allows the high-quality effluent to separate ('Explaining the Activated Sludge Process').

2. *Sequencing-batch Reactor (SBR)*
   SBR uses two or more batch reactors to optimize the performance of the system. However, in most SBR single processors, equalization, primary and secondary clarification, and biological treatment can be accomplished with a single reactor. A common process for a post-treatment with an SBR is such that wastewater enters a partially filled reactor with biomass acclimated to the wastewater constituents. Once full, the system works as the AS system but without continuous influent or effluent flow. Excess biomass is wasted throughout the process (EPA SBR).

3. *Trickling Filter (TF),* or biofilter (BF)
   TF is an attached-growth process system. Meaning, it is an aerobic treatment system that incorporates microorganisms attached to a medium to remove organic matter from the wastewater (EPA TF). As water travels through the filter, organics are degraded by the biofilm covering the filter (SSWM).

4. *Downflow Hanging Sponge (DHS)*
   DHS uses simple and economic PUR foams (packing material). This method is used to decrease energy demand, maintenance, and operating costs. This post-treatment option achieves a near perfect BOD removal and high coliforms removal (Chong et al. 2012).

5. *Stabilizing Pond (SP)*
   SP is used to recover nutrients from the UASB effluents. It is a man-made body of water which can be used individually or as a series for treatment. The types of SPs are 1) anaerobic ponds commonly used to reduce the organic load, 2) facultative ponds to remove BOD, and 3) aerobic ponds to remove pathogens and contaminants. It is recommended that SPs be used in this respective series (SSWM).

6. *Rotating-biological Contactor (RBC)*
   Like the TF, RBC is a fixed-bed reactor. However, the RBC consists of foam disks (polystyrene or polyurethane) mounted to a steel shaft and partially submerged in the effluent solution. These disks rotate and allow wastewater to flow through. RBCs allow for aeration and degradation of dissolved organic pollutants and nutrients.

7. *Constructed Wetland (CW)*
   CW is an artificial wetland which serves as a biofilter. This allows for natural processes to degrade organic matter and remove nutrients, pathogens, sediments, and pollutants from the wastewater. A CW is either, or a combination of, subsurface flow and free-water-surface flow less than one meter deep planted with vegetation. It aides in microorganism growth and degradation of organic matter (Chong et al. 2012).

Other post-treatment options which will not be discussed include dissolved-air-flotation, cascade-sponge reactor, and membrane reactors.

Table 1: Summary of Post-treatment Advantages and Disadvantages (Chong et al. 2012)

Option	Advantages	Disadvantages
Activated Sludge	• High efficiency • Resistant to variable flow and toxic loads • Consistent nutrification	• High mechanization level • High construction costs • Requires energy • Noise and aerosol pollution
Sequencing-batch Reactor (EPA SBR)	• Flexible operation and control • Low cost with limited clarifiers	• Sophisticated maintenance requirements • High maintenance cost • Potential plugging of aeration devices and equalization requirement
Trickling Filter (EPA TR)	• Simple and reliable • Small land requirement • Efficient in nitrification	• Moderate technical experience required for management • Accumulation of excess biomass • Regular operation requirements • Vector and odor issues
Downflow Hanging Sponge	• Low cost • Simple maintenance • Simultaneous nitrification and denitrification • No external aeration input	• Need of proper influent-distribution system design for full-scale plants and first generation • Less favorable for shock loads and nitrogen removal
Stabilizing Pond	• Low maintenance requirements • No energy requirement • Sludge accumulates slowly • High suspended solids (SS) production	• Large land requirement • Recovery of nutrients and removal of fecal coliforms affected by temperatures
Rotating-biological Contactor	• Low energy requirement • Resistance to high organic loadings • Low energy requirement • Easy maintenance	• Excess sludge removal unknown • More units of higher HRT's required for treatment at low temperatures
Constructed Wetland	• Easy construction and maintenance • Low surplus sludge	• High land requirement • Gravel clogs (e.g. near the inlet, shortening the lifespan of the wetland) • Limited nutrient and pathogen removal

*See Tables 4-5 in the Appendix for a more detailed advantages and disadvantages list from Chong et al. (2012).

Integrated Systems

Below are effluent results of the aforementioned post-treatment options coupled with a UASB reactor. This list is not all inclusive. See Chong et al. (2012) for full results.

