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Evaluating the Potential of Anaerobic Waste Stabilisation Ponds for Wastewater Treatment in a Temperate Climate

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ABSTRACT

A pilot scale baffled anaerobic waste stabilisation pond (aWSP) was designed based on an organic loading of 0.17 kg COD m^{-3} d^{-1} to evaluate the potential of aWSP as a passive, sustainable technology for domestic wastewater treatment in temperate conditions. After 4 weeks of operation and up to 45 days (end of study), average removals of 37% COD, 30% BOD and 36% suspended solids were observed which compares to the literature surveyed for aWSP treating domestic wastewater. A linear correlation between COD removal and time since start-up was observed and compared favourably to an anaerobic membrane bioreactor (aMBR) that was started up unseeded. Seeding the aWSP apparently augmented start-up and whilst higher COD removal for aWSP have been reported, it is anticipated that continued operation (>45 days) will yield further efficiency improvements. Methane reported in the gas and liquid phase was approximately 4.1% and 5.7 mg l^{-1} respectively suggesting relatively low production of methane. However, this does demonstrate that methanogenesis occurred soon after start up. Using this data to model a 5000 PE site, total energy output of 62 MWhy^{-1} (electricity and heat) was generated and only 6 MWh y^{-1} (electricity) consumed, this compares to an equivalent conventional activated sludge process (ASP) which uses approximately 655 MWh y^{-1} electricity for aeration. Results to date suggest that aWSP technology represents a viable sustainable alternative for domestic wastewater treatment in a temperate climate versus traditional high energy technologies.

EXECUTIVE SUMMARY

Introduction

Anaerobic waste stabilisation pond (aWSP) is a natural and passive (effectively zero energy) system which requires limited maintenance and substantially low operation cost for the treatment of wastewater. Activated sludge processes (ASP) for secondary treatment of wastewater requires intensive energy input and produces a substantial quantity of sludge which requires thickening, anaerobic or aerobic digestion, chemical conditioning and dewatering before ultimate disposal. The energy requirement associated with treating domestic wastewater using the ASP currently varies between 0.3 and 0.7 $KWhm^{-3}$ treated representing 54 to 97% of the total energy demand for domestic wastewater treatment. The associated energy demand has therefore stimulated water providers to consider alternative technological routes. In EU 80% of the treatment plants serve the population less than 5000 and employ the standard treatment technologies like ASP. aWSP have rarely been studied in temperate countries despite their numerous advantages. Whilst typically operated in developing countries with warmer climates, aWSP can prove to be a viable tool for wastewater management as a part of sustainable development in temperate countries. aWSP as roughing stage can significantly reduce the overall requirement of surface area for WSP system without additional energy input. Biodegradation of organics in the aWSP is effected by a combination of sedimentation which forms settled solids layer and secondly methanogenesis of the solids organic fraction in the settled layer.

Objectives

This study evaluated the potential of aWSP for wastewater treatment in temperate condition analysed the start up and organic removal potential and assessed the potential of energy savings associated with aWSP versus ASP.

Methods

A pilot scale baffled aWSP was constructed using PVC sheeting and made it air and water tight by covering it with bolted flange from top and welding it from outside and applying silicon from inside respectively. Influent and effluent were analysed for various parameters to assess its pollutants removal efficiency. Biogas was collected and analysed for its composition.

Results and Discussion

aWSP exhibited fast start up period due to its inoculation with flocculated anaerobic sludge. The removal efficiency of 37% COD, 30% BOD and 36% SS was observed after 4 weeks of operation and up to 45 days (end of study).The start up removal performance was compared with an unseeded anaerobic membrane bioreactor and found to be equivalent and also in agreement with literature surveyed for aWSP treating domestic wastewater. The treated effluent needs to be treated in secondary wastewater treatment plant for meeting the stipulated norms of water consent.

Methane was found in both gas and liquid phase although the concentration was substantially low. 4.1% of methane was found in gas phase and 5.7 mg l^{-1} in liquid phase (average from 5 chambers). The headspace gas capture was low as the aWSP was operated fully flooded which forced the formation of gas pockets within the chambers (as evidenced by liquid displacement to the gas collectors) and limited gas transmission to the collectors; future practice should ensure sufficient freeboard for maximising gas collection. Although only low volumes of gas were detected, this does demonstrate that methanogenesis occurred after a relatively short start-up period. In addition, production of methane in chamber 4 coincided with the highest liquid phase methane concentration of c.7.1 mg l^{-1}. From the gradual increase observed in liquid phase methane concentration along chambers 1 to 4, it may be hypothesised that acetogenesis and acidogenesis occur principally at the start of the reactor stimulating more extensive production of methane in the latter chambers.

An energy model incorporating aWSP and trickling filter (TF) was developed for 5000 PE and compared with standard ASP with the same wastewater quality and the scale. This model eliminated energy intensive ASP or land intensive facultative pond as secondary treatment unit and also the operational problems at wastewater treatment plants relating to bulking and rising of sludge at all sizes of ASP. 62.41 MWhy^{-1} energy will be produced from 6469 m^{3} year^{-1} generation and capture of methane from aWSP. This could yield 33.07 MWh heat and 19.97 MWh$_{e}$ electricity generations using combined heat generator. As both the systems (aWSP and TF) are gravitationally fed, there will be limited energy requirement for operation principally pertaining to the screen (c.0.7kW or 6.13 MWhy^{-1}). Therefore the process is energy positive by 13.8 MWhy^{-1} (69%).

Primary clarifier-ASP model will have approximately 655 MWhy^{-1} electrical demands for mixing and aeration in ASP. Based on an electrical output of 50 MWhy^{-1} from anaerobic digestion of the removed solids, the process is energy negative by 610.5 MWhy^{-1} (-1200% of electricity produced).

Conclusions

This work currently demonstrates the potential significance of aWSP for the UK wastewater treatment providers. Further work is required to maximise organic and suspended solids removal and to understand the implications of organic loading rate for plant size. However, with extensive studies n data interpretation thereof, almost zero energy demand aWSP-TF model can become a valuable tool for effective wastewater management as a part of sustainable development programme.

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LIST OF ABBREVIATIONS

aMBR	Anaerobic Membrane Bioreactor
ASP	Activated Sludge Process
aWSP	Anaerobic Waste Stabilisation Pond
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
sCOD	Soluble Chemical Oxygen Demand
tCOD	Total Chemical Oxygen Demand
CW	Constructed Wetland
HRT	Hydraulic Retention Time
SS	Suspended Solids
TP	Total Phosphate
UASB	Upflow Anaerobic Sludge Blanket
UWWTD	Urban Wastewater Treatment Directive
WSP	Waste Stabilisation Pond

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1 Introduction

1.1 General

Waste stabilisation ponds (WSP) are widespread and proven effective for the treatment of industrial and domestic wastewaters (DeGarie et al, 2000; Wang et al, 2005; de Oliveira, 1996); though less common, anaerobic WSP (aWSP) represent a sustainable alternative to both aerobic ponds and more conventional aerobic wastewater treatment process technologies due to the low capital requirement and negligible operational cost (Table 1.1). In addition, as methane is generated, renewable energy can be generated also creating a potential revenue stream. The aWSP is typically considered as a roughing stage with typical organic removal efficiencies of c.47% reported at a temperature range of 5 to 28 $^{\circ}$C (Picot *et al*, 2005).

Table 1.1: Energy usage in various treatment units (Metcalf and Eddy, 2004)

System	Energy Consumption
Complete mixing of flow in aeration tank using mechanical aerators	20 and 40 kW/10^3 m^3
Mechanical mixing of flow in anoxic zone	8 to 13 kW/10^3 m^3
Mixing requirement for homogeneity in equalisation tank	0.004 to 0.008 kW/m^3
Activated sludge with nitrification and filtration	1500 to 2800 MJ/10^3 m^3
Activated sludge	1100 to 2400 MJ/10^3 m^3
Trickling filter	600 to 1700 MJ/10^3 m^3

Downstream of the aWSP, aerobic biological polishing is required either in the form of a passive technology (e.g. facultative pond) or a more highly engineered energy intensive technology (e.g. activated sludge). The intended combination is principally to reduce energy and maintenance versus standard technologies such as activated sludge process; the secondary benefit is a substantial reduction in CO_2 generation based on the lower power input from aeration (c.6 kWh.m^{-3}, 3.2 kg CO_2 m^{-3}). Due to the passive nature of the system, an extended hydraulic residence time (cf. conventional treatment) facilitates suspended solids removal through sedimentation additionally enhancing particulate biological oxygen demand (BOD) removal. This sedimented layer undergoes anaerobic biodegradation subsequently generating a methane rich biogas (Alexiou and Mara, 2003). Methane rich biogas can be utilised for electrical and heat generation by the integration of localised combined heat and power systems. Currently, aWSP are almost exclusively installed without covering as they are used as a means of low cost organics biodegradation thus fugitive methane emissions result; under these conditions the potential for energy recovery is lost and the impact to the environment significant as CH_4 is 21 times more potent as a greenhouse gas than CO_2 (El-Fadel and Massoud, 2001; Show and Lee, 2008).

Table 1.2: Advantages and disadvantages of WSP versus other treatment processes (adopted from Arthur, 1983)

Criteria	PP	ASP	eASP	BF	OD	AL	WSP
Plant performance							
BOD removal	F	F	F	F	G	G	G
FC removal	P	P	F	P	F	G	G
SS removal	F	G	G	G	G	F	F
Helminth removal	P	F	P	P	F	F	G
Virus removal	P	F	P	P	F	G	G
Economic factors							
Simple and cheap construction	P	P	P	P	F	F	G
Simple operation	P	P	P	F	F	P	G
Land requirement	G	G	G	G	G	F	P
Maintenance costs	P	P	P	F	P	P	G
Energy demand	P	P	P	F	P	P	G
Sludge removal costs	P	F	F	F	P	F	G

FC, Faecal coliforms; G, Good; F, Fair; P, Poor; PP, Package plant; ASP, Activated sludge plant; e, extended; BF, Biological filter; OD, Oxidation ditch; AL, Aerated lagoon; WSP, Waste stabilisation pond.

The qualitative comparison reported by Arthur (1983) (Table 1.2) demonstrates the potential of WSP (anaerobic-facultative-maturation ponds configuration) as a low cost, sustainable alternative to the more traditional highly engineered routes; the main disadvantage is the land area requirement which reflects a cost penalty and limited site availability particularly in smaller European countries with low land masses and high population densities. Land requirement is extensive as the mixing regime is relatively poor thus lower mass transfer and biological reaction kinetics proceed comparative to ASP thus scale of application at a UK level maybe constrained; this is further compounded when operating aWSP as the specific bacteria have a substantially lower growth rate particularly at ambient European sewage temperature of 12 °C (Soares, 2009).

The utilisation of aWSPs for domestic wastewater is common practice in developing countries due largely to its simplicity, low cost and the abundance of cheap available land. The warmer climates are particularly favourable for anaerobic bacteria, therefore achieving reasonable quality effluent. In Europe, increasingly stringent discharge consents imposed by newly evolving legislation are forcing more extensive treatment, in some cases, inclusive of the application of tertiary treatment. This requirement increases specific cost (m^{-3} treated) due to the increased energy demand thus there is an increasing emphasis in UK water utilities to foster new practice in energy efficiency.

Based on the low energy requirement, low chemical cost and low skill requirement, aWSP offer significant potential for UK water utilities where scale can be achieved, however, to date aWSP have not been operated under temperate conditions.

1.2 Aims and Objectives

The aim of the thesis was to study the potential of aWSP for operation in temperate climates and on UK strength domestic wastewater. Of particular interest was to develop a covered aWSP design to capture methane generated during wastewater treatment for community scale application. The objectives were to:

- Demonstrate effective start-up of an aWSP under temperate conditions;
- Evaluate organic removal efficiency during the start-up period and compare this with anticipated literature data;
- Monitor methane production to validate maintenance of anaerobic conditions; and
- Undertake an energy balance based on experimental and literature data to demonstrate the potential of this flowsheet versus standard designs.

2 Literature Review

2.1 Composition of Untreated Wastewater

The composition of untreated (crude) domestic wastewater received at a treatment plant varies on the basis of seasonal di-urnal flow, catchment, source and climate (Metcalf, 2004). Crude sewage is typically fed direct to the aWSP without clarification thus both organic and suspended solids concentrations entering the aWSP are typically higher than that observed at UK ASP with tCOD and suspended solids concentrations typically ranging 245 mg l^{-1} to 699 mg l^{-1} and 171 mg l^{-1} to 1599 mg l^{-1} respectively (Table 2.1).

