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Anaerobic treatment in decentralised and source-separation-based sanitation concepts

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Abstract

Anaerobic digestion of wastewater should be a core technology employed in decentralised sanitation systems especially when their objective is also resource conservation and reuse. The most efficient system involves separate collection and anaerobic digestion of the most concentrated domestic wastewater streams: black or brown water and solid fraction of kitchen waste. Separate collection using minimal amount of transport water besides saving this resource allows to apply a targeted treatment. A relatively small volume of digested effluent can be directly reused for fertilisation or processed when a high quality product is required. Clean nutrient production requires advanced multi-step treatment but the quality of products is risk-free. The issue of organic micro-pollutants and their accumulation in the environment is recently often addressed. Anaerobic treatment of total domestic wastewater stream can be applied as well. Treated in this way wastewater can be discharged or used for irrigation or fertilisation. The post-treatment will be usually required and its rate of complexity depends on the anaerobic effluent quality and local requirements for final effluent quality. A variety of technological solutions for treatment of domestic wastewater streams and reuse of resources is discussed in this paper.

1. Introduction

Decentralised, sustainable sanitation concepts focus on treatment and recycling of resources present in domestic wastewater. Three main resources are nowadays considered: bio-energy generated from transformation of organic material, plant nutrients (nitrogen and phosphorus as main nutrients but also potassium and sulphur) and water (produced after advanced treatment of cleaner wastewater streams). Treatment of wastewater streams is selected in such a way that their reuse potential is preserved.

Both concentrated and less concentrated waste(water) streams are produced in a household. Black water (faeces and urine), grey water (originating from shower, bath, laundry and kitchen) and kitchen waste can be distinguished (Figure 1). In general those streams are combined and transported via extended sewer systems, often together with rainwater, to be treated in centralised wastewater treatment plants.

From a process technological point of view, separate treatment of black water, possibly together with kitchen waste, and grey water is most logic. Faeces and urine contain not only half of the COD and the major fraction of the nutrients in domestic wastewater, but also most of the pathogens and micro pollutants, like pharmaceuticals and hormones, while produced in a small volume. Concentrating risks in a very small volume enables their better control and limits the negative environmental effects.

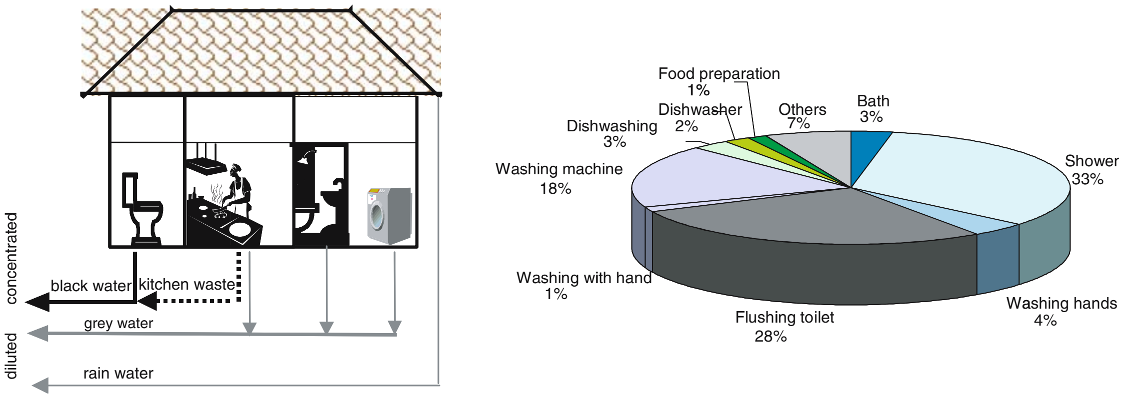

Figure 1. General types of wastewater streams from household. Water usage per activity in average Dutch household leading to generation of a specific wastewater stream (NIPO/VEWIN 2002). Similar water consumption and distribution per household activity was measured in other EU countries (EEA 2001). In general drinking water consumption will vary depending on geographic location. To give some examples in US daily indoor consumption of water is around 280 L capita^{-1} day^{-1} (AWWA 2005), in Europe around 140 (EEA 2001) and in sub-Saharan Africa 52 L capita^{-1} day^{-1} (IFPRI 2002).

The high concentration of black water makes anaerobic treatment with subsequent recovery of nutrients a very attractive treatment option. The collection method (toilet) applied will determine the actual black water concentration and therewith the anaerobic treatment technique to be applied and the feasibility of nutrient recovery.

In many situations it is not possible to separate the wastewater streams. Anaerobic treatment of a total wastewater stream can be applied as well, although possibilities for recovery of resources are limited. The treatment can be designed in such a way that its quality is suitable for reuse in agriculture, for irrigation and fertilisation.

Anaerobic digestion is suitable for many types of wastewater and environmental conditions, even when wastewater is very diluted and low in temperature. Depending on the final objective it can be considered as a pre-treatment or main treatment. Usually post-treatment will be required to upgrade the anaerobic effluent to standards for reuse or discharge. This applies mainly to pathogens, remaining biodegradable organic matter, nitrogen and phosphorus but also organic micropollutants (endocrine disrupters, pharmaceuticals residues) if their removal will be required in the future. This paper will review different decentralised sanitation concepts and incorporated anaerobic technologies, for both situations: total domestic wastewater and source separated streams.

2. Types and characterisation of domestic wastewater streams

In decentralised sanitation concepts two situations are distinguished: (1) treatment of total domestic wastewater and (2) treatment of separated wastewater streams. In source-separation based sanitation concepts wastewater streams are separated according to their degree and type of pollution and reuse potential of resources. Different degrees of separation can be applied. Generally three types of wastewater streams are distinguished: black water, grey water and rain water (Figure 1). Black water is a mixture of faeces, urine and flush water. A large fraction of the main components of domestic wastewater, viz. organics, nutrients (nitrogen, phosphorus, potassium), pathogens, pharmaceuticals residues and hormones are originally present in a very small volume of faeces and urine. The concentration of black water can be influenced by choice of a collection system (toilet).

Grey water is a voluminous stream characterised by lower concentrations (and even absence) of some components in comparison with black water. It consists of several sub-streams each having its own characteristics (Figure 1). Some of these sub-streams are lightly polluted – bath and wash water (light grey water, Henze and Ledin 2001); others – especially kitchen wastewater carry a significant pollution load.

Most of the plant nutrients present in domestic wastewater originate from faeces and urine. By diverting black water from grey water, 80–95% of the nutrients from households can be recovered (Figure 2, Table 2). In a healthy adult, the amounts of nutrients are in equilibrium within the body. All the plant nutrients consumed are excreted; normally via the urine or via the faeces (Guyton 1992). The nutrient content in urine and faeces will vary depending on the food intake, e.g. on protein intake (Drangert 2000; Jönsson et al. 2000).