Table 2: Treatment Performance of Integrated UASB and Post-treatment Systems (adap. Chong et al. 2012)

	T (ºC)	**UASB**					**Post-treatment**			**Concentration in final effluent (mg/L) [Average removal efficiency (%)]**			
System Combination		**Size**	**HRT (h)**	**OLR (kg COD/ m^3/d)**	**COD Inf. (mg/L)**	**COD Eff. (mg/L)**	**Size**	**HRT (h)**	**Other**	**COD**	**BOD**	**TSS**	**NH4-N**
UASB + AS	30	0.416	4	2.3-4.4	558	115	0.023	2.8	**F/M** 0.6-0.9	55 [90]		15 [91]	
	15-30	0.396	3.2	2.6	341	225	0.3	2.5	1.2	46 [87]		8 [92]	
UASB + SBR	21	150 L	6	2.1	569	228	90 L		**Aeration (h)** 22 10 4 2	46 [92] 46 [92] 46 [92] 51 [91]		16 [88] 18 [86] 21 [84] 21 [84]	0 [100] 0 [100] 0.5 [98] 33 [69]
UASB + TF	Sub-tropical	0.416	4	3.8	521	148	0.06	3 1.5 0.8		80 [86] 72 [83] 113 [78]	32 [90] 23 [92] 55 [81]	11 [91] 21 [83] 33 [73]	
	26	0.416	5.6	1.9	437	108	0.106	1.5		82 [81]	27 [87]	17 [89]	
UASB + DHS (1st generation)	25	0.155	7	2.3	672	144	1.215 L	1.3	parallels	42 [94]	2 [99]	0 [100]	7 [75]
UASB + DHS (2nd generation)	25	0.155	6	1.57	393	165	51 L	2	parallels series	65 [84] 68 [81]	4 [97] 10 [94]	28 [79] 46 [63]	20 [52] 15 [61]
			6	1.57	393	165	51 L	2	parallels series	65 [84] 65 [83]	8 [95] 4 [97]	 28 [79]	12 [70] 20 [50]
UASB + SP (Averages)		0.04-4477	0.3-9.8		318-871	151-337	1.44-49333	1.1-15 d	**Depth (m)** 0.4-2	110 [73]	33 [85]	60 [77]	7.6 [64]
UASB + RBC (Averages)	12-21	Single RBC with polystyrene foam disks						2.5-5	**SLR (g COD/m^2/d)** 10.5-20	79 [85]	**TKN** 39 [35]	**EC** 3.4E5 [1.5]	32 [32]
		Single RBD with polyurethane rotating disks						2.5-5	**SLR (g COD/m^2/d)** 4-11	68 [87]		2.4E4 [2.4]	6 [88]
		Series RBS (2-3x)						2.5-10	**SLR (g COD/m^2/d)** 6.5-47.25	56 [89]	8 [86]	8.2E4 [2.6]	13 [75]
UASB + CW (Averages)	14-38	1.3-25.5	6-11	0.7-2.2	315-1050	117-525	0.8-78	1.2-10.8 d	**SLR (g COD/m^2/d)** 7.2-52.8	47 [82]	17 [89]	12 [89]	17 [38]

*For a relative comparison, see Table 6 in the Appendix, outlined by Chong et al. (2012).