Table 2.1: Typical reported mean composition of untreated wastewaters at aWSPs

	Crude wastewater						
Location	**pH**	**SS mg l^{-1}**	**BOD mg l^{-1}**	**COD mg l^{-1}**	**NH_4-N mg l^{-1}**	**TP mg l^{-1}**	**Reference**
Sesimbra	7.7	375	N/A	699	N/A	N/A	Toprak (1995)
Mèze (1981-1982)	N/A	171	172	430	24	N/A	Picot *et al* (2005)
Mèze (1988-1990)	N/A	251	NA	541	27	N/A	Picot *et al* (2005)
Mèze (2000-2003)	N/A	266	405	645	36	7.9	Picot *et al* (2005)
Mèze (2003-2004)	N/A	256	347	557	36	7.1	Picot *et al* (2005)
Jining*	7.82	206.8	84.6	245.4	25.9	4.8	Wang *et al* (2005)
Bornova**	8.27	1599	N/A	685	22.5	N/A	Toprak (1995)
Campina Grande***	7.3	283	186	502	N/A	N/A	de Oliveira *et al* (1996)

NA, Not Available;fc N/a, Not available; *mixed domestic and industrial wastewaters; ** Bornova wastewater channel, wastewater used for experimental studies; *** Pilot scale plant located at Campina Grande WWTP, Estaçao da Catingueira.

2.2 Treatment Options for Extensive Treatment Systems

Several forms of extensive wastewater treatment are available, all of which may be characterised by simple design with a low energy and minimum labour input. These systems are based on fixed film cultures (infiltration-percolation and vertical or horizontal flow reed bed filters), suspended growth cultures (WSP, macrophyte lagooning and aerated lagooning) or hybrid systems. Reed bed systems are also called constructed wetlands (CW). The selection of any system depends on advantages and disadvantages it offers (Table 2.2).

Table 2.2: Summary of advantages and disadvantages of extensive wastewater treatment systems (adopted from EU guide on extensive wastewater treatment systems, http://www.environment-integration.eu/download/34-Water/ExtensiveWasteWaterTreatmentProcesses.pdf)

Approach	**Advantages**	**Drawbacks**
Infiltration-percolation through sand	• Excellent results on BOD, COD, SS and advanced nitrification; • Surface area need is much less than with natural lagooning; • Interesting decontamination capacity.	• Requires a primary settling structure; • Risk of clogging that must be managed; • Requires having great quantities of sand available; • Adaptation limited to hydraulic surcharges.
Vertical flow reed bed filters	• Easy to operate and low operating cost. No energy consumption if the topography makes this possible; • Processing of raw domestic sewage; • Management of organic matter retained in the 1st stage filters is reduced to a minimum; • Adapts well to seasonal variations in population.	• Regular operation, annual cutting of the exposed portion of the reeds, manual weeding before reeds are established; • Using this approach for capacities greater than 2000 p.e. remains very delicate for reasons of controlling costs and hydraulics compared with traditional approaches; • Risk of presence of insects or rodents.
Horizontal flow reed bed filters	• Low energy consumption; • No noise pollution and integrates well into the landscape; • No highly-qualified personnel needed for maintenance; • Responds well to variations in loads.	• A lot of ground space is needed, British and Danish approaches included. The latter is about 10 m^2/p.e. (equivalent to the surface of a natural lagoon). • A plant for sizes from 2000 to 15000 p.e. can only be considered if there is some serious thought given to the conditions of adapting the

		design basis and of the insurance of controlling hydraulics.
Natural lagoons (stabilisation ponds)	• An energy supply is not necessary if the difference in level is favourable; • Operation remains simple, but if overall cleaning does not take place in time, the performance of the lagoon drops off very rapidly; • Eliminates a large portion of the nutrients: phosphorus and nitrogen (in summer); • Very good elimination of pathogenic bacteria in the summer; • Reduced water flows and fluxes in summer; • Adapts well to large variations in hydraulic load; • No “hard permanent” constructions, civil engineering remains simple; • Integrates well into the landscape; • Pedagogic initiation to nature; • Absence of noise pollution; • Sludge from cleaning is well stabilised except for that which is present at the head of the first basin.	• Much ground space needed (10 m^2/p.e); • Investment costs depend very heavily on the type of substratum. With unstable or sandy land, it is preferable not to consider this type of lagoon; • Performance is less that with intensive processes on organic matter. However, discharging organic matter takes place in the form of algae, which has less adverse effects than dissolved organic matter for oxygenation of the zone downstream; • Quality of discharge varies according to season; • Controlling the biological balance and purification processes remains limited.
Aerated lagoons	• Tolerates large variations in hydraulic and/or organic loads; • Tolerates highly concentrated discharges; • Tolerates effluents that are unbalanced in nutrients (cause of bulking in activated sludge); • Joint treatment of industrial and	• Discharge of average quality for all parameters; • Presence of electromechanical equipment requiring maintenance by a specialised agent; • Noise pollution linked with the presence of the aeration system;

	domestic biodegradable discharges; - Integrates well into the landscape; - Stabilised sludge; - Removal of sludge every two years	- High energy consumption.

CW and WSP are discussed hereunder.

2.2.1 Constructed Wetland

Constructed wetlands (CW) were developed by Dr K. Seidel in Germany in 1960 (Arceivala, 1998, p.253). These were widely adopted in Europe from around 1980. The CW can act as an environmentally sustainable alternative to conventional high energy processes for the treatment of domestic and industrial wastewaters, domestic wastewater sludge, urban run-off, landfill leachate, acid mine drainage and livestock slurry with BOD removal efficiencies between 60% and 90% reported in horizontal flow reed beds (Arceivala, 1998, p.260). More than 1200 constructed wetlands have been installed in the UK (MSc notes, Biological Processes, 2008) with only 5 sited in India (Arceivala, 1998, p.253).

CW utilise a plant based system incorporating root, stem and leaves upon which microorganisms can thrive and subsequently breakdown the organic compounds. The physical mechanism involving CW is that the wastewater pass through the porous area and root systems; chemical mechanism involves precipitation of insoluble compounds or co-precipitation with insoluble compounds (N and P) and adsorption on the substrate or by plants (N, P and metals) whereas biological mechanism involves biodegradation of organic matters, nitrification in aerobic zones and denitrification in anaerobic zones (EU guide on extensive wastewater treatment processes, 1991). Bed materials range in depth between 0.6 and 1 m. CW can be designed as subsurface flow (horizontal flow and vertical flow) and surface flow wetlands. The wastewater is passed through a gravel lava stone or sand on which the vegetation is grown in the subsurface flow wetlands whereas the wastewater is passed above the soil in the planted marsh in case of surface flow wetlands. In horizontal and vertical subsurface flow system, the wastewater being treated is passed horizontally and vertically respectively from the planted layer down through the substrate and then sent out after the treatment (Figure 2.1). The whole CW is lined by impervious layer to prevent the seepage of wastewater into the ground.

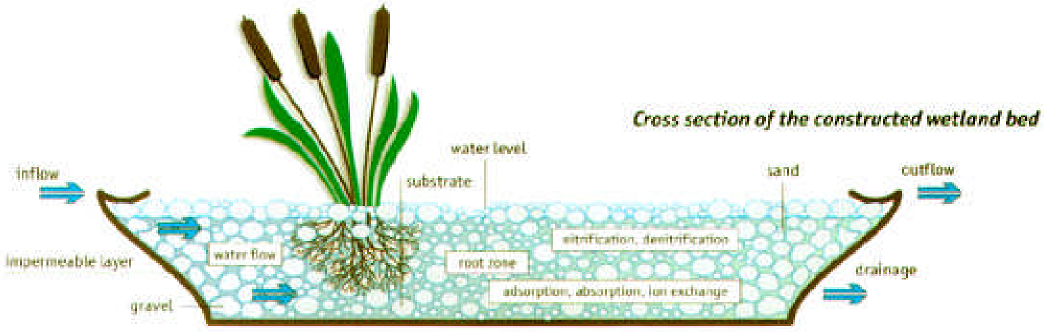

Figure 2.1: Horizontal flow constructed wetland (Source: http://www.artcenter-slovenia.org/images/program/environment/poster-reed-bedsmall2.jpg)

CW process design is generally based on detention time, organic loading rate, hydraulic loading rate, area needed, bed aspect ratio and harvesting frequency. Typical values of process design of subsurface flow CW in South Africa have been reported in Table 2.3 (Batchelor and Loots, 1995). The major disadvantage of CW is that they require substantial land area typically between 2 and 5 m^2 $person^{-1}$ (Arceivala, 1998, p.253); in addition, mosquito breeding may occur if inadequately maintained.

Table 2.3: Typical process design values of subsurface CW

Design parameter	**Design values**
Detention time, d	2-7
Maximum BOD loading rate, kg/ha/d	75*
Hydraulic loading rate, mm/d	2-30*
Area requirement, m^2/p.e.	2-5 (warm), 5-10 (temperate)
Bed aspect ratio (length:width)	up to 5:1
Harvesting frequency, years	3-5

* Considerable BOD/COD and TSS removal can be observed at much higher loadings also, however, ammonia-nitrogen reduction is less certain.

2.2.2 Waste Stabilisation Ponds

WSPs are process stable systems with a high operational safety (Barjenbruch and Erler, 2005) and are most effective in warm climates as this favours the proliferation of anaerobic microbiology and are applied extensively in developing countries. WSPs have been used widely for the past 50 years (Shilton *et al*, 2008) for the treatment of wastewater for scale ranging from <300 PE to >1000000 PE. Several WSPs have been implemented in the UK based on facultative and maturation designs for full flow treatment of domestic wastewater at the local community scale (Abis *et al*, 2005). Similarly in continental Europe, numerous countries including Greece and Portugal have installed ponds for municipal domestic wastewater (Gemitzi *et al*, 2007; Toprak, 1995). In France, approximately 20% of flow principally comprised of community scale dwellings of an average 600 PE, are treated by WSP with an estimated 2500 to 3000 reported (Racault and Boutin, 2005). However, currently there are no aWSP in operation in the UK or to this author’s knowledge, elsewhere in Europe.

Table 2.4: Reported WSP installations in developed countries worldwide

Country	Scale/ Type	Number	Reference
UK	<300 PE/ >1000000 PE; Facult./Mat.	N/a	Shilton *et al* (2008)
Greece			Gemitzi *et al* (2007)
Portugal		95	Toprak (1995)
France	600PE; Facult./Mat.	2500	Racault and Boutin (2005)
New Zealand*	N/a	N/a	Park and Craggs (2007)
Israel*	22000PE	N/a	Alexiou and Mara (2004)
Australia*	120,000 m^3 d^{-1}; aWSP	N/a	DeGarie *et al* (2000)

PE, Population equivalent; Facult., facultative; Mat., maturation; N/a, Not available. *Covered for methane capture.

At both full scale and pilot scale, only a limited number of studies are available that report methane data from capture using covered aWSP. In Melbourne, Australia a domestic wastewater flow of 120,000 m^3 d^{-1} (Table 2.4) is treated anaerobically in an aWSP and produces around 6000 kW of electricity 8-10 hrs d^{-1} $year^{-1}$ (DeGarie *et al*, 2000). Similarly fullscale aWSP have been installed at Arad, Israel (Alexiou and Mara, 2004) and New Zealand (Park and Craggs, 2007).

WSP systems consist of facultative pond, anaerobic pond, facultative aerated lagoon, complete mix-aerated lagoon, sedimentation pond and maturation pond. These ponds may be implemented and configured individually or in the combination (Figure 2.2).