The nutrients in urine are in a water-soluble form. Nitrogen is mainly found as urea (80%), ammonia (7%), and creatine (6%), while the remainder is mainly free amino acids or shorter peptides (Johnston & McMillan 1952; Lentner et al. 1981; Guyton 1992; Kirchmann & Pettersson 1995). The biochemical activity of the enzyme urease (Alef & Nannipieri 1995) transforms the urea into ammonia and carbon dioxide (Vinnerås et al. 1999). The phosphorus is mainly found as inorganic phosphates (>95%) and the potassium mainly as free ions (Lentner et al. 1981; Guyton 1992). Sodium and chlorine are present in high concentrations when comparing with other domestic wastewater streams. Concentrations of heavy metals in urine are low. From a healthy person the urine in the bladder is sterile. It will get contaminated with different types of dermal bacteria when excreted. Urine is also a main source of pharmaceuticals and their metabolites excreted to the environment.

Approximately 50% of the faecal nitrogen is water-soluble (Trémolières et al. 1961). A 20% of water soluble nitrogen in faeces is ammonia, biochemically degraded from urea, peptides and amino acids. About 17% of the total nitrogen content is found in living bacteria and the remainder is mainly found as organic nitrogen combined in molecules such as uric acid and enzymes (Lentner et al. 1981). The main proportion of the phosphorus in the faeces is found as undigested mineral calcium phosphates. Potassium on the other hand is mainly found in its ionic form in equilibrium with the liquids outside the intestine (Guyton 1992; Fraústo da Silva & Williams 1997). Due to a low uptake in the body, heavy metals pass through and are found in excreta. Many different types of pathogens (bacteria, viruses and parasites) can be present in faeces. Faeces are the second, after urine, source of pharmaceuticals, hormones and their metabolites excreted by the human body.

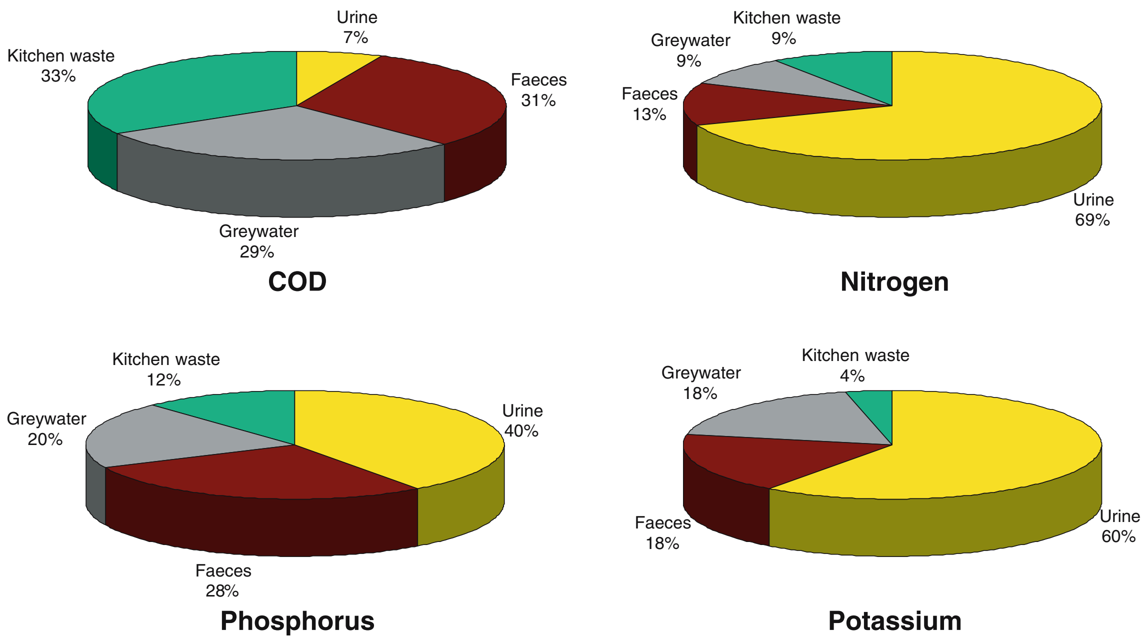

Figure 2. Distribution of organic matter (COD) and nutrients (N,P,K) over major groups of domestic (waste)water streams (based on Table 2).

Application of urine diverting toilets allows to distinguish between two additional wastewater streams: urine with or without some flush water (yellow water) and faeces with water (brown water).

Grey water is usually defined as a household wastewater stream without any input from the toilets, consisting of wastewater produced during bathing/showering, washing hands, laundry and from kitchen sink, each having its own characteristics and variations. Grey water contains a major fraction of heavy metals but a minor proportion of nutrients (Table 2). The heavy metals in grey water originate from dust (wiped out during house cleaning activities) and chemicals used in the household (Cd in P-containing detergents and Zn in anti-fungal shampoo). The nutrients in grey water are mainly inorganic. Potassium and phosphorus are used in detergents and their concentrations will mainly reflect the usage rate of these products (Vinerås 2002). The other sources of nutrients are (solid) kitchen residues (food leftovers) ending up in a kitchen water. The content of pathogens in greywater is low. Winblad and Simpson-Hébert (2004) state that untreated greywater is likely to contain far lower densities of pathogens than effluent water, even from an advanced wastewater treatment plant. Although considered as a relatively clean, simple wastewater, polluted with mainly COD, the concentration and composition of COD can vary considerably from one to another location (Jefferson 2001). The variation in concentration and composition is due to personal and cultural habits with respect to water use and waste handling and the quality and quantity of products used for kitchen, laundry and personal care. Handling of food rests in the kitchen may have an important impact on composition of kitchen refuse water. Food rests can either end in the sink and will subsequently make part of the grey water wastewater, or as solid can be collected as (green) household waste. Henze (1997) shows that the application of 'clean tech cooking', where large part of the cooking waste is transferred from the sink to the solid waste, can reduce the COD load of grey water from 55 to 32 gCOD person^{-1} day^{-1}.

For maximal recovery and reuse of resources also solid kitchen refuse, produced during meals' preparation and food leftovers, can be collected, transported and finally treated with the black water. Solid kitchen refuse carries an organic load comparable to black water and is easily biodegradable. At this moment solid kitchen refuse is in the Netherlands separately collected and together with garden waste transported for (mainly) co-composting. Direct transport of solid kitchen waste from the kitchen sink to the on-site treatment would be a convenient practice and economic option. Kitchen grinders enabling to incorporate the food residues into domestic wastewater are common in the United States. Their use is associated however with high water consumption (1.1–4.5 L p^{-1} day^{-1}). Research performed in the Netherlands shows that connection of a grinder to a vacuum system enables to transport any kind of kitchen waste with 0.2–1 L water per person per day (Wisgerhof 2003). The list of all types of wastewater streams produced in a household with their qualitative characteristics is given in Table 1.

The daily loadings from domestic wastewater streams are presented in Table 2. Knowing a type of a collection system for faeces and urine, concentrations of black, brown and yellow water can be calculated.

The wastewater composition will vary to a certain extent from one to another geographic location, determination approach, selected test group or calculation procedure. The magnitude of variation will be also different for different source-separated wastewater streams. To give an example nitrogen concentration in urine varies in literature from 3.6 to 19 gN/person per day (Flameling 1994; Marchini et al. 1996; Fricker et al. 1991; Egun et al. 1992; McClelland & Jackson 1996), Polprasert (1989) and Wijn de and Hekkens (1985). Analogously, nitrogen in feaces, according to some literature sources, varies from 0.27 to 2.4 gN person^{-1} day^{-1} (Fricker et al. 1991; Egun et al. 1992; Cummings et al. 1993; Marchini et al. 1996). Grey water composition depends strongly on amount of clean water available for purposes other than flushing toilets, lifestyle, customs, installations used, product preferences and washing habits of the population (Jefferson et al. 2004). Consequently, for design purposes of any wastewater treatment the available wastewater characterisation originating from the considered location should be taken otherwise measurements need to be performed.