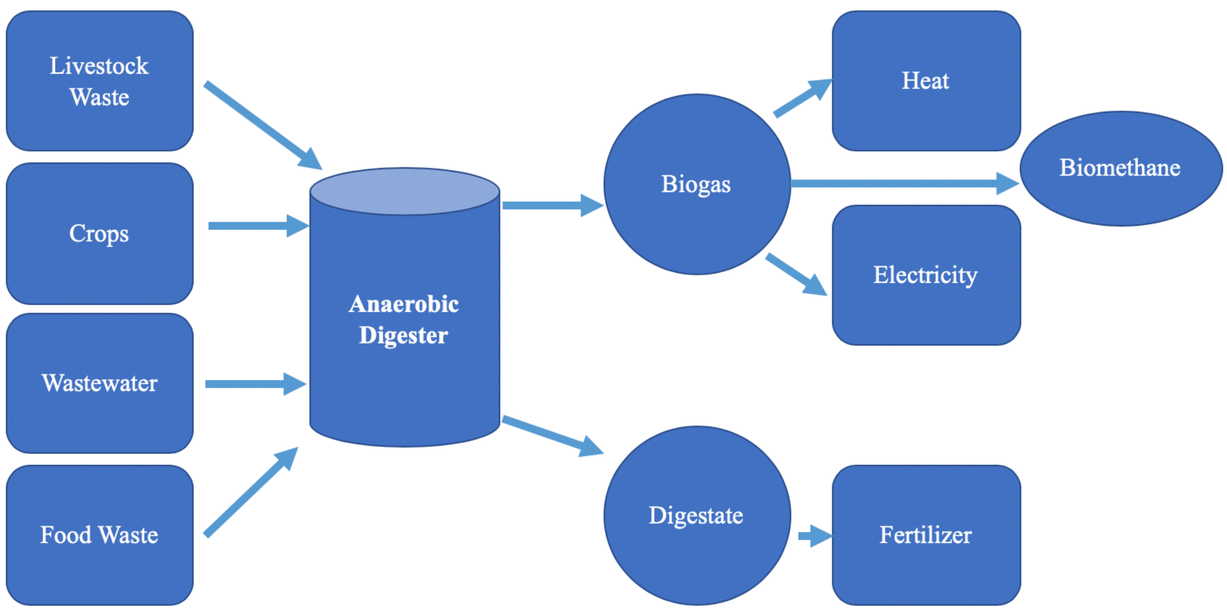
BIOGAS

Biogas is a clean, renewable source of energy that is produced from the decomposition of organic waste in an anaerobic environment, such as the UASB reactor. A gas is released that is a mixture of 50-70% methane, 30-40% carbon dioxide (Tanigawa 2017), and other gases. This raw biogas can be used for fuel, electricity, and heat. Furthermore, biogas is a reliable energy feedback which is healthier for the user over other energy sources, such as biomass.

Renewable natural gas (RNG) is biomethane, treated biogas so it retains no carbon dioxide, water vapor, or other contaminating gases. RNG is used as a replacement of natural gas and is used more frequently than raw biogas for energy.

See Figure 1 for the process to create biogas and RNG.

Figure 1: Biogas Process (Tanigawa 2017)



Use of Raw Biogas

Raw biogas can be used directly from the UASB reactor, however for that to occur, the method of use, e.g. a stove burner, needs to be directly connected to the system itself through a hose or pipe. Furthermore, when biogas is used in its raw form, it is much less efficient than if it were converted into RNG. Therefore, the appliance which uses the fuel most be adapted to maximize the energy potential coming from the raw biogas.

Household Burner: Using biogas with a stovetop is a great example of how to convert the appliance to use raw biogas. In order to alter a stove top to maximize its performance and increase flow of gas, it is recommended (without study) that the cross-section of the injector be expanded 2-4 times than the size meant for propane. If this does not achieve satisfactory results, another recommendation is to increase the size of the jets. The pressure of biogas being released through the appliance should be between 75-150 mm of the water column so the flame is stable, compact, and blue ('Biogas Appliances'). This can be best done with a lotus burner. See Figure 2.

Figure 2: Example of a Lotus Burner and Flame (Shutterstock)

Refrigerator: Absorption refrigerating machines operating on ammonia and water can be fueled with biogas. The only part which needs to be modified on this appliance is the burner itself. However, one must check that all safety features (e.g. safety pilot) function properly.

Gas Lamp: Using biogas as a fuel for light has a very low efficiency (~3%) ('Biogas Appliances'). This means that the bulb gets very hot and may be a fire hazard. In order to modify the lamp for optimization, there must be a pre-control of biogas supply and air without the mantel. This will result in an elongated flame. Next, the incandescent body and air supply should be adjusted finely. When the flame is too large, the incandescent body will show black spots, therefor the lamp is at its maximum efficiency when the flame is adjusted just smaller than when the black spots appear. This must be done on a biogas specific lamp, and there is no possibility of changing the injector size.

*One should not discount the possibility of buying an appliance specifically designed for raw biogas input.

Efficiency of Raw Biogas

Raw biogas can be used in a variety of ways, as seen above. However, they all have different efficiencies and consumption rates. Estimations of these rates are listed below ('Biogas Appliances').