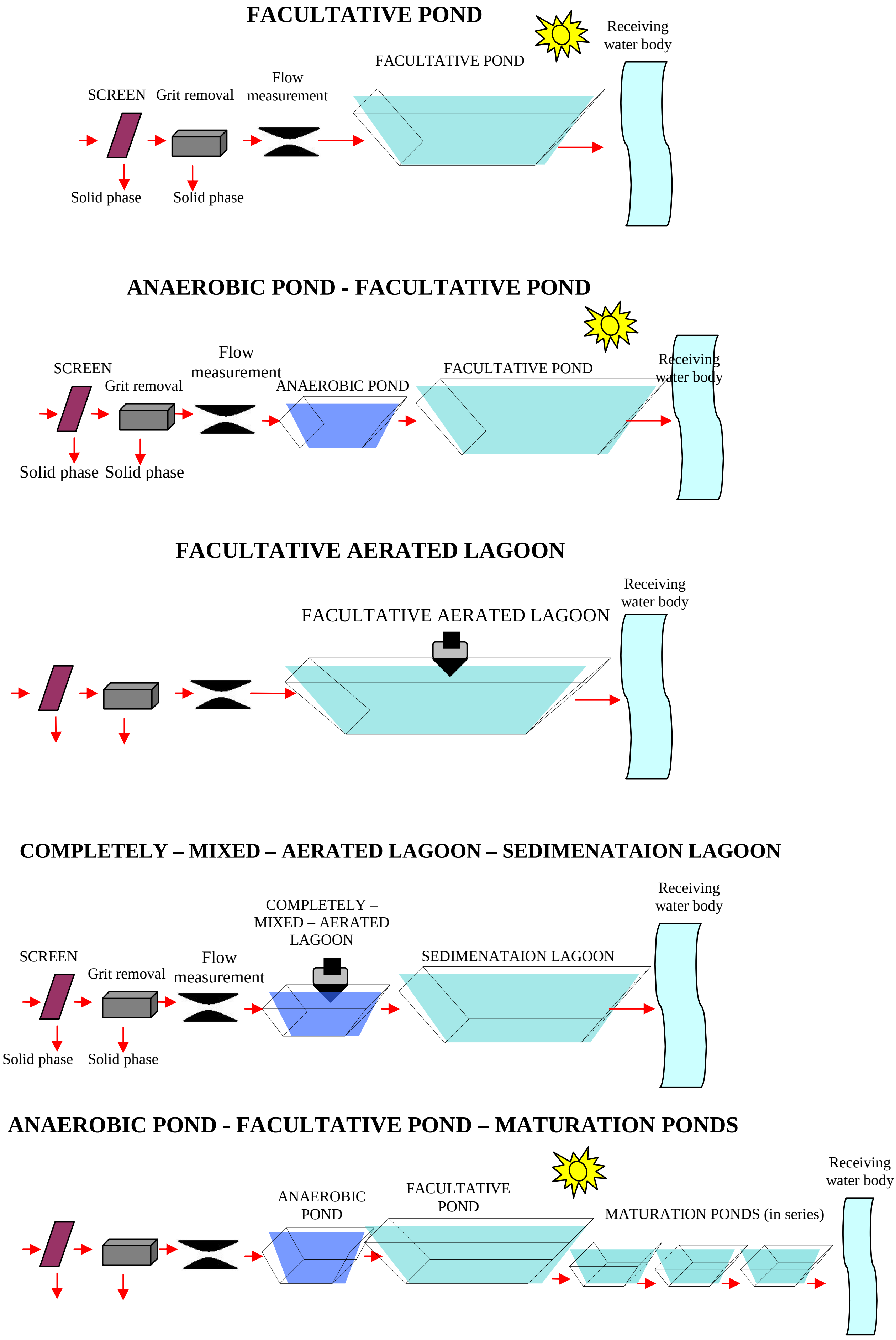

Figure 2.2: Various configurations of WSPs (adopted from von Sperling, p7)

Common to all aWSP flowsheet configurations is the upstream removal of gross solids by coarse screen and subsequent grit removal. The most common aWSP flow sheet then comprises aWSP-facultative pond-maturation pond. The aWSP is designed to remove the bulk of the organic material; the following facultative pond subsequently acts as a polishing step with some nutrient removal supported. A final shallow maturation pond is designed to allow UV penetration to promote pathogen kill with effective Coliform removal of up to 99.9999% reported. These WSP configurations have different removal efficiencies too (Table 2.5).

Table 2.5: Typical characteristics of WSP systems (adopted from von Sperling, 2007, p.5)

	Facult.	**Anaerobic-Facult.**	**Facult.-Aer.**	**Comp. mix aer. – sed.**	**Anaerobic-facult.-mat.**
Removal (%)					
BOD	75-85	75-85	75-85	75-85	80-85
COD	65-80	65-80	65-80	65-80	70-83
SS	70-80	70-80	70-80	80-87	73-83
Ammonia	<50	<50	<30	<30	50-65
Nitrogen	<60	<60	<30	<30	50-65
Phosphorus	<35	<35	<35	<35	>50
Coliforms	90-99	90-99	90-99	90-99	99.9-99.9999
Requirements					
Area (m^2/inhab.)	2.0-4.0	1.2-3.0	0.25-0.5	0.2-0.4	3.0-5.0
Power (W/inhab.)	≈0	≈0	1.2-2.0	1.8-2.5	≈0
Costs (US$/inhab)					
Construction	15-30	12-30	20-35	20-35	20-40
O & M	0.8-1.5	0.8-1.5	2.0-3.5	2.0-3.5	1.0-2.0

O&M, Operation and maintenance; Costs based on Brazilian WWTP; Facult., facultative; Aer., aerated; Comp. mix., completely mixed; Sed., Sedimentation; Mat., maturation.

Anaerobic-facultative-maturation ponds system configuration has maximum removal efficiency for BOD, COD, SS ammonia, phosphorus and coliforms with zero energy demand; however it requires 3-5 m^2 land area per inhabitant. Complete-mix aerated lagoon-sedimentation pond system has almost same removal efficiency too for BOD, COD and SS but it removes only 50% of ammonia, nitrogen and phosphorus with 1.8 to 2.5 W inhabitant^{-1} energy demands and up to 10 times less requirement for land area.

A common alternative flowsheet to the one presented integrates an upflow sludge blanket (UASB) reactor in place of the aWSP. The advantage is a lower footprint and higher mass transfer due to the increased mixing/ contact area available. However, the UASB does present an energy penalty as fluid flow is directed upward through a granular bed creating a substantial pressure drop; this is particularly pertinent when these technologies are implemented without energy recovery.

2.2.2.1 Anaerobic Waste Stabilisation Pond

The present investigation focuses on the application of aWSP and its design for the treatment of domestic wastewater in temperate climates (mean sewage temperature 12 °C). The process is designed as a roughing stage rather than as a one stage process. aWSP can be typically characterised as large basins of moderate depth between 2 and 5 m (Kayombo, web reference; Arceivala,1998 p.210). Under these conditions, strict anaerobes proliferate in the absence of dissolved oxygen . Anaerobic conditions are achieved by applying a comparatively high BOD loading m^{-3} which exerts a greater demand than the available oxygen can support (von Sperling, 2007, p.46) thereby improving the selection of anaerobic conditions. A schematic representation of anaerobic WSP process design is illustrated in Figure 2.3.

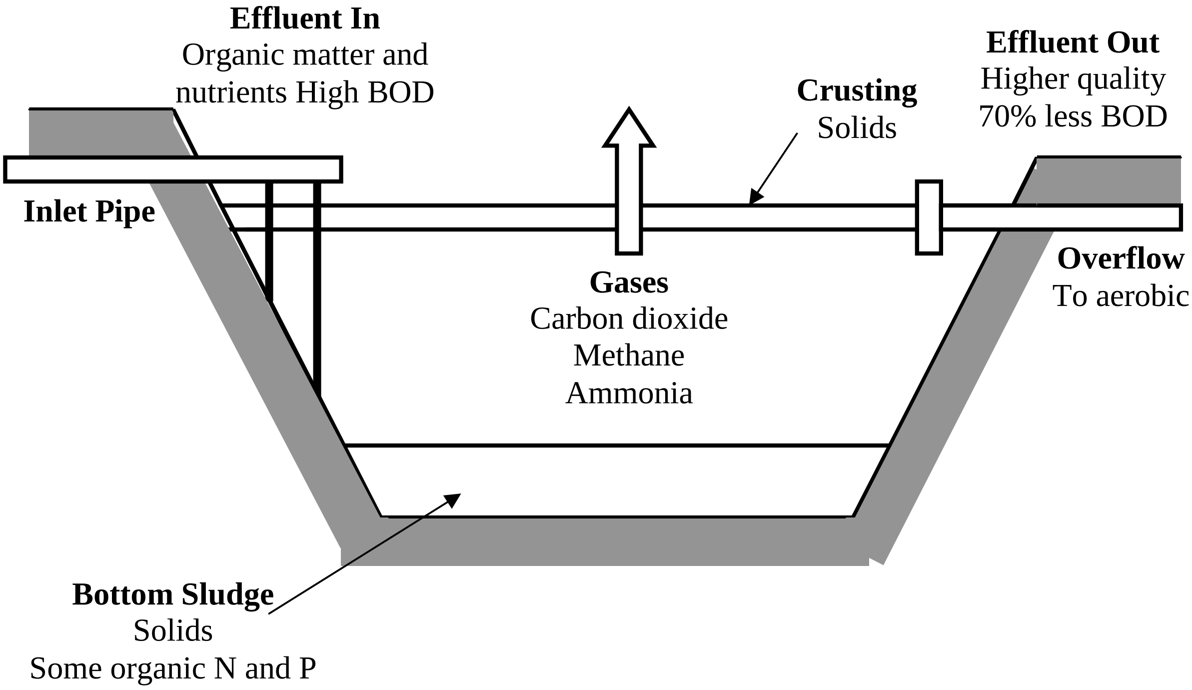

Figure 2.3: Simplified illustration of aWSP (adopted from www. stabilizationponds.sdsu.edu/)

Construction of aWSP is analogous to modern landfill design using an underlying 250mm bentonite/ clay band lined with an impervious plastic membrane (Alexiou and Mara, 2004). The design is cost effective and previously installed aWSP have demonstrated longevity with operating lifetimes of 25 to 30 years reported. In addition, due to the material construction, the carbon footprint is substantially below that of conventional processes where the aeration tanks and sedimentation basins are constructed of cast concrete (c.2.0 GJ m^{-3} of concrete). However, most aWSP remain uncovered thus permitting escape of fugitive methane emissions, substantially raising the carbon footprint. Various cover designs can be implemented to seal the WSP for methane capture including floating membranes (DeGarie *et al*, 2000). There is very little understanding as to how covering will impact upon treatment capacity or start-up; the reliance on, for example, UV for treatment performance is uncertain. Table 2.6 summarises typical values used for the design of various WSP systems (von Sperling, 2007, p.6).

Table 2.6: Typical process design values of WSP systems (adopted from Von Sperling, 2007)

Design Parameter	Anaerobic	Facultative	Facultative aerated	Completely mixed aerated	Sedimentation	Maturation
Detention time t (d)	3-6	15-45	5-10	2-4	≈2	(*)
Surface loading rate L_s ($kgBOD_5$/ha.d)	-	100-350	-	-	-	-
Volumetric loading rate L_v ($kgBOD_5/m^3$.d)	0.10-0.35	-	-	-	-	-
Depth H (m)	3.0-5.0	1.5-2.0	2.5-4.0	2.5-4.0	3.0-4.0	0.8-1.2
L/B ratio (length/breadth)	1 to 3	2 to 4	2 to 4	1 to 2	-	(**)
BOD removal coefficient K (complete mix) (20 ^{0}C) (d^{-1})	-	0.25-0.40	0.6-0.8	1.0-1.5	-	-
Temperature coefficient θ (complete mix)	-	1.05-1.085	1.035	1.035	-	-
BOD removal coefficient K (dispersed flow) (20 ^{0}C) (d^{-1})	-	0.13-0.17	-	-	-	-
Temperature coefficient θ (dispersed flow)	-	1.035	-	-	-	-
Dispersion number d (L/B = 1)	-	0.4-1.3	-	-	-	0.4-1.1
Dispersion number d (L/B = 2 to 4)	-	0.1-0.7	-	-	-	0.1-0.5
Dispersion number d (L/B >5)	-	0.02-0.3	-	-	-	0.03-0.23
Effluent particulate BOD ($mgBOD_5$/mgSS)	-	0.3-0.4	0.3-0.4	0.3-0.6	-	-
Average O_2 requirements (kg $O_2/kgBOD_{5\ removed}$)	-	-	0.8-1.2	1.1-1.4	-	-
Power level (W/m^3)	-	-	<2.0	>-3.0	-	-
Coliform die-off coefficient K_b (complete mix) (20 ^{0}C) (d^{-1})	-	0.4-5.0	-	-	-	0.6-1.2(***)
Temperature coefficient θ (complete mix)	-	1.07	-	-	-	1.07
Coliform die-off coefficient K_b (dispersed flow) (20 ^{0}C) (d^{-1})	-	0.2-0.3	-	-	-	0.4-0.7
Temperature coefficient θ (dispersed flow)	-	1.07	-	-	-	1.07

(*) The detention time in maturation pond is a function of the pond shape and the required coliform removal efficiency

(**) L/B ratio including baffles in a single pond >10; L/B ratio in each pond of a series of more than 3 ponds: 1-5

(***)Coefficient K_b (complete mix) for maturation pond: values given are for ponds in series (baffled ponds are not well represented by the complete-mix model)

2.3 Factors influencing Design of aWSP

2.3.1 Organic Loading Rate

Organic loading rate (OLR) is the main design parameter which influences the volume and hydraulic retention time (HRT) of an aWSP for the effective reduction of BOD or COD load applied to the pond. There are many references available in the literature which reveals that the WSP can be designed in a range of low OLR depending on the location and local experience (Table 8). The OLR of AWSP is greatly influenced by the temperature and is usually operated at ambient temperature which varies with the hours of the day and therefore the temperature of wastewater. Psychrophiles which are responsible for the biodegradation of organic material thrive at the temperature below 15 °C in terms of growth and reproduction. The temperature used for the design of aWSP is taken from the mean air temperature of the coolest month. It dictates the OLR as higher temperatures favours the increase in microbial activity and hence the organic removal rate. Thus the performance of aWSP suffers drastically at the lower temperature in cold regions (Wang *et al*, 2005).