Table 1. Qualitative characteristics of wastewater types produced on a household level

Type wastewater	Definition	Characteristics
Total domestic wastewater	All wastewater produced during different human activities mixed together	All types of contaminations present in moderate concentrations
Black water	Urine and faeces flushed together with higher or lower amount of water	High organic and nutrient content, pathogens, pharmaceutical residues, hormones
Yellow water	Urine transported with or without water	Highest nutrient content, pharmaceutical and hormone residues, high salts concentration
Brown water	Faeces with small contribution of urine diluted in water	High organic and nutrient content, highest pathogens, present pharmaceutical residues and hormones
Kitchen waste	Solid fraction of food leftovers and from preparation of meals	High organic biodegradable fraction
Grey water	All wastewater other than toilet	Organic load comparable to that of faeces but diluted in large volume, little nutrients and little pathogens; highest load of personal care products and detergents
Light grey water	Wastewater from personal care and washing the clothes	Diluted with little amount of nutrients but high of personal care products and detergents, some persistent
Kitchen wastewater	Wastewater originating from kitchen activities, washing-up, food preparation	Most-concentrated among other grey water sub-streams

Table 2. Volume and composition of separated domestic wastewater streams

Parameter	Unit	Urine	Faeces	Greywater	Kitchen refuse
Volume	g or L p^{-1} d^{-1}	1.25–1.5	0.07–0.17	91.3	0.2
Nitrogen	gN p^{-1} d^{-1}	7–11	1.5–2	1.0–1.4	1.5–1.9
Phosphorus	gP p^{-1} d^{-1}	0.6–1.0	0.3–0.7	0.3–0.5	0.13–0.28
Potassium	gK p^{-1} d^{-1}	2.2–3.3	0.8–1.0	0.5–1	0.22
Calcium	gCa p^{-1} d^{-1}	0.2	0.53		
Magnesium	gMg p^{-1} d^{-1}	0.2	0.18		
BOD	gO_2 p^{-1} d^{-1}	5–6	14–33.5	26–28	
COD	gO_2 p^{-1} d^{-1}	10–12	45.7–54.5	52	59
Dry matter	g p^{-1} d^{-1}	20–60	30	54.8	75
Heavy metals					
Cu	mg p^{-1} y^{-1}	4	400	2900	549
Cr	mg p^{-1} y^{-1}	3.7	7.3	365	137
Ni	mg p^{-1} y^{-1}	2.6	27	450	82.3
Zn	mg p^{-1} y^{-1}	16.4	3900	3650	700
Pb	mg p^{-1} y^{-1}	0.73	7.3	365	275
Cd	mg p^{-1} y^{-1}	0.25	3.7	15	2.7
Hg	mg p^{-1} y^{-1}	0.30	3.3	1.5	0.25

Given ranges or concentrations of wastewaters' components are compilation of mainly European data (after Hellström & Kärrman 1996; Jönsson et al. 1997; STOWA 2001; Vinnerås 2002; Erikkson et al. 2002; Kujawa-Roeleveld et al. 2003b).

3. Collection of wastewater streams in source separation based concept

When a source separation based sanitation concept is applied, maximal advantage of the reuse potential can be achieved at black water collection with a minimal amount of water. The more the black water is diluted, the more volume there is to be treated, stored, transported and spread on the fields for the same nutritional value.

Furthermore, water-saving black water collection systems reduce the household water consumption up to 25% (Dutch conditions) or more. To avoid an excessive dilution of faeces and urine many types of low-flush or extremely low-flush toilets are currently available on the market or are under development (WRS 2001). The general categories of flushing toilets compared to a traditional system are given in Table 3.

Separate collection of wastewater on a household level will require more complex piping system; dual (black water, grey water), triple (brown water, urine, grey water) or even foursome (when solid kitchen waste is collected using water based in-sink grinders).

4. Anaerobic treatment

Anaerobic digestion of wastewater is a sustainable option as recovery of energy is applied while nutrients are preserved for reuse. The application of anaerobic digestion of domestic wastewater has been restricted to tropical countries where large-scale plants have been or are under construction (Hulshof-Pol et al. 1997) in centralised concepts. Results of recent research on digestion of sewage under lower temperature conditions (e.g. Elmitwalli 2000; Mahmoud 2002; Seghezzo 2004) and experience from industrial sector proves a large potential of anaerobic treatment for total domestic wastewater or separated concentrated streams. Despite of various advantages of anaerobic treatment (Lettinga et al. 2001), generally it does not produce effluents that can comply with the standards for reuse in agriculture or discharge to the environment. Therefore post-treatment will be in most cases required. Currently, the main objectives of the post-treatment are: (1) removal of pathogens, (2) removal of remaining organic matter, (3) removal or recovery of nutrients depending on local requirements and reuse potentials.

Selection of wastewater separation grade, collection and transport system influences strongly the choice of subsequent treatment technology and reuse options. A kind of resources reuse will determine the extent (complexity) of a treatment. The distance of the treatment to the agricultural field will amongst others determine the possibility of direct reuse. The choice of crop and type of irrigation system will moreover determine the extent of post treatment to remove pathogens. Recovery of N and P from the effluent becomes interesting for concentrated wastewaters.

This paper focuses mainly on the treatment of concentrated or relatively concentrated wastewater streams. Next to their treatment as a main objective, conservation, recovery and reuse of resources (energy and nutrients) are addressed. Conventional aerobic (activated sludge) or alternative physical–chemical wastewater treatment consumes resources instead (energy for aeration, chemicals for precipitation, oxidation, etc.) quantitatively proportional to the wastewater strength. This is why it will be further not considered in this paper.

One of the objectives of a decentralised concept is implementation of a simple, effective and robust treatment system. For anaerobic digestion of domestic waste(water) several simple technical configurations can be considered. They can be generally divided into systems with and without sludge/biomass retention. The systems without sludge retention are applied for more concentrated wastewater streams while the systems with

Table 3. Different categories of flushing toilets and their comparison with a traditional system

Toilet type	One flush (L flush^{-1})	Large flush (L flush^{-1})	Small flush (L flush^{-1})	Total volume (L person^{-1} d^{-1})
Very low flush with gravity sewers	0.6–1	2	0.2	3–6
Vacuum	0.8–2			
Urine diverting		4–6	0.2	5–7
Conventional low flush (two buttons)		4	2	14
Conventional	6–12			36–72

Total water consumption is calculated under assumption that one individual produces 1 time faeces and 5 times urine per day (after WRS 2001); large flush is to flush faeces and small to flush urine.

sludge retention are applied for more diluted wastewater streams (Zeeman et al. 2001). For the anaerobic treatment of wastewaters with a large fraction of particulate matter, the hydrolysis of particulates is generally the rate-limiting step. Long sludge retention time (SRT) is therefore needed to provide a sufficient hydrolysis and methanogenesis. To prevent long hydraulic retention time (HRT) and application of large reactors' volumes when treating relatively diluted streams, the solids must be retained in the system while the liquid needs only a short retention time. The anaerobic digestion process is covered in more detail by other contributions to this special journal issue (e.g. van Haandel et al. 2005, Submitted to Reviews in Environmental Science and Bio/technology).