- *Household Burner:* 150-450 L/hr
- *Refrigerator (100 L):* 30-75 L/hr
- *Gas Lamp (60 W Bulb):* 120-160 L/hr

APPENDIX

Table 3: Recent Studies on the Enhancement of Start-up and Granulation in UASB Reactors
(adap. Chong et al. 2012)

Table 4 – Recent studies on the enhancement of start-up and granulation in UASB reactors.

Ref.[a]	Enhancements (e.g. additives, reactor modifications)	Digester size (L)	T (°C)	Substrate	Influent COD (mg/L)	Dose (mg/L)	SMA (g CH_4-COD/g VSS/d)[b]	Approx. mean agglomerate size (mm)[b]	Start-up/ granulation[c]	COD removal efficiency[c]
Multivalent cations:										
[1]	Ferrous chloride tetrahydrate ($FeCl_2.4H_2O$)	7.3	35	Synthetic	4,000	150	1.26	≥1.8	0	0
						300	1.14		+	0
						450	1.07		+	0
						600	0.81		−	0
						800	0.74		−	0
[2]	Calcium chloride dehydrate ($CaCl_2.2H_2O$)	7.3	35	Synthetic	4,000	150–300	1.04–0.58	≥2.3	+	0
[3]	Aluminium chloride ($AlCl_3$)	7.3	35	Synthetic	4,000	300	1.10	≥1.8	+	0
[4]	Aluminium chloride ($AlCl_3$)	1.3	26	Synthetic	665–738	50		<0.1	−	0
						200			−	−
						300			−	−
Natural polymers:										
[5]	WEMOS (2.5%)	2.3	29	Domestic	320	2 ml/L[d]	0.22		+	0
[6]	*Reetha* extract: Cationic	3.25		Synthetic	750–850	25[e]		0.114	+	0
	Reetha extract: Anionic					25[e]		0.111	+	0
	Reetha extract: Bulk					25[e]		0.107	0	0
	Chitosan					25[e]		0.129	+	0
Commercial and synthetic polymers:										
[7]	Commercial cationic AA 184 H	4.4	35	Synthetic	4,000	5	0.71–1.76	0.1–2.4	+	+
						10	0.71–2.54	0.1–2.0	+	+
						20	0.71–2.36	0.1–2.6	++	+
[8]	Commercial cationic AA 184 H	4.4	35	Synthetic	5,000	20	1.3–2.5	≤ 2.4	+	0
						40		≤ 2.2	+	0
						80		≤ 2.65	++	+
						160		≤ 2.65	+	0
						320		≤ 2.92	+	0
[9]	Synthetic granular sludge, A and B	0.84	37.5	Synthetic	>250			2–3.84	+	+
[10]	Commercial cationic polymer	12.57	22–31	Synthetic	300–630	0.083[f]	0.29–0.59	0.3–3.03	−	−
Others:										
[11]	PVA-gel beads	12.5	35	Synthetic	768–10,910				+	+
[12]	PE cubes, bi-circulation	5.9	35	Wastewater from fruit juice factory	8,000–12,000			0.26	+	
[13]	ZVI	5.9	35	Synthetic	1,000–8,000			0.1–0.25	+	+
	ZVI-bicirculation							0.25–0.84	++	++
[14]	ZVI	18.5	35	Synthetic	1,400–8,000			0.1–0.21	+	+
	ZVI-electric field							0.1–0.73	++	+

Table 4: Advantages and Disadvantages of Post-treatment Options (adap. Chong et al. 2012)

Table 19 – Summary of pros and cons for various post-treatment options.