Table 2.7: Typical OLR at various temperatures with BOD removal efficiency

OLR ($g\ BOD_5\ m^{-3}\ d^{-1}$)	**Temperature (°C)**	**BOD Removal (%)**	**Reference**
100	-	N/a	Prescod (1996)
100-350	depending on design temperature	N/a	Alexiou and Mara (2004)
100-400	higher loading for 27-30	N/a	Arthur (1983)
Not higher than 300	for Mediterranean Europe for summer conditions	N/a	Mara and Pearson (1987)
100-300		N/a	Mara *et al* (1992)
100	<10	40	Mara and Pearson (1998)
20T-100	10-20	2T + 20	Mara and Pearson (1998)
10T+100	20-25	2T + 20	Mara and Pearson (1998)
350	>25	70	Mara and Pearson (1998)
100	<10 winter design loading (Germany/ Israel)		Alexiou and Mara (2003)
240	17	82	Pearson *et al* (1996)
max 100 @ 4000 m altitude	9	N/a	Juanico *et al* (2000)
max 200 @ 2500 m altitude	20	N/a	Juanico *et al* (2000)
max 400 @ 400 m altitude	24	N/a	Juanico *et al* (2000)
340	13.5-23.5	75	Alexiou and Mara (2003)

Table 2.8: Typical OLR at various temperatures with COD removal efficiency

OLR (kg COD m^{-3} d^{-1})	**Temperature (°C)**	**COD Removal (%)**	**Reference**
0.508	23	54	de Oliveira *et al* (1996)
0.185	20.4	61	Toprak (1995)
0.141	17	34	Picot *et al* (2005)
0.212	23	40	Yagoubi *et al* (2000)
0.26	25	68	Peňa *et al* (2000)
0.09	23	29	Ghazy *et al* (2008)
0.372	23	34	Peňa (2003)
0.244	18.6	22	Picot *et al* (2003)

The removal of CD, BOD and suspended solids has been reported (Table 2.9).

Table 2.9: Performance of various WSP systems with OLR and temperature

Feed/ Location	**Vol.**	**HRT**	**OLR**	**Temp**	**COD**			**BOD**			**Suspended solids**			**Effluent Hygiene**	**Reference**
	(m^3)	(d)	(kg m^{-3} d^{-1})	(°C)	In	Out	%	In	Out	%	In	Out	%	CFU/ml	
Domestic/ India	10400	1	0.457	22.8	457	157	66[a]	N/a	N/a	N/a	N/a	N/a	N/a	N/a	Sato *et al* (2007)
Domestic/ India	28500	2.1	2.10	20.9	996	166	83[a]								Sato *et al* (2007)
Domestic/ India	30000	2.1	0.95	207	458	191	58[a]								Sato *et al* (2007)
Domestic/ Ecuador	1500	1	0.30	20	N/a	N/a	N/a	300	72	76	N/a	N/a	N/a	N/a	Johnson (2005)
Domestic/ Portugal	6080	5.07	0.17	20.4	699	291	58	N/a	N/a	N/a	375	N/a	N/a	N/a	Toprak (1995)
Domestic/ France	7130x2	4.6	0.86	17	645	179	72[b]	405	50	88[b]	266	109	59[b]	frm6 to2 FC (log10/100ml)	Picot *et al* (2005)
Mixed/ Mongolia	208800	7.7			245.4	131	46.6	84.6	41	52	206.8	38	81.6		Wang *et al* (2005)
Domestic/ Morocco	3500	2-3		21.47[c]	490	53	89[d]	190.1	16	91.6[d]	200.4	28	86[d]	30/ml	Kouraa *et al* (2002)
Mixed/ Turkey	338000	2.5	0.115	12[e]	N/a	N/a	N/a	462	273	40.86	N/a	N/a	N/a	N/a	Toprak (1993)

[a]Based on removal across anaerobic, facultative and maturation ponds in series. N/a – not available. [b]Based on removal across anaerobic, step fed facultative, maturation and polishing ponds in series. [c]Based on average temperature all over the year. [d]Based on removal across anaerobic, aerobic and facultative ponds in series. eBased on yearly average temperature.

Average COD, BOD and SS removal efficiency of these WSP systems is 59%, 70% and 76% respectively at various OLR and temperature. The concentration of COD and BOD in treated effluent is 167 mg l^{-1} and 45 mg l^{-1} (average) respectively excluding mixed effluent from Turkey WSP system which has 273 mg l^{-1} BOD.

Juanico *et al* (2000) discuss that aWSPs are effective at the altitude of 4000 m with the water temperature as low as 7 to 9 °C. Above table 2.9 illustrates the dependency of OLR on temperature which is well supplemented by Figure 2.4 (adapted from von Sperling, 2007, p.49).

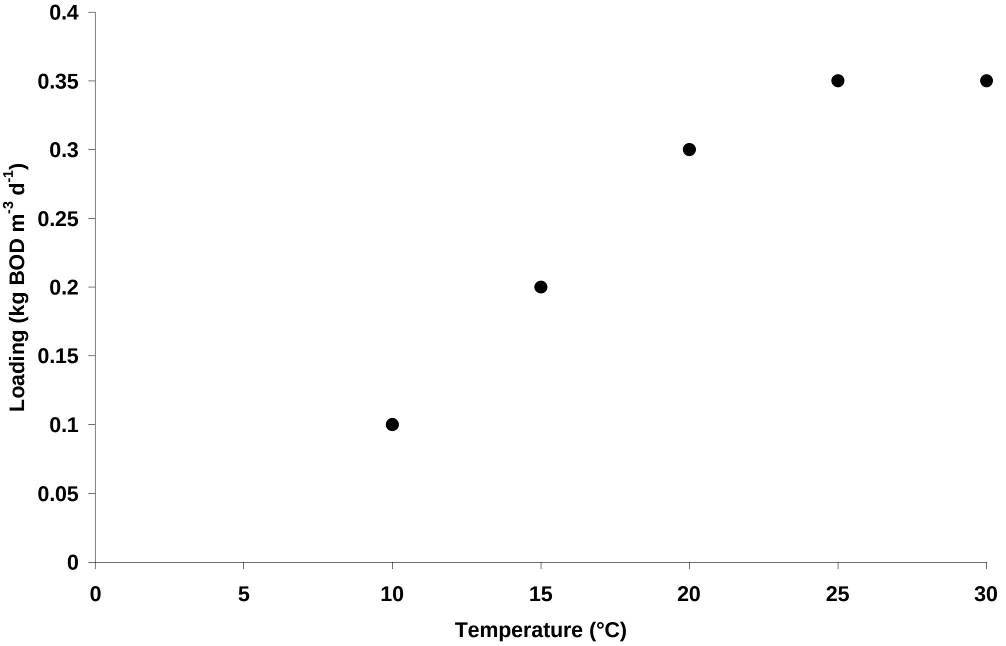

Figure 2.4: Organic loading rate versus temperature

It is understood from the above table and the figure that the OLR can be increased with increase in temperature up to 25 °C where it attains plateau. For colder climates like the UK, the AWSP can be designed at the lower end of the OLR. The OLR of 100 g BOD m^{-3} d is permissible at ≤ 10 °C with linear increase up to 300 g BOD m^{-3} d at 20 °C and slowly to 350 g BOD m^{-3} d at 25 °C and above (Peňa and Mara, 2004). Thus the volume of the pond can be determined once the temperature is known using an empirical formula (von Sperling, 2007, p.49). The formula takes the form as given under:

$$V = L/L_v \qquad (1)$$

where V is required pond volume in m^3, L is total BOD (filtered and particulate) load of influent (kg BOD_5 d^{-1}), L_v is volumetric loading rate (kg BOD_5 m^{-3} d). The pond area (m^2) is then simply calculated by dividing the required pond volume (m^3) by the selected depth of pond (m).

The removal efficiency of the pond can be expressed through total and filtered COD, BOD and SS respectively of influent and effluent (Barbosa and Sant'Anna, 1989). Empirical criteria are used as there is not still any conceptual mathematical model available for the estimation of removal of BOD after treatment in the pond. The empirical formula for the estimation of BOD removal in hot climate with complete mixing and at pH range of 6.8-7.2 suggested by Vincent *et al* (1963) is given as under:

$$P = P_0/6(P/\ P_0)^{4.8}\ R+ \qquad (2)$$

where P is pond and effluent BOD in mg l^{-1}, P_0 is influent BOD in mg l^{-1}, R is HRT for completely mixed separate pond in d.

The relation between BOD removal efficiency and temperature is graphically illustrated in Figure 2.5 as proposed by Mara (1997).

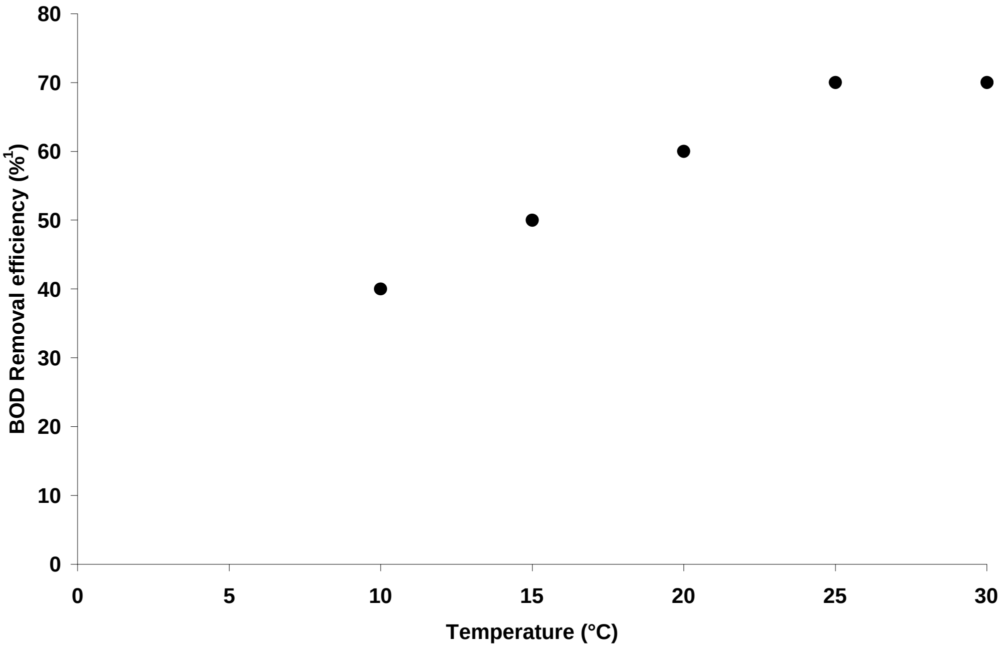

Figure 2.5: BOD removal efficiency versus temperature (adopted from von Sperling, p.52)

It is possible to calculate the effluent BOD after an estimation of removal efficiency is done using Figure 2.5, (Eq. 3).

$$BOD_{effl} = (1\text{-}E/100).\ S_0 \qquad (3)$$

where S_0 is total BOD of influent in mg l^{-1} and BOD_{effl} is total BOD of effluent in mg l^{-1}.

Toprak (1995) has described a mathematical expression correlating COD removal efficiency and liquid temperature by using Minitab Statistical Package (Minitab Inc., 1991) which is given here under (r= 82.8%):

$$E = -1.384 + 2.688(T_{l,e}) \qquad (4)$$

where E is COD removal efficiency in % and $T_{l,e}$ is effluent liquid temperature in °C.

WSPs can be simulated with respect to pollutant removal by the fully mixed model whereas plug flow model overestimates the plant performance (Ferrara and Harleman, 1981). Hydraulic behaviour of WSPs can be described using completely mixed tank reactor model (Moreno, 1990). The model uses first order kinetic for COD removal for completely mixed rector without recycle and ignores water losses owing to seepage and evaporation and is given as under:

$$C = C_0/(1 + k_T\ .\ t) \qquad (5)$$

where C_0 and C are COD of influent and effluent in mg l^{-1}, t is mean HRT in day, k_T is first order COD removal rate constant at liquid temperature T per day, k_T is a function of temperature and can be expressed as follows:

$$k_T = k_{20}\ (\theta)^{(T\text{-}20)} \qquad (6)$$

where k_{20} is the COD removal rate constant at 20 °C per day, θ is the temperature correction factor and T is the pond liquid temperature in °C.

An empirical relation between BOD removal efficiency and HRT is given (Catunda and Haandel, 1996) below:

$$EBOD = 1\text{-}2.4/HRT^{0.5} \qquad (7)$$

where EBOD is the BOD removal efficiency in %.