5. Anaerobic treatment of total wastewater

Often it is not possible to provide regional sewerage facilities due to socio-economic constraints. In many situations total domestic sewage is collected and transported to a central place in the community where it is discharged after treatment, if any. On-site solutions, whether house-on-site, community on site or combination of both are often the only option to improve sanitation in these regions or, unfortunately in many cases, to introduce sanitation.

Collection and treatment of whole wastewater mixture is not an ideal alternative, in light of earlier considerations, to achieve an optimised treatment and maximal recovery of resources in one. Nutrients are diluted in large wastewater volumes and their recovery is economically less feasible. Energy recovery and reuse from moderate concentrated in terms of organic matter total wastewater stream is also less attractive than in case of highly concentrated medium. Still, however, by an appropriate combination of technologies sustainable solutions can be applied.

Fresh water scarcity increases opportunity for local reclamation/reuse solutions. The use of anaerobic treatment completed by post-treatment techniques offers cost-effective method for reclaiming domestic wastewater and nutrients for agricultural production.

A commonly used on-site system to (pre)treat the whole wastewater is a *septic tank* followed in some cases by soil absorption (U.S. EPA 1980, 2000b, Figure 3). In general little attention has been paid on the design improvement of these systems often operating under sub-optimal temperature conditions. The processes occurring in septic tanks are: settling of suspended matter, anaerobic conversion of organic matter and accumulation of inert particles. As a result of the horizontal flow of the incoming wastewater stream, no contact between sludge and wastewater is established, resulting at low conversion of dissolved components.

At the bottom of the tank sludge accumulates and forms a sludge bed, reducing the net volume and hence the wastewater hydraulic retention time (HRT). Before the efficiency of settling deteriorates and particles are washed out of the reactor the sludge needs to be removed. Oil, fat and other floating materials form a scum layer on the surface. Up to 50% of organic matter, depending on temperature and solids retention time (SRT), decompose, while the remainder must be removed periodically by pumping from the tank (EPA 2000a). Tanks require pumping at frequent intervals to avoid reduction of the effective volumetric capacity. The frequency of tank emptying (desludgeing) depends on sludge and scum

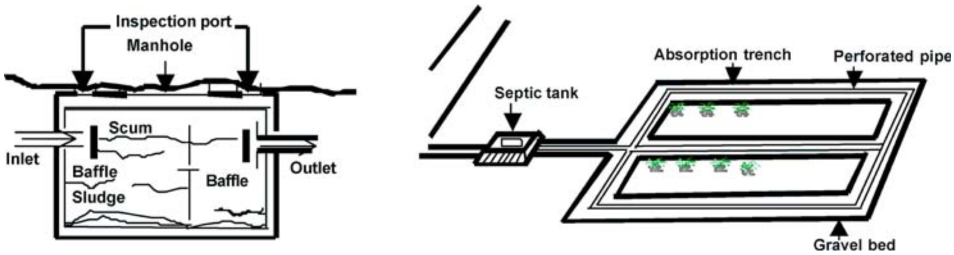

Figure 3. Traditional treatment facilities used in unsewered regions and for collective treatment of wastewater from small populations: septic tank followed or not by absorption (filtration) field (by Vogel & Rupp 2002).

accumulation rates and usually varies between half and several years.

Implementation of an up-flow anaerobic sludge blanket (*UASB) reactor* or a *UASB septic tank* system (Figure 4) providing higher process efficiency would be a more suitable and profitable solution for on-site treatment of total wastewater (Lettinga et al. 1993). The UASB reactor is worldwide used for treatment of various types of wastewater. A good removal efficiency of organic matter is achieved thanks to the establishment of a dense sludge bed at the bottom of the reactor, in which all biological processes take place. The sludge bed is formed by accumulation of inert suspended solids (SS) from the influent and produced biomass. The up-flow conditions enhance aggregation of bacteria in flocs and granules (Hulshof-Pol 1989). The sludge bed of a UASB reactor fed with wastewater containing high fraction of suspended solids will consist of a flocculent sludge. Dense aggregates are not susceptible to washout from the system (Seghezzo 2004). Retention of a high concentration of active sludge ensures a good treatment performance. Natural turbulences caused by the influent flow and biogas production provide good biomass-wastewater contact. Reductions of total COD from sewage up to 80–90% are reported. At temperatures above 20 °C average removal of total COD of 70% can be expected. The frequency of the excess sludge withdrawal is low due to a low sludge growth rate (e.g. once, twice per year (Seghezzo 2004).

The UASB-septic tank system is a promising alternative for the conventional septic tank (Bogte et al. 1993; Lettinga et al. 1993). Applying the UASB principle to a conventional septic tank, viz. upward flow and a gas/solid/liquid separation, situated on the top of the reactor, will result in a significant improvement of the process efficiency. The major difference in relation to the conventional UASB system is that the UASB-septic tank also accumulates the stabilised sludge thanks to more available reactor volume. Therefore, the UASB-septic tank is a continuous system regarding the liquid and a fed-batch system with respect to the influent solids. A part of the sludge needs to be removed once in 1 or 2 years depending on the design of the reactor.

The contact between biomass and substrate is improved in relation to a conventional septic tank. Both physical removal of suspended solids and biological conversion of dissolved compounds increase, determining the final removal efficiency and conversion to methane. Removal of suspended solids occurs by settling, adsorption and entrapment. The following hydrolysis and methanogenesis rates depend on the process temperature and solids retention time (SRT). In a UASB septic tank long retention of biomass (accumulation) is achieved at a relatively short HRT.

The UASB septic tank has not been extensively investigated. Bogte et al. (1993) and Lettinga et al. (1993) investigated the use of UASB septic tank to treat black water collected with conventional flush toilets and total domestic sewage at Dutch and Indonesian ambient temperature conditions. At higher temperatures very high organic matter removal efficiencies could be achieved. Under low temperatures (12 °C) the conversion of produced VFA to methane was

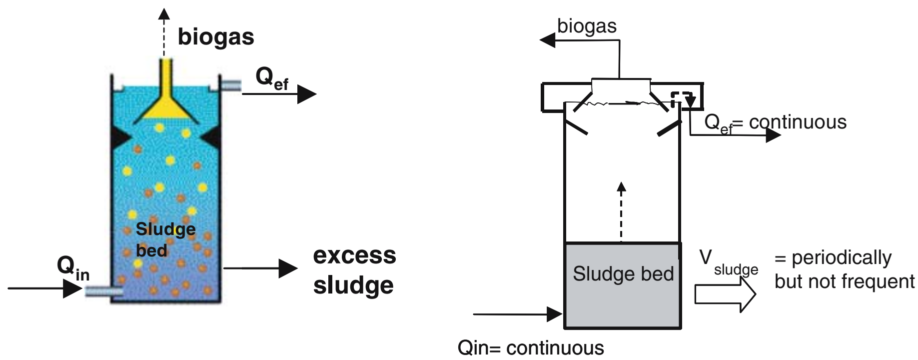

Figure 4. Schematic representation of a UASB reactor and UASB septic tank.

too low. In such situation implementation of a two-step UASB reactor can be considered (Zeeman & Lettinga 1999). The first reactor would serve for accumulation of solids and provide limited hydrolysis, acidification and methanogenesis in colder months. In the second reactor mainly methanogenesis would occur. In the warmer months the subsequent hydrolysis/acidification/methanogenesis will proceed faster in the first reactor while the second UASB septic tank may serve as a polishing step for removing and converting the remaining soluble and suspended COD, washed from the first reactor because of increased biogas production. Obtained removal efficiencies in a UASB septic tank treating black water and total wastewater at household level are shown in Table 4.