Post-treatment unit	Advantage	Disadvantage	Ref.
Sequencing-batch reactors (SBR)	1. High efficiency and operational flexibility (variation of cycles) 2. Effective separation of solid and liquid phases due to non-interaction of sedimentation and liquid movement, thereby resulting in lower TSS and VSS, lower production of excess sludge 3. Simple reactor configuration due to the need of only three reactors 4. Simple mechanical equipment as only SBR has moving parts 5. Satisfactory independence from climate conditions 6. Low land requirement 7. Satisfactory nutrient removal	1. Start-up is not very easy 2. The desired microbial populations requires appropriate control of anaerobic and aerobic residence times, thus the need of high sophistication in the control units for efficient organic removal 3. Low coliforms removal 4. Need of more studies on nutrient and pathogen removal. Especially for simultaneous removal of nitrogen and phosphate 5. Great installed power than the other activated sludge systems 6. Treatment and disposal of sludge is required	von Sperling (1996); Torres and Foresti (2001); Guimarães et al. (2003); von Sperling and Chernicharo (2005); Chan et al. (2009); Moawad et al. (2009)
Downflow-hanging sponge (DHS)	1. Low cost and easy maintenance 2. Satisfactory independence from climate conditions 3. No external aeration input 4. No withdrawal of excess sludge required 5. Excellent settleability 6. Favourable for simultaneous nitrification and denitrification 7. DHS systems very close to plug-flow, favouring coliforms removal, although further disinfection may be needed to meet standards	1. Need of proper influent-distribution system design for full-scale plants for the first generation 2. Less favourable in the case of shock loads especially in terms of nitrogen removal 3. Need of further studies on the durability of the packing material and the physical and biological interaction for coliforms removal 4. Scale-up problem	Agrawal et al. (1997)a,b; Machdar et al. (1997); Machdar et al. (2000); Uemura et al. (2002); Tandukar et al. (2005, 2006a); Tandukar et al. (2006b); Tandukar et al. (2007); Sumino et al. (2007); Oliveira and von Sperling (2009); Takahashi et al. (2011)
Activated sludge (AS)	1. High efficiency and operational flexibility 2. High efficiency in BOD removal 3. High resistance to variable flow and toxic loads 4. Satisfactory independence from climate conditions 5. Consistent nitrification 6. Sludge stabilisation in the reactor itself	1. High mechanisation level 2. High construction and operational costs 3. High energy consumption 4. Sophisticated operation due to the need for treating a substantial amount of sludge (although stabilization is not required) 5. Problems of bulking and production of stable foam 6. Limited coliforms removal 7. Requires complete treatment and final disposal of the sludge 8. Possible environmental problems with noise and aerosols	von Sperling et al. (2001); von Sperling and Chernicharo (2005); La Motta et al. (2007); Tawfik et al. (2008); Cao and Ang (2009); Mungray and Patel (2011)
Trickling filter (TF)	1. Flexible for short HRTs 2. High efficiency in BOD removal 3. Simpler than activated sludge 4. Low land requirements 5. Low operational cost	1. Less operational flexibility than activated sludge 2. Need of packing media 3. Ammonia removal not satisfactory 4. Higher construction costs 5. Need of complete sludge treatment and disposal 6. High head loss	von Sperling (1996); Chernicharo and Nascimento (2001); Gonçalves et al. (2002); Pontes et al. (2003); de Almeida et al. (2009); Oliveira and von Sperling (2009); Tawfik et al. (2010)

(continued on next page)

Table 5: Advantages and Disadvantages of Post-treatment Options cont. (adap. Chong et al. 2012)

Table 19 – (continued)