2.3.2 Hydraulic Retention Time

HRT is a second parameter given due importance in the design of aWSP. In fact for domestic wastewater the volume of aWSP is a compromise between HRT and OLR with emphasise being given to satisfy both the parameters to the maximum. The estimation or measurement of quantity of flow of wastewater thus assumes a greater significance as it influences the construction cost and the size of aWSP. Literature survey reveals typical HRT between 1 and 6 days (Tables 2.10 and 2.11) for better BOD or COD removal rate, however the trend of designing aWSP for HRT of 2 days or less is increasing (Von Sperling, 2007, p.50).

Table 2.10: Some reported HRT versus BOD removal with temperature for aWSP

HRT (d)	**BOD removal (%)**	**Temperature (^{0}C)**	**Reference**
2–3	40-60%	20-30	Arceivala (1998)
2 – 6.8	Not Available	23.6-26.3	Silva (1982)
2.5	60	>20	Mara (1976)
5	70	>20	Mara (1976)
1	50	>20	Mara (1976)
4.3	58.7	Not Available	Alabaster *et al* (1991)
1.2	75	13.5-23.5	Alexiou and Mara (2003)
6	60-80	Not Available	DeGarie *et al* (2000)
1	60-80	warm-temperate and tropical climates	Mara and Mills (1994) Mara and Pearson (1998)

Table 2.10: Some reported HRT versus COD removal with temperature for aWSP

HRT (d)	**COD Removal (%)**	**Temperature (°C)**	**Reference**
1	54	23	de Oliveira *et al* (1996)
4.5	61	20.4	Toprak (1995)
2.28	34	17	Picot *et al* (2005)
1.23	40	23	Yagoubi *et al* (2000)
2	68	25	Peňa *et al* (2000)
6.22	29	23	Ghazy *et al* (2008)
2	34	23	Peňa (2003)
2.41	22	18.6	Picot *et al* (2003)

The performance of aWSP can be sustained to a high level only when there is an intimate interaction of wastewater and biomass and the retention time of the biomass in the pond is high. This can be achieved by introducing wastewater at the bottom of the pond at several locations from the inlet launder to mimic the principle of UASB digester (von Springer, 2007, p.50).

2.3.3 Depth of the Pond

Strict anaerobic condition can be maintained in aWSP by providing deep depth. This helps minimising the possibility of the pond acting as a facultative pond. Generally the depth between 3.5 and 5.0 m is acceptable with consideration given to the excavation cost too. Table 2.11 illustrates the depths provided at some of the aWSPs

.

2.3.4 Geometry of the Pond

aWSP is built in square or rectangular shape with length to width ratio of 1:3 (von Sperling, 2007, p.51; Alexiou and Mara, 2004) and the inlet and outlet of the pond is located diagonally opposite corners for minimising hydraulic short circuiting (Shilton and Harrison, 2003). Mara (2003) recommends the length to width ratio of 2:1 for avoiding the accumulation of sludge near pond inlet.

The performance of aWSP can be enhanced by incorporating baffles. A series of vertical baffles induces wastewater to the bottom of the tank and then it passes over them in alteration. This kind of arrangement forces microorganisms to rise and settle and travel horizontally slowly. Thus there is a great amount of interaction between wastewater and active biomass as the wastewater travels down through the baffles configuration (Ujang *et al*, 2001). Anaerobic baffled reactor has better resilience compared to UASB and aerobic filters to hydraulic and organic loadings, longer solids retention time, lower sludge yield and its ability to separate the various phases of anaerobic catabolism.

Table 2.11: Process configurations with dimensions and biogas characteristics

Process Config.	**Process Layout**	**Mean Flow (m^3 d^{-1})**	**Vol. (m^3)**	**Geometry L x W x D (m)**	**Pond slope**	**HRT (d)**	**Biogas prod. rate (l m^{-2} d^{-1})**	**Vol. biogas prod. rate (l m^{-3} d^{-1})**	**Biogas conv.ratio (m^3kg $COD^{-1}_{removed}$)**	**Biogas composition (%)**		**Reference**
										CH_4	**CO_2**	
aWSP	AnP-FP-MP	1336.73	6080	2604 x 3.20	1:2.5	5.07	28.68–83.17	19.57	0.160 – 0.702	52 - 80	7 - 28	Toprak (1995)
aWSP	AnP-FP-MP	10000	10400	1500 x 4	-	1.0						Nobuyuki *et al* (2007)
aWSP	AnP-FP-MP	13500	28500	81x40 x 4.4	-	2.1		263 CH_4				Nobuyuki *et al* (2007)
aWSP	AnP-FP-MP	14500	30000	85 x 43 x 4.1	-	2.1		82.88 CH_4				Nobuyuki *et al* (2007)
Lab aWSP	-	0.0125 and 0.025	0.058	1.85 x 0.2 ø each 2 reactors	-	4.72/ 2.36	0.897	17	0.20 m^3CH4 kg-1 SCOD	70		Toprak, (1995)
Exp. AP	-	120 and 150	570	21x21x4	2:1	4.75/ 3.80						Papadopoulos *et al* (2003)
aWSP	Biodigester-AnP	1296	1632	0.06 ha (600) X 2.72		2.50						Nelson *et al* (2004)
aWSP	AnP-AP-FP	6750*,45000pe	3500	700 x 5		2-3						Kouraa *et al* (2002)
aWSP	AP-SFP-MP-PP	3127, 19000pe (1120 kg BOD/d)(72kgBOD/ha.d)	14260	0.23 ha (2300) x 3.1x2	-	3.5						Picot *et al* (2005)
aWSP	AnP-FP-MP	1600	1880	940 x 2		1.23						Yagoubi *et al* (2000)
aWSP	AnP-FP	1500	1500	31.6x15.8x3	2:1	1						Johnson *et al* (2005)
IIPS	SAP-IAP-FP-PP	27117	208800	290x180x4		7.7						Wang *et al* (2005)
Exp. aWSP	AnP-FP-MP	3.24	3.24	1.80x1.20x1.5		1						de Oliveira *et al* (1996)
aWSP	aWSP	845000	3380000	1332000m^2x2.5		2.5	37.69[a]	15.07[a]				Toprak (1993)

* considering 150 l $person^{-1}d^{-1}$, aWSP: Anaerobic WSP, FP: Facultative Pond, MP: Maturation Pond, AP: Aerated Anaerobic Pond, SFP: Step Fed Facultative Pond, IIPS: Integrated Intensive Pond System, IAP: Intensified Anaerobic Pond, SAP: Settling Anaerobic Pond. [a]Estimated values as methane

aWSP has been implemented as an integrated part of WSP system to reduce the land area particularly for large pond system (Saqqar and Pescod, 1995; Mara *et al*, 1992; Meiring *et al*, 1968; Parker *et al*, 1950; Mara and Pearson, 1986)(Table 2.11). aWSP implemented at Izmir wastewater treatment facility treats 845000 m^3 d^{-1} effluent with 2.5 d HRT with a moderate depth of 2.5 m whereas Nobuyuki *et al* (2007) reported mean flow of 14500 m^3 d^{-1} with 2.1 d HRT and 4.4 m depth.

2.4 Biogas Generation

Anaerobic biodegradation of organic matters in the wastewater reduces the concentration of pollutants and generates methane rich biogas. Biogas production varies with temperature and the rate of production of biogas increases with increase in temperature. Anaerobic treatment has been proved to be occurring at temperatures between 10 and 20 °C in suspended and attached growth reactors however the degradation of long chain fatty acids in this temperature range is often rate limiting (Metcalf & Eddy, 2004). Lower temperature range requires longer solid retention time, lower OLR and larger volume of tank (Banik and Dague, 1996; Collins *et al.*, 1998). Toprak (1993) has demonstrated through the estimation the change in methane production with temperature (Table 2.10). At 26.55 °C, the treatment efficiency of aWSP is reported to be 62.4% whereas only 30% removal efficiency is observed at temperature between 9 and 14 °C.

2.4.1 Biogas Yield

At standard conditions of 0 °C and 1 atmospheric pressure, 0.35 L of methane g $COD^{-1}_{removed}$ is produced under anaerobic conditions (Metcalf & eddy, 2004). Universal gas law is used to determine the quantity of methane produced at other than standard conditions as under:

$$V = nRT/P \qquad (8)$$

where V is volume occupied by the gas in L, n is moles of gas in mole, R is universal gas law constant (0.082057 atm.L/mole.K), T is temperature in K and P is absolute pressure in atm.

Below 15 $^{\circ}$C and at 23 $^{\circ}$C water temperature, biogas production rate of 0.0028 m^3 m^{-2} d and 0.0462 m^3 m^{-2} d respectively has been reported at constant BOD load (Benefield and Randall, 1980), whereas Toprak, (1993, 1995) has reported 0.03769 m^3 m^{-2} d and 0.045 m^3 m^{-2} d biogas production rate. Ostwald *et al* (1970) reported biogas production rate of 0.01573 m^3 m^{-2} d.

Methane production rate of 0.00252 m^3 m^{-2} d (Iwema *et al*, 1987), 0.0021 m^3 m^{-2} d (Benefield and Randall 1980) and 0.01818 to 0.04874 m^3 m^{-2} d (Toprak, 1995) depending on influent COD and temperature has been reported.

Biogas conversion ratio of 0.197 and 0.702 m^3 kg $COD^{-1}_{removed}$ for aWSP (Toprak,1995), 0.11 m^3 kg $COD^{-1}_{removed}$ for fixed film reactor (Noyola *et al*, 1988), 0.16 m^3 kg $COD^{-1}_{removed}$ for anaerobic filter (Kobayashi *et al*, 1983) and 0.21 m^3 kg $COD^{-1}_{removed}$ for UASB reactor (Lettinga *et al*, 1983) has been reported.

Table 2.10: Estimated generation of methane with temperature and BOD removal efficiency

Months	Mean Ambient Air Temp ^{0}C	Predicted Water Temp ^{0}C	Treatment Efficiency %	Effluent BOD mg/L	BOD load Removed kg/d	Methane Produced m^3/d	Methane Prod. rate l/m^2/d	Vol. Methane Prod. rate l/m^3/d	Methane Conv. ratio m^{3}kg BOD$^{-1}_{removed}$
January	7.62	9.12	30	323	117065	37461	27.70	44.33	0.32
February	8.24	9.74	30	323	117065	37461	27.70	44.33	0.32
March	10.25	11.75	30	323	117065	37461	27.70	44.33	0.32
April	14.40	15.96	31.9	315	123825	39624	29.30	46.89	0.32
May	19.23	20.73	42.2	267	164385	52603	38.90	62.25	0.32
June	24.20	25.70	57.1	198	222690	71261	52.70	84.33	0.32
July	25.96	27.46	62.4	174	242970	77750	57.50	92.01	0.32
August	25.05	26.55	59.7	186	232830	74506	55.10	88.17	0.32
September	21.60	23.10	49.3	234	192270	61526	45.50	72.81	0.32
October	17.38	18.88	37.80	288	146640	46925	34.70	55.53	0.32
November	12.57	14.07	30	323	117065	37461	27.70	44.33	0.32
December	9.55	11.05	30	323	117065	37461	27.70	44.33	0.32

Influent flow = 845000 m^3/d, Influent BOD = 462 mg/l, Area of ponds = 1352000 m^2, Volume = 3380000 m^3

2.4.2 Impact of Solubility on Methane Generation

Methane solubility is low in water. The solubility curve of methane in water is given here under (Figure 2.6).

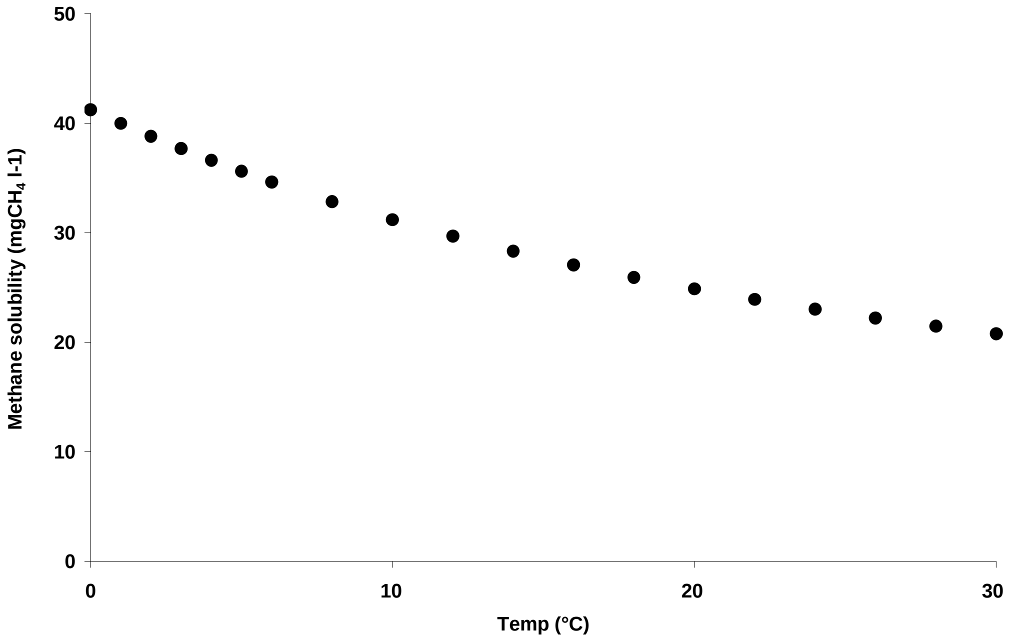

Figure 2.6: Methane solubility versus temperature

The solubility of methane decreases with increase in temperature as can be seen from Figure 2.6. aWSPs are generally operated at ambient temperature ranging between 20 and 25 °C. It is therefore understood from this figure that the solubility of methane ranges approximately between 23 and 25 mg l^{-1} of water. A fraction of generation of biogas thus is dissolved in water. aWSP is a roughing stage in most of the treatment plants which significantly reduces organic load on the following stages. This soluble methane is then passed into the subsequent unit. If aWSP is followed by ASP then the dissolved methane will be stripped off to the atmosphere by virtue of aeration.