The intended final disposal/use of the effluent and sludge will determine the extent of the required post-treatment. When a one step UASB is applied, the produced excess sludge will be usually well stabilised and can be used for agricultural purposes, for soil conditioning or fertilisation. Desinfection to secure hygienic safety will be sometimes required depending of the type of final sludge reuse.

Table 4. Removal efficiencies of COD fractions (total and suspended) and total suspended solids (TSS) in the UASB septic tank reactor treating total domestic wastewater at different temperature conditions (based on Bogte et al. 1993; Lettinga et al. 1993)

Removal efficiencies (%)	Temperature (°C)	Grey + black water
COD_{total}	5–20	58*
COD_{ttotal}	> 20	67–77**
$COD_{suspended}$	5–20	62*
Total suspended solids	> 20	74–81**

*normal water use, **low water use.

The effluent from the anaerobic digester contains nutrients, salts and pathogens and usually is to be post-treated to remove at least the remaining biodegradable organics and pathogens. Due to the low content of suspended matter the effluent can be transported via a small bore sewer system to a community on site post-treatment system (Figure 5). Small bore sewer systems were first constructed in Australia in the 1960's. They were designed to collect liquid effluent from septic tanks. It was estimated that this alternative for transportation of pre-treated wastewater leads to a reduction in construction costs of the whole collection system by 30–65% (Fadel 2001), and construction is faster, requiring less time to provide service to community. Also routine maintenance seems to be lower in cost in comparison to the traditional sewer.

5.1. *Anaerobic treatment of domestic wastewater at tropical conditions (community level)*

Many examples of application of UASB reactors to treat domestic wastewater in tropical areas can be given. The first pilot-plant was built in Colombia (Cali) to treat a rather dilute sewage (Schellinkhout et al. 1985). At an average temperature of 25 °C satisfactory results were obtained with COD and BOD removal efficiencies higher than 75% (Lettinga et al. 1987). Full scale applications followed: in India (Kanpur and Mirzapur), Colombia (Bucaramanga), Brazil, Portugal, Mexico (Vieira 1988; Maaskant et al. 1991; Draaijer et al. 1992; Schellinkhout & Collazos 1992; Haskoning 1996; Monroy et al. 2000) and others. Trickling filters or polishing ponds

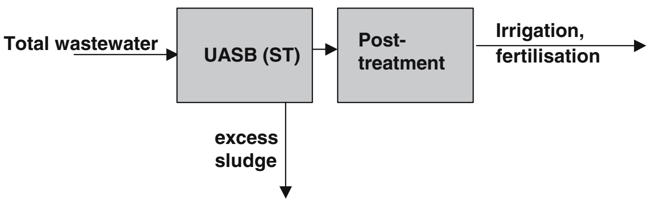

Figure 5. General scheme of a house-on-site (h.o.s.) or community on-site (c.o.s.) treatment of total domestic wastewater followed by community-on-site post-treatment for pathogens removal and subsequent reuse in agriculture for irrigation and fertilisation.

have been applied in some of the above-mentioned applications for effluent polishing. For post-treatment of anaerobic effluents many other systems can be applied; this aspect is covered elsewhere this special journal issue.

5.2. *Application of anaerobic treatment of domestic wastewater at sub-optimal temperature (community level)*

The anaerobic process to treat domestic sewage with a high suspended matter content has been implemented to a smaller extent in regions with (temporary) lower temperatures. The lower hydrolysis rate at sub-optimal temperature causes accumulation of suspended matter leading to deterioration of methanogenic activity and overall reactor performance when short HRTs are applied. Removal of colloidal COD is insufficient at lower temperatures. Several technological options were investigated to overcome the obstacle of low temperature in treating domestic wastewater, namely:

- using granular seed sludge (Lettinga et al. 1993)
- removing suspended matter prior to the anaerobic reactor (Kalogo & Verstraete 2000)
- treating presettled sewage in expanded granular sludge bed (EGSB) or anaerobic fluidized bed (AFB) at high upflow velocity (Schwitzenbaum & Jewel 1980; Jewel et al. 1981; Yoda et al. 1985; van de Last and Lettinga 1992)
- applying a two step system (Wang 1994) consisting of a UASB and EGSB reactor for treatment of raw wastewater at low temperature. The first reactor is meant to remove suspended COD through its partial hydrolysis and removal and the second one for the conversion of dissolved COD into methane
- applying a two step system consisting of anaerobic filter (AF) and anaerobic hybrid reactor (AH) (Elmitwalli et al. 2001)
- applying one stage UASB system supplemented by a sludge digester (Mahmoud 2002).

Inoculation with granular sludge enhances the methanogenic capacity of the reactor. In the course of time, however, accumulation of suspended solids from the influent due to a low hydrolysis rate leads to deterioration of the methanogenic activity of sludge (Zeeman & Lettinga 1999).

Settling or physical-chemical pre-treatment of domestic wastewater prevents against accumulation of solids and may lead to formation of granular sludge in the anaerobic reactor (Vieira & Souza 1986). The negative effect of suspended solids accumulation is avoided by applying a high upflow velocity providing good contact between wastewater and biomass. *EGSB* (expanded granular sludge bed) and *AFB* (anaerobic fluidized bed) ensure the required good contact. High removal of dissolved COD at lower temperatures can be then achieved but a settler will be usually required afterwards. To secure the required hydraulic conditions, a tall reactor and/or high recirculation rates are needed. These imply higher construction, operation and maintenance costs.

In the first step of a *two-step system*, removal of suspended solids and its partial hydrolysis and acidification will occur. At low temperature, the accumulated solids have to be frequently discharged from the first step. Consequently the SRT in the first reactor is low, so the biological conversion of the organic matter occurs in the second step. Since little suspended solids enter the second step, its methanogenic capacity is high. The sludge produced in the first step is not sufficiently stabilised (Zeeman et al. 1997; Elmitwalli et al. 2002) and needs to be further stabilised in a separate, preferably heated sludge digester (van Haandel & Lettinga 1994; Wang 1994; Mahmoud 2002).

An *anaerobic filter (AF)* followed by an *anaerobic hybrid (AH)* reactor with granular sludge represents a suitable configuration for treatment of domestic sewage at low temperatures. The AF reactor is a fixed-bed anaerobic reactor retaining the suspended COD. The AH reactor is a system consisting of a sludge bed in the lower part and the filter material in the upper part (Figure 6). The filter zone in the AH reactor physically retains biomass and exerts some biological activity contributing to further COD reduction. Elmitwalli (2000) found a removal efficiency for total COD of 71% when operating a combined AF-AH system fed with domestic sewage at 13 °C at an HRT of 4 and 8 h, respectively.