Post-treatment unit	Advantage	Disadvantage	Ref.
Stabilising pond (SP)	1. Simple, low maintenance, suitable for rural communities 2. No energy requirement 3. High COD, BOD removals regardless of climate temperature fluctuations 4. High SS production (algae) 5. Low rate of sludge accumulation especially in tropical regions, if efficient anaerobic treatment (e.g. with a UASB reactor) is applied	1. Large land requirement 2. Need of de-sludging (some authors have shown if coupled with efficient anaerobic treatment, the de-sludging of ponds becomes optional) 3. May subject to high evaporation rates, therefore water loss and increased salinity 4. High SS concentration 5. Recovery of nutrients and removal of faecal coliforms affected by temperatures	Cavalcanti et al. (2002); von Sperling et al. (2002); von Sperling et al. (2003); von Sperling and Mascarenhas (2005); von Sperling and de Andrada (2006); Sato et al. (2006); El-Shafai et al. (2007); Oliveira and von Sperling (2009); Walia et al. (2011)
Rotating-biological contactor (RBC)	1. Low-shear – no distribution problems, no recirculation required 2. Relatively easy scale-up 3. Resistance to high hydraulic and organic loadings 4. Low energy requirement 5. Low maintenance 6. Good nitrification efficiency 7. Possible for complete removal of E.coli	1. More units or higher HRTs required for treatment at lower temperatures 2. Excess sludge removal not studied 3. Needs frequent motor and bearing maintenance, problem of excessive film build up on disc after power failure, leading to the possibility of motor failure	Tawfik et al. (2002a); Tawfik et al. (2002b); Tawfik et al. (2003); Tawfik et al. (2005); Tawfik and Klapwijk (2010); Kassab et al. (2010)
Constructed wetland (CW)	1. Simple construction, operation and maintenance, suitable for rural communities 2. Enhanced removal of SS and COD improves the overall performance and reduce the gravel-bed clogging problem 3. Utilization of natural processes 4. Low surplus sludge	1. High land requirement 2. Problems of clogging in the gravel over time, especially near the inlet, shortening the lifespan of wetland 3. Contingent upon microbial activity, HRT, loading rate, temperature 4. Limited nutrient and pathogen removal 5. May require support media/ engineered structures 6. May subject to high evaporation rates, therefore water loss and increased salinity 7. Nutrient removal is susceptible to the ageing phase of the plants 8. Need of appropriate practices in monitoring the excess sludge removal from the UASB reactor	de Sousa et al. (2001); de Sousa et al. (2003); El Khateeb and El-Gohary (2003); Kaseva (2004); Mbuligwe (2004); Green et al. (2006); Ruiz et al. (2008); Barros et al. (2008); Dornelas et al. (2009); El Khateeb et al. (2009)
Dissolved-air flotation (DAF)	1. Compact, high loading rates, small flocculation tanks 2. Low detention time 3. Great operational versatility 4. Partial striping of the volatile gases 5. Resistant to shock discharges and rapid flow oscillations 6. Permits high quality effluent with low coagulant consumption (low phosphorus, TSS and organic matter concentrations) 7. Good to excellent removal of *Crytosporidium* and *Giardia* 8. Works with already thickened sludge, thus requires less post-processing	1. Need of coagulant and/or flocculant 2. Auxiliary operating costs caused by the recycle water which requires pumping of up to 10% of the feed flow to between 400 and 700 kPa 3. Needs to be protected from the weather to prevent float freezing leading to settling of previously floated solids caused by snow and rain 4. Poor removal of ammonium and faecal coliforms	Reali et al. (2001a); Reali et al. (2001b); Chernicharo (2006); Crossley and Valade (2006)

Table 6: Overall Relative Comparison of Reviewed Post-treatment and UASB Options (adap. Chong et al. 2012)

Table 18 – An overall relative comparison of the reviewed coupled systems.

Coupled system	In compliance with Australian guidelines (Class D, Table 6)?[a]				Effect of temperature	Full-scale operation			
	BOD, TSS	TN	TP	FC		Land requirement[b]	Sludge quantity[c]	Construction costs[d]	Operational & maintenance costs[e]
AF + AH/UASB	N				L	L	L	L	L
UASB + CSTR	N				L				
HUSB/UASB + UASB	Y				L	L	M	M	M
UASB + AS	Y			N	L	L	M	M	H
UASB + SBR	Y	Y	Y	N	L	M	H	M	H
UASB + BF	N	Y		N	M	L	M	L	M
UASB + DHS	Y	N		Y	L				
UASB + Pond	N	Y	Y	N	H	H	L	L	M
UASB + RBC	N	Y			L	M	H	H	H
UASB + CW	Y	N	Y	Y	M	H		M	M
UASB + DAF	Y	N	Y	N	L	L	M	L	M

a Y: yes; N: no; blank: data not available.
b Reference: von Sperling Chernicharo (2005).

Scale: L | M | H → 0, 0.2, 0.4 — **Average land requirement (m^2/inhab)**

c Reference: Sperling and Chernicharo (2005), Khan et al. (2011).

Scale: L | M | H → 0, 30, 60 — **Average sludge for disposal (L/inhab/year)**

d Costs are based on Brazilian experience (Basis: year 2002), adapted from Sperling and Chernicharo (2005).

Scale: L | M | H → 0, 30, 60 — **Average construction costs (US$/inhab)**

e Costs are based on Brazilian experience (Basis: year 2002), adapted from Sperling and Chernicharo (2005).

Scale: L | M | H → 0, 1.75, 3.5 — **Average operational & maintenance costs (US$/inhab)**

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