EVALUATING THE POTENTIAL OF ANAEROBIC WASTE STABILISATION PONDS FOR WASTEWATER TREATMENT IN A TEMPERATE CLIMATE

ABSTRACT

A pilot scale baffled anaerobic waste stabilisation pond (aWSP) was designed based on an organic loading of 0.17 kg COD m^{-3} d^{-1} to evaluate the potential of aWSP as a passive, sustainable technology for domestic wastewater treatment in temperate conditions. After 4 weeks of operation and up to 45 days (end of study), average removals of 37% COD, 30% BOD and 36% suspended solids were observed which compares to the literature surveyed for aWSP treating domestic wastewater. A linear correlation between COD removal and time since start-up was observed and compared favourably to an anaerobic membrane bioreactor (aMBR) that was started up unseeded. Seeding the aWSP apparently augmented start-up and whilst higher COD removal for aWSP have been reported, it is anticipated that continued operation (>45 days) will yield further efficiency improvements. Methane reported in the gas and liquid phase was approximately 4.1% and 5.7 mg l^{-1} respectively suggesting relatively low production of methane. However, this does demonstrate that methanogenesis occurred soon after start up. Using this data to model a 5000 PE site, total energy output of 62 $MWhy^{-1}$ (electricity and heat) was generated and only 6 MWh y^{-1} (electricity) consumed, this compares to an equivalent conventional activated sludge process (ASP) which uses approximately 655 MWh y^{-1} electricity for aeration. Results to date suggest that aWSP technology represents a viable sustainable alternative for domestic wastewater treatment in a temperate climate versus traditional high energy technologies.

Keywords: Anaerobic; waste stabilisation pond; start-up; energy model

INTRODUCTION

Activated sludge processes (ASP) for secondary treatment of wastewater requires intensive energy input and produces a substantial quantity of sludge which requires thickening, anaerobic or aerobic digestion, chemical conditioning and dewatering before ultimate disposal. The energy requirement associated with treating domestic wastewater using the ASP currently varies between 0.3 and 0.7 $KWhm^{-3}$ treated representing 54 to 97% of the total energy demand for domestic wastewater treatment. The associated energy demand has therefore stimulated water providers to consider alternative technological routes. In EU 80% of the treatment plants serve the population under 5000 (Alexiou and Mara, 2003) and employ the standard treatment technologies like ASP. Extensive treatment systems are natural and passive (effectively zero energy) which require limited maintenance and substantially low operation cost. Waste stabilisation ponds (WSP) are such technology and have been implemented for scales between 5000 PE (Barjenbruch and Erler, 2005) and 1mn PE (Ramadan and Ponce, 2009). Whilst typically operated in developing countries with warmer climates, some implementation has been observed in the UK and mainland Europe (Alexiou and Mara, 2003; Racault and Boutin, 2005; Abis, 2002). Due to their passive design (low mixing potential), organic loading is typically limited to c0.3 Kg COD m^{-3} which is one magnitude below activated sludge. Thus the basic land requirement is more significant. However, estimated capital and operating costs remain substantially below that of other processes. Johnson *et al*, 2007 have quoted Alexandre *et al* 1997 for the average capital, operation and maintenance cost for wastewater treatment using various treatment processes in France for 1000 PE (Table 1).

Anaerobic waste stabilisation pond (aWSP) utilises similar design principle, however no such system is suitable for UK. This might be also related with perception that the UK climate is not favourable for anaerobic treatment, high land cost and the stipulated norms of treated wastewater can not be attained easily. aWSP as roughing stage can significantly reduce the overall requirement of surface area for WSP system without additional energy input (Picot *et al*, 2003). aWSP are instrumental in treatment of wastewater with high suspended solids and organics (Toprak, 1995) and convert large proportion of organic carbon into methane and carbon dioxide with lower sludge production. aWSP have rarely been studied in temperate countries despite their numerous advantages. Biodegradation of organics in the aWSP is effected by a combination of sedimentation which forms settled solids layer and secondly methanogenesis of the solids organic fraction in the settled layer.

The aim of this study is to evaluate the potential of aWSP for wastewater treatment in temperate condition, analyse the start up and organic removal potential and understand the potential energy savings associated with aWSP versus ASP.

MATERIALS AND METHODS

Experimental set up

The reactor was constructed of 12 mm PVC sheeting. The length to width ratio was designed as 3:1 in accordance with the literature (von Sperling, 2007; Peña and Mara, 2004). The reactor contained five chambers of near equal volume with four baffles placed at 325 mm interval to maintain over-under flow of wastewater alternately to induce passive mixing with the active biomass. The aWSP was made air tight using a bolted flange; the flange seal comprised 3mm rubber sheet and was made water tight by welding it from outside and applying silicone from inside. Liquid and gas sampling ports were provided for each chamber.

The aWSP was seeded with 17 % v/v using anaerobic flocculated sludge. Partially settled wastewater from Cranfield University Wastewater Treatment Works was taken into a short retention time feed tank and stirred using circulation of influent by peristaltic pump to prevent the settling of suspended solids. The influent was then introduced near the bottom of the first chamber of the reactor at the design flow rate of 74.82 $l.d^{-1}$. Throughout the study, the hydraulic retention time of 2.3 d was maintained (Table 2). Any generation of biogas was initially vented out to atmosphere. However, following the first 4 weeks of start up individual gas sampling bags were added for each independent gas line (Figure 1). In total the reactor was operated from commissioning for 45 days. Effluent analysis was based on data recorded after 28 days and was arbitrarily selected as a cut-off to omit data variations observed in the early period of start up.

Wastewater sampling and analysis

Influent and effluent samples were collected daily in precleaned 250 ml polyethylene containers and transported to the laboratory within the shortest time possible for physico-chemical analysis. The ambient temperature was noted while collecting the samples and measurements for pH and DO using Jenway 3540 pH and conductivity meter and Hach HQ10 probe respectively. Influent and effluent were analysed for Suspended solids, soluble COD (sCOD), total COD (tCOD), BOD, ammonical nitrogen, alkalinity, total phosphate (TP) and particle size distribution. The analyses for SS, BOD and alkalinity were carried out in accordance with Standard Methods (APHA, 1989) whereas COD, total phosphate and ammonical nitrogen were analysed using preprepared kits and Merck’s spectrophotometer (Nova 60). Malvern Mastersizer 2000 was used for particle size distribution analysis. The filtration of influent and effluent samples was effected using Whatman No. 40 filter paper.

Biogas sampling and analysis

Biogas sample bags with PVF septum valve (Cole-Parmer Instrument Company) were affixed to each gas collection port. Collected biogas samples composition was analysed using 200 Series Gas Chromatograph (Cambridge Scientific Instruments) equipped with Alltech CTR concentric packed columns (outer column 6ft x ¼” packed with activated molecular sieve; inner column 6ft x 1/8” packed with porous polymer mixture) and thermal conductivity detector. Helium was used as a carrier gas (5 psi). Oven temperature was operated isothermally (100 ºC).

RESULTS AND DISCUSSION

Start up of an aWSP on a UK domestic wastewater

Organics removal during start-up

The performance of reactor can be presented based on total influent and total effluent, filtered influent and filtered effluent and total influent and filtered effluent based on COD, BOD and SS removal (Barbosa and Sant'Anna (1989). Present study reports all the results based on total influent and total effluent basis and the performance of this aWSP was assessed based on COD removal. The start up performance of aWSP for the removal of COD was evaluated. 30% and 37% COD removal efficiency was observed by the end of 30 and 45 days respectively (Figure 2). This performance is in agreement with a reported literature stating 25% to 40% removal efficiency can be achieved in aWSP purely due to physical settlement of suspended solids (Toprak, 1993). It has been reported from various studies that COD removal efficiency of aWSP can vary between 22% and 70% depending on organic loading rate and temperature (de Oliveira et al, 1996; Toprak, 1995; Picot *et al*, 2005; Yagoubi *et al*, 2000; Peňa, 2000; Gahazy *et al*, 2008; Broome *et al*, 2003). The linear removal of COD with time indicated that aWSP performance shifted towards stabilisation and can achieve optimum removal efficiency with time. Start up period is a very crucial step for early stabilisation and stable operation of anaerobic reactor at the designed OLR (Foresti, 2001) and previous works have cited steady state operation achieved in aWSP after 6-8 months and 8-12 months in South Africa and Australia respectively (Alexiou and Mara 2003; Parker *et al*, 1959) and start up period lasted 6 months for an unseeded UASB reactor treating domestic wastewater (Passig *et al*, 2000).

The start up removal efficiency of this aWSP was compared with highly energy intensive anaerobic membrane bioreactor (aMBR) (Martin, 2009) operated with similar influent characteristics and ambient condition. aMBR uses membranes for physical separation of solids from wastewater. The comparison revealed that the COD removal efficiency of aWSP (55 hr HRT) was almost equivalent to that of aMBR (15 hr HRT). This might be attributed to the fact that the particulate COD associated with suspended solids was being removed effectively and not soluble COD by aMBR. aWSP had also been incorporated with four baffles. A reactor with four baffles has better organic removal efficiency than with two baffles (Abbas *et al*, 2006) as the baffles create hindrance to the suspended solids and reduce their velocity through the reactor which helps in accelerating sedimentation with better capture. This difference between removal efficiency closes the performance gap between aMBR and aWSP on start up and when flocculated. aMBR was operated for 125 days and achieved 60% COD removal efficiency. Due to the trend of current performance, COD removal efficiency of aWSP may reach up to 60% by 125 days. The fast start up of aWSP could be attributed to its inoculation with good quality flocculated anaerobic sludge which accelerated the biodegradation potential of this reactor as evident from the existing removal efficiency.

Evaluation of effluent quality

COD, BOD, Suspended solids and total phosphate were removed by 37%, 30%, 36% and 12% respectively. The mean COD, BOD, SS and ammonical nitrogen concentrations in the effluent were 230 mg l^{-1}, 106 mg l^{-1}, 95 mg l^{-1} and 37 mg l^{-1} respectively (Figure 3). 29% of sCOD was also removed from the wastewater. tCOD removal is attributed to the sedimentation and anaerobic digestion of organic matter whereas anaerobic degradation is responsible for sCOD removal in water column. The wastewater in aWSP during its operation was anaerobic in nature which was represented by anaerobic activity indicators of pH, alkalinity and ammonical nitrogen. pH of the effluent decreased (5%), however alkalinity and ammonical nitrogen increased (9% and 12% respectively) in the effluent. Previous studies also reported decrease in pH (4.5 to 5%), increase in alkalinity (7 to 18%) and ammonical nitrogen (3 to 13%) (Picot *et al*, 2003; Picot *et al*, 2005; Toprak, 1995). Increase in alkalinity in the wastewater indicated HCO^{-}_{3} production as an end product of the anaerobic degradation (Toprak, 1995) whereas ammonia forms in the anaerobic break down of compounds containing nitrogen (Leslie Grady *et al*, 1999). The overall removal efficiency of aWSP was in agreement with the referenced literature. Mèze aWSP located on the Mediterranean coast of France removed 34% COD, 46% BOD, 38% SS and 13% TP respectively (Picot *et al*, 2005) whereas an aWSP in a rural area of Egypt removed 29% COD, 22% BOD and 24% SS (Ghazy *et al*, 2008). EU UWWTD stipulates that the treated effluent must meet the water consent with BOD ≤ 25 mg/l and SS ≤ 15 mg/l in treated effluent. A well operated aWSP can remove up to 70% of COD from wastewater (Sato *et al*, 2007). Therefore, a potential of installation of aWSP as roughing stage can be looked into in a temperate climate like UK as it can subsequently help reduce energy consumption in secondary biological unit like ASP.