In an integrated system consisting of an UASB operated at low temperature conditions and complemented with a digester (Figure 7),

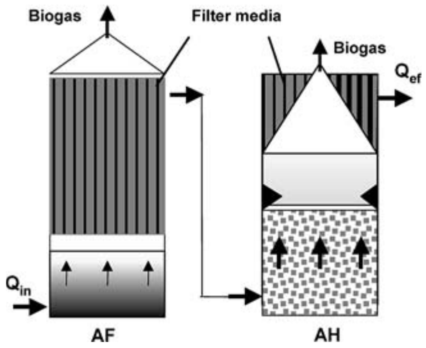

Figure 6. Two step AF-AH system for treatment of domestic wastewater at lower temperatures.

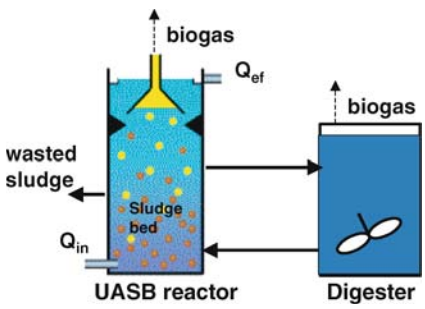

Figure 7. UASB-digester system for community-on-site treatment of total domestic wastewater at sub-optimal temperature conditions.

treatment of wastewater and sludge stabilisation are achieved. The suspended solids from the raw influent are captured in the UASB reactor operating at ambient conditions and transported as a concentrated sludge to the digester operating at optimal process conditions regarding temperature (mesophilic) and SRT. Digested sludge containing methanogens is recirculated to the UASB reactor to enhance its methanogenic capacity. Dispersed biodegradable solids attached to the sludge flocs are degraded in the digester. In this way accumulation of non-degraded solids in the sludge bed is prevented, the removal efficiencies are substantially improved and wasted sludge is well stabilised. Optimised sludge recirculation rate is expected to lead to a complete conversion of biodegradable soluble COD. Produced biogas in the digester should be reused for its heating (Mahmoud 2002).

5.3. *Separate urine collection*

Since treatment of the whole wastewater stream is not an optimal approach leading to maximisation of nutrient recovery and recycling, in some (already existing) cases urine can be separately collected and reused for agricultural purposes. Urine diversion requires a specially constructed toilet where mixing of urine and faeces is avoided (WRS 2001). Simple toilets with urine diversion have been used in parts of China, in Japan and in other parts of the world for centuries (Winblad & Simpson-Hébert 2004). The collected urine can either be used directly in the garden or stored on site for later collection either as liquid fertiliser or further processed to a clean fertiliser (STOWA 2005).

Although urine is originally almost sterile, fecal cross-contamination occurs during its separate collection in the no-mix toilet. The fate of any enteric pathogens present in urine is crucial for the risk assessment for transmission of infectious diseases. A proper storage of urine provides inactivation of pathogenic organisms. The risk for transmission of infectious diseases by reuse is dependent on the storage temperature and the duration of the storage (Table 5, Höglund 2001). Further inactivation of pathogens is expected in the field and the risk for infection by ingestion of crop will be reduced during the time between fertilisation and consumption. The choice of crop will significantly reduce the risk for infections.

Table 5. Effect of storage on pathogens inactivation in source separated urine (Höglund 2001)

Storage temperature	Storage time	Possible pathogens remained	Recommended crops
4 °C	≥1 month	Viruses, protozoa	Processes feed, food crops
4 °C	≥6 months	Virus	Feed crops, processed food crops
20 °C	≥1 month	Virus	Feed crops, processed food crops
20 °C	≥6 months	Probably none	All crops

Urine collected from individual households and used for the household's own consumption involves less risk than large-scale systems and is suitable for fertilising all types of crops if 1 month is allowed between fertilisation and consumption (Höglund 2001).

Using urine directly as fertiliser implies transport of liquid. This is costly where great distances have to be covered, typically from densely populated urban areas to farmland. In some situations urine would have to compete with animal manure as a potential recycled fertiliser. Modern and highly specialised agriculture is very demanding, making the acceptance and finally reuse of urine difficult or undesired. Production of pure nutrients needs to be developed. Recovery techniques of nutrients from concentrated urine involve struvite formation (Lind et al. 2000; Ronteltap et al. 2003), ammonia stripping following absorption, volume reduction by evaporation, partial freezing or reverse osmosis (Maurer et al. 2003a, b) or ion exchange (Nguyen & Tanner 1998).

The remaining wastewater mixture, brown water and grey water, contains significantly less nutrients. After anaerobic digestion the post-treatment will focus on removal of organic matter and pathogens to produce an effluent quality suitable for irrigation, discharge or infiltration.

5.4. *Post-treatment of anaerobic effluent*

Because of not complete degradation of organic matter in anaerobic reactors, there will be always a fraction of remaining COD present in the effluent, next to pathogenic organisms and nutrients. The choice of a post-treatment depends strongly on the characteristics of the anaerobic effluent and on local standards set by authorities for reuse of treated effluent or discharge to the environment. In Europe anaerobic sewage treatment normally has to comply with COD discharge standards established by the Council Directive 91/271/EEC on Urban Wastewater Treatment (European Council of Ministers 1991, less than 125 mgCOD L^{-1}). For unrestricted irrigation the World Health Organisation (WHO 1989) set the standards of less than 1000 fecal coliform in 100 mL and less than 1 helminth egg per l treated wastewater.

In some situations, related to the growing seasons, restrictions apply for the ammonium and phosphate content. A flexible post-treatment has to ensure required *periodical* nitrogen and phosphate reduction by implementation of biological nitrification–denitrification and chemical precipitation respectively. Removal of pathogens will be partially accomplished in biological system. To meet the regulations desinfection of the post-treated effluent will be often required.

Several post-treatments methods are proposed in literature: waste stabilisation ponds (van Haandel & Lettinga 1994), rotating biological contactor (Castillo et al. 1997; Tawfik 2002), integrated duckweed and stabilisation pond system (van der Steen et al. 1999), trickling filters (Chernicharo & Nascimento, 2001), the down-flow hanging sponge reactor (Uemura et al. 2002), activated sludge (von Sperling et al. 2001), a baffled pond system (von Sperling et al. 2001), soil absorption field (EPA,) reed bed systems (Yu et al. 1997) and others.

Waste stabilisation ponds, lagoons and algal ponds require a long liquid retention time, often exceeding 20 days (Tawfik 2002), even under favourable conditions in tropical regions (Cavalcanti 2003). This provides a high rate of mineralisation of the remaining biodegradable organics and a high rate of helmints eggs and FC reduction. Generally, baffled ponds or ponds in series are used. The large area required constitutes the limitation of this system.

Fixed film systems due to retention of biomass require significantly shorter liquid retention time to achieve similar efficiency of COD removal as suspended growth systems. A high volumetric loading can be applied at relatively low energy costs. These compact systems cause little odour nuisances and evaporation of water is minimised. Trickling filters require even distribution of the load over the whole carrier surface. If this is not maintained the system is not volume effective (del Pozo et al. 2002).