The organic removal performance of aWSP during start up was also compared with other anaerobic processes viz. aMBR and upflow anaerobic sludge blanket (UASB) reactor (Table 4). These processes were operated on the same effluent as that of aWSP. UASB reactor had grey to black granular sludge with better settling characteristics while aWSP had flocculated sludge characterised by light, small and non spherical grains. aMBR was unseeded and the biomass was developed during the course of study. UASB had faster start up time and its performance was close to the compliance with the water consent (Figure 4). The better efficiency was due to stable bio matrices as result of impulsive agglomeration of microorganisms to give rise to compact granules with better settling characteristics (Sabry, 2008), the upflow effluent direction to remove dissolved and colloidal organic matter and the presence of gas solid separator which separates solids from gas and prevents their escape into the treated effluent at the top (Catunda and Haandel, 1996). Since aMBR uses membrane for solid separation, the particulate COD removal efficiency was higher than UASB and aWSP. The effluents quality from aWSP and aMBR did not differ extensively as former were inoculated with flocculant sludge which reduced start up time too.

Organic loading rate (OLR), temperature and hydraulic retention time (HRT) affect the removal of organics from wastewater (Alexiou and Mara 2003). The start up COD removal efficiency (37%) with organic loading rate (0.17 kg COD m^{-3} d^{-1}) was compared with reported studies (Figure 5). 22% COD removal at 0.244 kg COD m^{-3} d^{-1} OLR (Picot *et al*, 2003), 29% at 0.1 kg COD m^{-3} d^{-1} OLR (Ghazy *et al*, 2008), 30% at 0.17 kg COD m^{-3} d^{-1} OLR (Toprak, 1995), 34% at 0.141 kg COD m^{-3} d^{-1} OLR (Picot *et al*, 2005), 40% at 0.212 kg COD m^{-3} d^{-1} OLR (Yagoubi *et al*, 2000), 53% at 0.25 kg COD m^{-3} d^{-1} OLR (Papadopoulos *et al*, 2003), 68% at 0.26 kg COD m^{-3} d^{-1}

OLR (Peňa *et al*, 2000) and 72% at 0.24 kg COD m^{-3} d^{-1} OLR (Parker *et al,* 1959) have been reported. The current performance of aWSP was found in agreement with above studies. Figure 4 also showed that the COD removal efficiency increased with increase in organic loading rate which was also in agreement with results reported for Sesimbra aWSP (Toprak, 1995).

Temperature has a significant impact on COD removal efficiency of aWSP. Annual average liquid temperature in UK is 12 °C (Soares, 2009). Organic removal efficiency attains plateau at 25 °C (Mara, 1997). However no such linear relation was found (Figure 5). In winter a small quantity of organic biodegradation occurs anaerobically at a temperature below 15 °C and any removal of organic matter is due to sedimentation of suspended solids (Pescod, 1996) as lower microbial growth kinetics reduces organic biodegradation. However aWSP have been reported to operate effectively at temperature between 7 °C and 9 °C in Bolivia at high altitude with methane bubbles observed at pond surface which contradict other studies that claim a very low anaerobic degradation in ponds occur below 13 °C (Juanico *et al,* 2000) or stops below 15 °C liquid temperature (Gloyna, 1971; EPA, 1983; WHO, 1987). Present study reported at 22 °C found 37% COD removal at start up. This result is also in line with various studies as reported in Figure 5. However, Figure 5 contradicts the findings of literature studies (Mara, 1997; Pescod, 1996). Therefore, it is highly recommended to consider the reported values as guidance only for the design and the actual design of aWSP should be based on the local experience and condition.

Recent trend in designing aWSP at 1 d HRT reduces land requirements for whole pond system by 75% at design temperatures above 16 °C (Pearsons, 1996) and they are found to be performing quite satisfactory too (de Oliveira *et al*, 1996; Yagoubi *et al*, 2000). A collection of studies show that removal efficiency improves with increasing HRT (Catunda and Haandel, 1996) however DeGarie *et al*, 2000 quoted Mara and Mills, 1994 and Mara and Pearson 1998 that the removal efficiency in terms of BOD can reach up to 80% with 1 d HRT in warm temperature and tropical climates whereas 70% BOD removal with 12 hours HRT can be achieved in high rate anaerobic ponds at 25 ^{0}C (Peña, 2002). At 2.28 d HRT, 34% COD removal efficiency (Picot *et al*, 2005) and at 2.4 d HRT 22% efficiency (Picot *et al,* 2003) has been reported. However, 60% BOD reduction has been suggested with 2.5 d HRT at >20 °C

(Mara, 1976). In current study, 2.3 d HRT with 37% COD removal efficiency was observed which was also in agreement with these two studies.

Methane Generation

Biogas was principally captured from chamber 4 (Figure 1) with analysis demonstrating a methane concentration of 4.1% which is low compared to the study of Toprak, 1995 and DeGarie *et al*, 2000 in which they reported headspace gas composition of 52 to 80% and 65% respectively when operating long-term and in a more moderate climate (mean sewage temperature 20 °C). The headspace gas capture was low as the aWSP was operated fully flooded which forced the formation of gas pockets within the compartment (as evidenced by liquid displacement to the gas collectors) and limited gas transmission to the collectors; future practice should ensure sufficient freeboard for maximising gas collection. Without consistent gas flows, it was not possible to determine specific methane yield, thus the typical methane yields reported for aWSP ranging 0.0021 to 0.04874 $m^3\,m^{-2}\,d^{-1}$ depending on influent COD and liquid temperature (Benefield and Randall, 1980; Toprak, 1995) still require validation in temperate climates. Although only low volumes of gas were detected, this does demonstrate that methanogenesis occurred after a relatively short start-up period (cf. Alexiou and Mara, 2005; Parker *et al.*, 1959). In addition, production of methane in chamber 4 coincided with the highest liquid phase methane concentration of c.7.1 mg l^{-1}. At the operating temperatures of 19 to 26 °C achieved in this study, the saturation constant for methane approximates to 21 mg l^{-1} (Yamamoto *et al*, 1976) and whilst not achieved in this study, it is anticipated that at steady-state a value more closely associated with the Henry's constant will be found. From the gradual increase observed in liquid phase methane concentration (Table 5) along chambers 1 to 4, it may be hypothesised that acetogenesis and acidogenesis occur principally at the start of the reactor stimulating more extensive production of methane in the latter chambers.

Process Model

Present investigation demonstrated an encouraging start up results in terms of COD BOD and SS removal. A model has been developed to evaluate energy usage and consumption for the aWSP flowsheet versus a standard ASP flowsheet with specific consideration of organics and suspended solids removal. The limits of the model were to consider COD removal efficiency of 45%, SS removal 30% and methane yield of 0.11 m^3 CH_4 $kgCOD^{-1}$ (Mcadam, 2009). The model is proposed for 5000 PE with wastewater characteristics of Cranfield University campus sewage. The flowchart comprises of a covered aWSP followed by trickling filter (TF) to meet the permitted consent (Figure 6a). Covering of aWSP will also make this model neighbourhood friendly as it will eliminate odour problem if any and can therefore be implemented near the populated areas. TF has been incorporated as secondary biological treatment unit due to its many advantages over other standard treatment processes. TF requires minimum or no energy for effluent distribution arm operation and produces a small quantity of sludge. TF can treat effluent with consistent quality to meet the stipulated norms of water consent.

The treatment process will involve the removal of inert gross solids from influent using screen (6mm). The screened influent will be sent to aWSP by gravity. The influent will be discharged at the bottom of the aWSP using influent distribution pipe network for distributing the influent uniformly over the surface to minimise short circuiting and for proper or passive mixing with settled active biomass for COD reduction. The effluent will rise up to mimic UASB flow pattern for sedimentation of suspended solids due to gravity. The top of the aWSP will be covered to collect methane rich biogas and subsequent utilisation for heat and electricity generation. The treated effluent will be taken off from 300 cm below the surface (Mara and Pearson, 1987) in a weir for secondary treatment in TF. The effluent will be distributed across the surface of TF using effluent distribution arm. TF will be installed with media on which biofilm of microorganisms will grow to reduce COD from the wastewater. The treated effluent will be sent to humus tank for sludge settlement and stream disposal. The settled sludge from humus tank will be sent back to the inlet of aWSP.

This model has eliminated energy intensive ASP or land intensive facultative pond as secondary treatment unit. Alexiou and Mara, 2003 quoted CEDEX (1996) and Chambers (1993) that in Europe most of the operational problems at wastewater treatment plants are related to bulking and rising of sludge at all sizes of ASP. Thus this flowsheet will eliminate this major operational problem too. 62.41 $MWhy^{-1}$ energy will be produced from 6469 m^3 $year^{-1}$ generation and capture of methane from aWSP. This could yield 33.07 MWh heat and 19.97 MWh_e electricity generations using combined heat generator. As both the systems are gravitationally fed, there will be limited energy requirement for operation principally pertaining to the screen (c.0.7kW or 6.13 $MWhy^{-1}$). Therefore the process is energy positive by 13.8 $MWhy^{-1}$ (69%).

A comparison of energy demands for ASP (Figure 6b) treating an identical flow and an identical feed is reported. This flow sheet uses primary clarifier and ASP for compliance with water consent.

Treatment process will involve screening (6mm) of influent before being sent to primary clarifier for the sedimentation of suspended solids which will remove 50% of SS from the influent. The clarified effluent will then be taken into ASP plant for the biodegradation of organic matters. Air will be provided through blowers for meeting the mixing and aeration requirement. The effluent will be sent to secondary clarifier for the settlement of active sludge. A part of settled sludge will be recycled back to the inlet of ASP to maintain the concentration of mixed liquor suspended solids in the tank. The clarified effluent will finally be discharged to a water body. The settled sludge from primary clarifier and waste activated sludge from secondary clarifier will be co-digested in the anaerobic digester for volume and pathogen reduction and biogas generation.

Electrical demand for mixing and aeration in ASP is approximately 655 $MWhy^{-1}$. Based on an electrical output of 50 $MWhy^{-1}$ from anaerobic digestion of the removed solids, the process is energy negative by 610.5 $MWhy^{-1}$ (-1200% of electricity produced).

CONCLUSIONS

This work currently demonstrates the potential significance of aWSP for the UK wastewater treatment providers. Further work is required to maximise organic and suspended solids removal and to understand the implications of organic loading rate for plant size. However, with extensive studies n data interpretation thereof, almost zero energy demand aWSP-TF model can become a valuable tool for effective wastewater management as a part of sustainable development programme.

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TABLE AND FIGURES

Table 1: Capital, operation and maintenance costs of treatment in France in 1997

Treatment process	Capital cost (ecu per PE)[a]	O & M cost (ecu per PE year)[a]
Activated sludge	230	11.5
Trickling filter	180	7.0
Rotating biological contactor	220	7.0
Aerated lagoon	130	6.5
Constructed wetland	190	5.5
Waste stabilisation ponds	120	4.5

[a] Average exchange rates in 1997 (www.oanda.com/convert/fxhistory): 1 ecu = GBP 0.69 = USD 1.13

Table 2: Designed parameters of covered anaerobic waste stabilisation reactor

Reactor Size (m)	Baffle Thickness (m)	Volume (L)	Effluent Flow ($L.d^{-1}$)	Hydraulic Retention Time (d)
1.575 x 0.5 x 0.225	0.012	172	74.82	2.3

Table 3: Mean characteristics of influent from 28th day of operation

Parameter	Influent
Temp, ^{0}C	19-26.8
pH	7.34
SS, mg/l	148
CODt, mg/l	330
CODs, mg/l	208
BOD, mg/l	152
TP, mg/l	7
Alkalinity as $CaCO_3$, mg/l	220
Ammonical nitrogen, mg/l	33
Particle size distribution, d_{50}	104.48

Table 4: Start up guide for UASB, aMBR and aWSP

	UASB	**aMBR**	**aWSP**
Seed	Seeded	Unseeded	Seeded
Flow direction	Up flow	Vacuum pumped/lateral	Passive/lateral
Seed type	Granular	Flocculated	Flocculated
Organic loading rate	Higher	Higher	Lower
Energy demand	Higher	Moderate/higher	Low
Solid separation	Sedimentation	Physical	Sedimentation

Table 5: Concentration of methane in various compartments

	Chamber 1	Chamber 2	Chamber 3	Chamber 4	Chamber 5
CH_4, mg/l	2.7	3.3	9.5	5.7	7.3

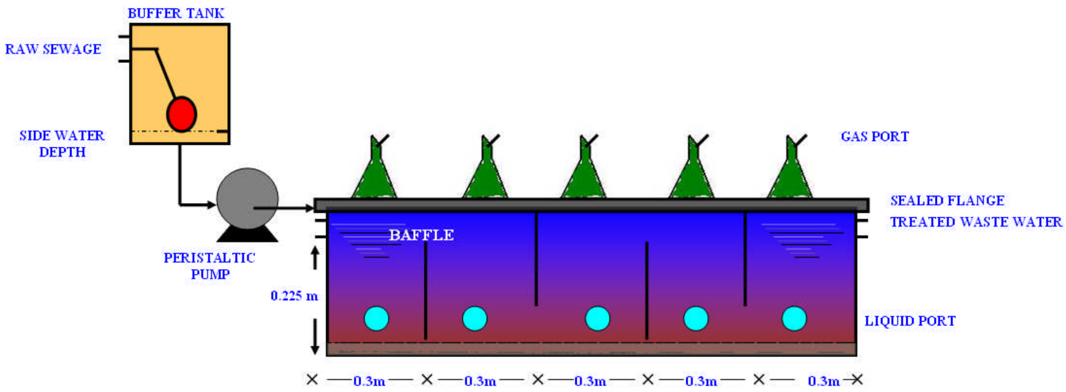

Figure 1: Schematic of the aWSP system for the present study. 12 mm PVC sheeting was used for the construction of main unit and 3 mm rubber sheet was used with bolted flange to make it air tight from the top. The unit was welded from outside and silicone was used from inside to make it water tight.

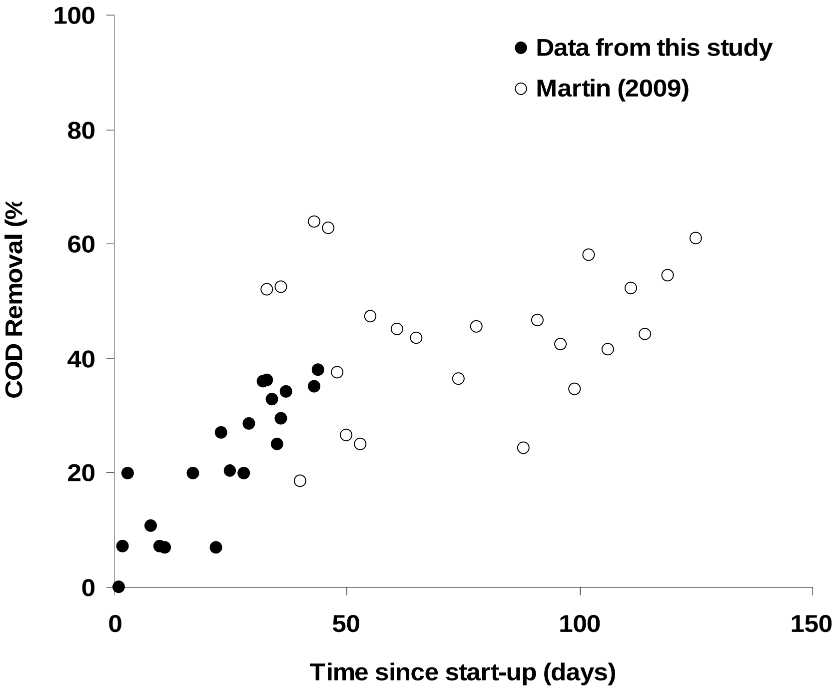

Figure 2: Start up COD removal efficiency of aWSP versus intensive aMBR. This plot compares the removal efficiency of seeded aWSP with unseeded aMBR. Initial results up to 45 days demonstrate the speedy start up of aWSP due to inoculation of flocculant sludge and identical removal efficiency with aMBR.

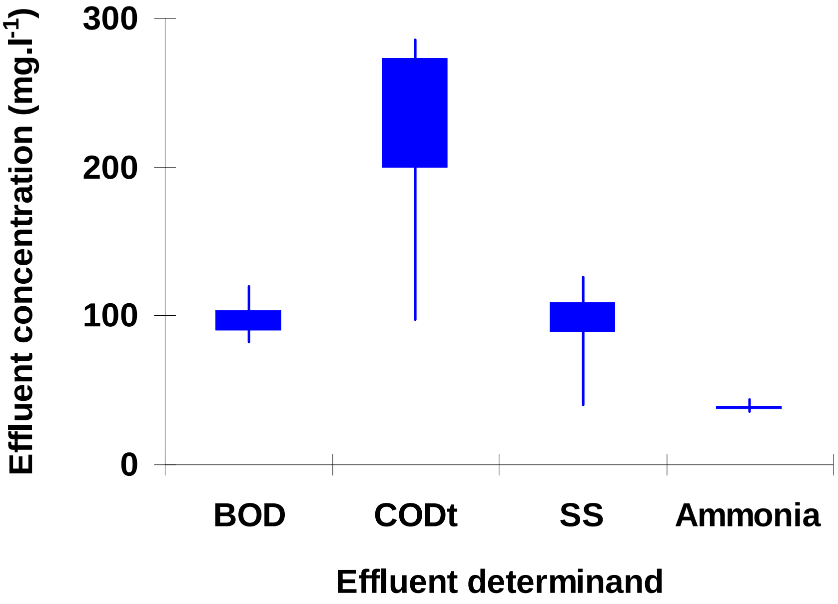

Figure 3: Box whisker plot to demonstrate effluent quality produced from the aWSP between days 28 and 45. Boxes represent 25th and 75th percentile; whiskers represent minimum and maximum values achieved.

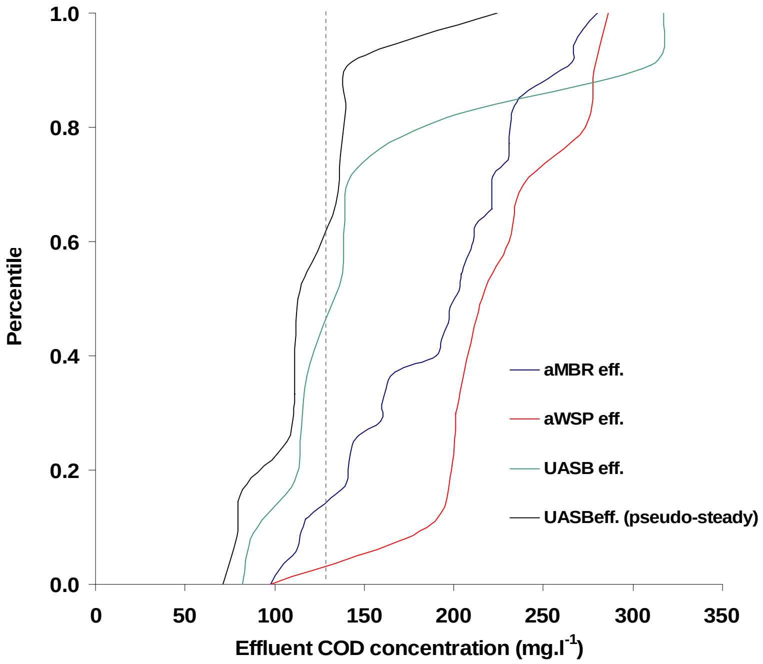

Figure 4: Comparison of effluent quality from UASB, aMBR and aWSP during start up. The second UASB plot illustrates the transition from start up to pseudo state. Data plotted as percentile distributions (days 28 to 45).

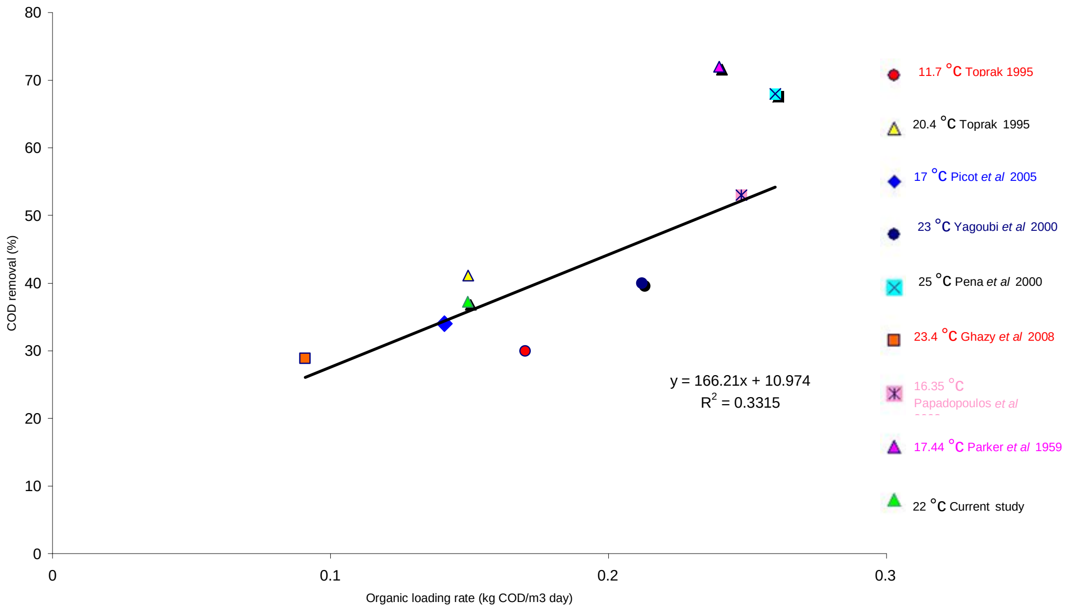

Figure 5: COD removal efficiency in aWSP as function of organic loading rate and temperature. Start up COD removal efficiency of aWSP in agreement with full scale working aWSP at various locations.

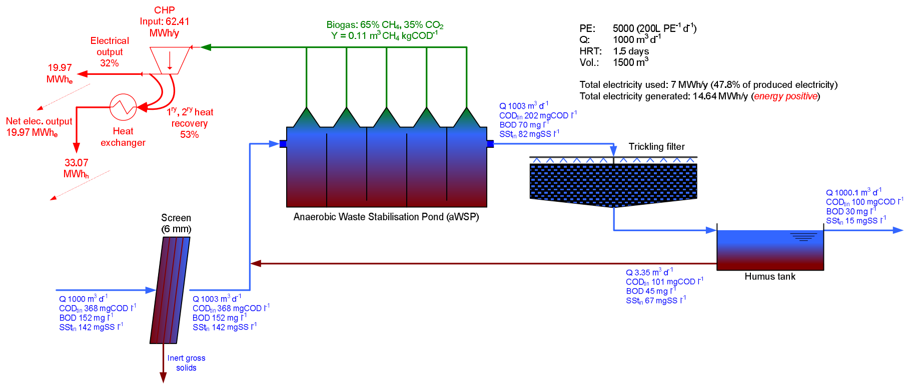

Figure 6a: Model of aWSP-TF system for 5000 PE to demonstrate the energy generation and conservation. 62 MWh y^{-1} energy can be generated with 19.97 MWh$_e$ electricity output and 33 MWh$_e$ heat recoveries making it energy positive model. This flowsheet will also meet the norms of water consent.

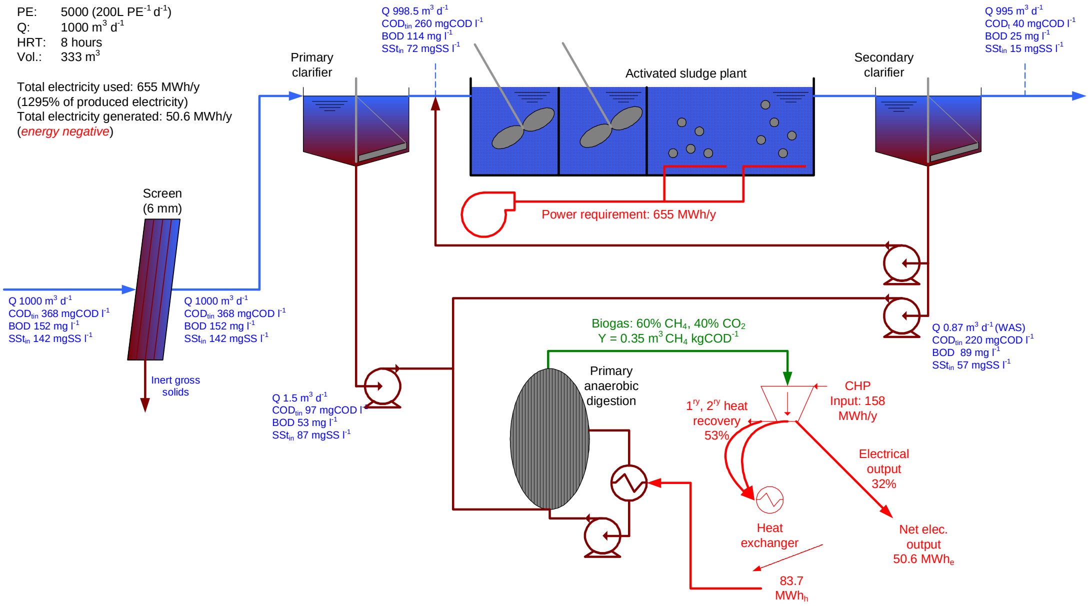

Figure 6b: Model of Primary clarifier – ASP for demonstrating the energy usage and consumption to meet the water consent norms. 655 MWh y^{-1} electricity required for mixing and aeration requirements with 50 MWh y^{-1} energy generation in anaerobic digester making it energy negative project.

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