Rotating biological contactors (RBC) have been tried out in single- and multiple-stage configurations for removal of organic matter (Huang 1982), nitrification and pathogens removal (Tawfik 2002). The most important removal mechanism of *E.coli* (and other pathogenic organisms) is adsorption followed by sedimentation. Bacterial die-off is of relatively minor importance in a biofilm system (Omura et al. 1989).

A down-flow hanging sponge (DHS) was extensively investigated for the post-treatment of UASB effluents (Agrawal et al. 1997; Machdar et al. 2000). In the DHS biofilter the waste (anaerobic effluent) is trickled through the polyurethane sponge cubes, which are diagonally linked. Sponge elements act as a support media for growth of various microorganisms, providing longer SRT and enhancing the diffusion of air into the wastewater, so no forced aeration is needed (Tandukar et al. 2004). The UASB-DHS combined system turned often to be superior to the conventional activated sludge process since it was able to achieve also a high reduction of fecal coliforms (Uemura et al. 2002).

A soil absorption field is typically a perforated piping network that lies on a gravel bed. The soil must remain un-compacted to absorb the wastewater and support the microbial organisms that degrade pollutants.

6. Anaerobic treatment in source separation based system

In situations where no infrastructure is available (no sanitation at all, new residential area) separation of domestic wastewater streams can be applied leading to targeted treatment, maximal recovery of resources and reuse applications. The high organic content makes black water and optionally kitchen waste particularly suitable to be separately collected and anaerobically treated. Anaerobic digestion results in a partial conversion of potentially oxygen demanding- and odorous organics to methane. Moreover, it also produces a sludge-liquid mixture, which is high in nitrogen and phosphorus, valuable fertiliser ingredients.

The amount of flushing water used affects linearly the size of the reactor and consequently its cost. Furthermore with little dilution the nutrients are concentrated in a small volume, which is much easier to handle for agricultural purposes (transport). The concentrated mixture of black water can be treated in a completely stirred tank reactor (CSTR), generally applied for the digestion of sewage sludge and animal manure. Alternatively a fed batch or accumulation (AC) system can be used where also co-digestion with other concentrated streams, like kitchen waste or animal manure, is possible (Figure 8). Recently a pilot-plant UASB septic tank was successfully applied for anaerobic treatment of concentrated black water (Kujawa-Roeleveld et al. 2005).

The choice between CSTR, AC and UASB septic tank will depend on the local situation, particularly on the concentration of the black water as determined by the collection system (toilet) used and frequency that the digested medium can be used in agriculture. During no-vegetation periods (low temperatures) it is not allowed to apply fertilisers. In such a situation a long storage period will be needed. Combined storage and digestion is then a feasible alternative (Zeeman 1991) for other digestion systems.

The accumulation system (AC) is a continuously fed reactor, by which its effective (digestion) volume increases in time. After the maximum volume or the demanded reaction/storage time is reached, the reactor is emptied at once or left without feeding for further stabilisation – additional storage. It is the most simple configuration for anaerobic digestion of waste(water). It

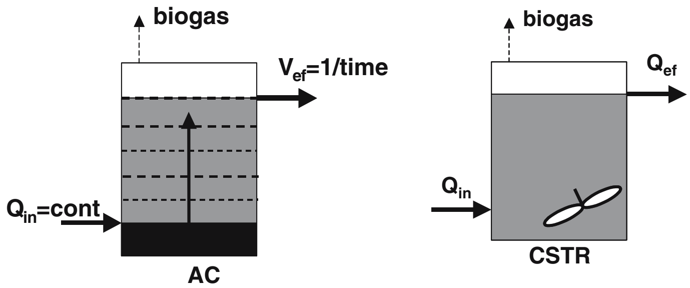

Figure 8. Possible digesters configurations to treat source separated black water, CSTR and accumulation system.

combines the biological conversion of the treated medium and its storage. Besides the tank, facilities for collection and further management of formed biogas are needed. More efficient treatment requires higher temperature, thus heating facilities and isolation of the tank. Long retention times compensate however, for lower operational temperatures. When emptying the reactor after the required storage, attention should be paid to leave a volume of digested medium, serving as well adapted inoculum to the next run. Accumulation time will be determined by a required stabilisation rate of digested medium and the time that it can be applied on fields (different for different vegetation zones). The accumulation system has been used for the digestion of liquid animal manure (Wellinger & Kaufmann 1982; Zeeman 1991; El-Mashad 2003) and tested for digestion of concentrated black water, brown water and kitchen refuse (Kujawa-Roeleveld et al. 2003a, b; Elmitwalli et al. 2005). After digestion and subsequent hygenisation step (if needed), the digested medium can be used for soil conditioning and fertilisation.

As mentioned, the characteristic feature of an AC system is that it is continuously fed with waste(water), effluent is not produced daily but only once per time when the storage time is reached and the treated mixture is needed as a fertiliser, leaving a volume of inoculum for the next cycle. Based on this definition the designed volume of the reactor depends on: (1) daily amount of provided wastewater, (2) demanded accumulation period and (3) volume of inoculum sludge. The accumulation time will be determined by a required stabilisation rate and the time that it can be put on fields (different for different vegetation zones).

Even when using vacuum toilets to collect black water and treat it in an accumulation system, still significant influent volumes are provided, resulting finally in relatively large reactor volumes. Required volumes for 6 months storage are approximately 1.4–1.6 m^3 reactor volume per person when black water and kitchen refuse are treated. Assuming the existence of a vacuum separation toilet where faeces are separately collected with vacuum, only 0.3–0.5 m^3 $person^{-1}$ would be needed to co-digest brown water with kitchen refuse also transported with minimal amount of water. From this point of view an accumulation system is recommended for concentrated media, like brown water and kitchen refuse collected and transported with a minimum amount of water (Kujawa-Roeleveld et al. 2003a, b). Brown water can be only attained when no-mix toilets are applied.

Another reason to exclude urine from the accumulation system is its low contribution to the biogas production while significant to the volume especially when flush water is used to transport urine to the reactor. Accumulation systems are an attractive option for tropical conditions replacing pit latrines, consequently alleviating the problem of ground water pollution (Shaggu 2004). Implementation of accumulation system is recommended for situations when digested mixture can be reused in close neighbourhood (rural areas, urban agriculture). Co-digestion on-farm with animal manure can be considered.

Accumulation systems fed with black and brown water collected with vacuum toilets and the solid kitchen refuse was investigated, proving to be an efficient and robust treatment. About 58% conversion (transformation of influent organics to biogas) was achieved for digestion of brown water and kitchen refuse at 20 °C for a period of 105 days (Elmitwalli et al. 2005). For the first start-up an inoculum with elevated concentrations of ammonium have to be considered. Additional storage without feeding can be applied to provide further stabilisation of digested medium and significant elimination of pathogens (Kujawa-Roeleveld et al. 2005). For restricted fertilisation thermal desinfection is to be applied. Some possible process configurations involving anaerobic digestion of source separated concentrated domestic wastewater in an AC system are presented in Figures 9 and 10.

CSTR systems. The CSTR is the most generally applied system for sludge and slurry digestion at mesophilic conditions and hydraulic retention times (HRT) between 15 and 30 days (Van Velsen 1981; Zeeman 1991; Angelidaki & Ahring 1994; Zeeman et al. 2000). It is a continuously fed tank consisting of a mixture of bacteria and treated medium. Both bacteria and waste(water) have the same retention times, so HRT equals SRT. The term steady state can be applied to the CSTR reactor under condition that the system is "well" adapted and loading is

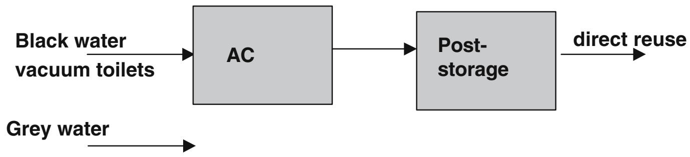

Figure 9. Source separation based sanitation concept involving digestion of black water in accumulation system followed by additional unfed storage for post-digestion and pathogens inactivation.

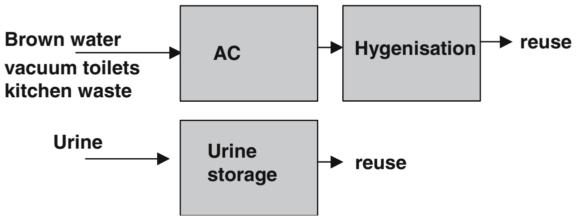

Figure 10. Accumulation system for co-digestion of brown water and solid kitchen waste with post-stabilisation by composting. For efficient inactivation of pathogens, thermal desinfection can be applied instead. Urine is collected separately and stored for some period for desinfection before reused in agriculture. Grey water is treated separately.

constant. Steady state conditions will ensure stable biogas production and effluent quality. In general mesophilic CSTR systems can be applied when the medium to be treated is so concentrated that it will provide enough biogas to cover the energy requirement to heat the reactor. The higher the concentration the more surplus energy is produced for other applications. Moreover concentration of the medium to be treated (e.g. vacuum collected black water) will result in a smaller reactor volume to be installed, provided that the same SRT can be applied for a diluted and a concentrated influent (considering that no inhibiting compounds are present). The digested effluent can be more easily applied in agriculture as transport cost will be limited when small volumes are produced. When digested effluent is to be reused an additional tank will be usually needed for storage of effluent. Agricultural reuse will require desinfection of the anaerobically treated effluent (Figure 11).

A mesophilic CSTR system is applied in a source-separation pilot project Lübeck-Flintenbreite, Germany to treat concentrated black water from vacuum toilets and solid kitchen waste (Otterpohl et al. 1997) prior to its pasteurisation at 55 °C for 24 h

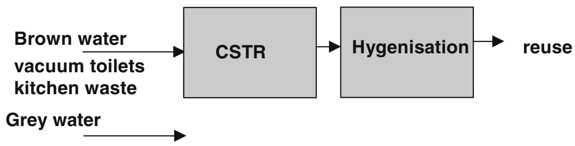

Figure 11. Source separation based sanitation concept where a CSTR reactor is used to treat concentrated domestic wastewater followed by a desinfection step when direct reuse of treated effluent is possible. Grey water is collected and treated separately.

complying with local requirements. The biogas produced can be used in combined heat power systems for district heating and local power generation. The digested mixture is transported by a tanker truck for use in agriculture as a secondary fertiliser (Mels et al. 2005).

UASB septic tank. The feasibility of a UASB septic tank to treat very concentrated black water from vacuum toilet was investigated in a range of temperatures (Kujawa-Roeleveld et al. 2005). The average effluent quality and removal efficiency for two operational temperatures, 15 and 25 °C are given in Table 6 for the first and the second year of operation respectively. High removal of particulate material and total COD was observed in the reactors. Continuously produced effluent contained nitrogen and phosphorus, mainly in soluble forms of ammonium and phosphate. Heavy metals in the effluent did not constitute any problem for reuse in light of WHO standards for irrigation (WHO 1989). Concentration of pathogens was still high. Further treatment of the effluent for recovery/removal of nutrients is then necessary. In some cases direct reuse for close locations can be considered (e.g. urban agriculture).

Depending on the operational temperature and sludge-wastewater contact, high removal of dissolved organic matter can be achieved, although not complete. Solids are concentrated

Table 6. Average effluent quality in terms of COD fractions (in mg COD L^{-1}), nutrients (mg N or P L^{-1}) and removal efficiencies obtained by the UASB septic tanks fed with concentrated black water from a vacuum toilet at two temperatures

Constituent	$T = 15$ °C		$T = 25$ °C	
	Effluent	% Removal	Effluent	% Removal
COD_{total}	3700	61	2855	77
$COD_{suspended}$	980	88	820	91
VFA	1245		120	
Ammonium	830		1180	
Soluble phosphate	50		65	

in the sludge bed that slowly develops. The frequency to remove part of the sludge will depend on process conditions, efficiency and required rate of sludge stabilisation. Sludge removal should not be applied more often than once a year.

7. Separate treatment of grey water

Grey water is less heavily polluted than black water. Little nutrients, pathogens and salts are present in this stream. Pre-treatment is usually needed, otherwise fats (mainly kitchen water) and other biodegradable organic compounds may clog the transport and treatment system or create bad odours. The septic tank or its advanced version – UASB septic tank could be an appropriate pre-treatment technique for most treatment systems in rural as well as urban areas.

For larger applications commercially available compact pre-treatment units, like screens and filters can be used. After separation of settleable matter the effluent can be treated in extensive or intensive biological systems, viz.: sand or soil filtration system (v. Buuren et al. 1999), constructed wetland system, biofilm systems like trickling filters or RBC, activated sludge combined with filtration such as membrane bioreactors (MBR) or biological aerated filter (Jefferson et al. 1999). Physical processes developed for grey water treatment comprise mainly depth sand filtration, membrane filtration combined with appropriate pre-treatment, coagulation and advanced oxidation (Holden & Ward 1999; Jefferson et al. 1999).

Appropriately designed and operated soil or sand filters provide a high removal of organic compounds. Removal efficiency for BOD is typically around 90–99% and for bacteria and viruses 95–99% removal is reported (Stevik et al. 1999). By using a trickling filter or other more intensive applications (e.g. biorotors or activated sludge) the space needed for treatment is reduced but these system consume more energy and produce sludge.

Ponds and wetlands are continuously saturated with water, which is usually unfavourable for oxygen-consuming processes due to gas transfer limitation. Anaerobic conditions occur then easily. At higher temperatures the use of oxygen produced by plants can save the cost of aeration. The plant biomass has to be removed regularly from the system to prevent secondary pollution. Examples of pond systems using primary production directly are the so-called high-rate ponds where, typically, bluegreen algae are cultivated for single-cell protein production (Feachem 1980) and fish polyculture (Zweig 1985). Large footprint in subtropical regions and water evaporation in arid climates are the main drawbacks of these systems. In cold climates the treatment efficiency is uncertain.

MBRs combine an activated sludge reactor with a micro- or ultrafiltration membrane. An important property of the MBR reactor is high retention of biomass enabling application of high loading rates. An MBR effectively removes organic matter and pathogens, meeting even the most stringent water recycling standards. Another compact system combining depth filtration with a fixed film biological reactor is BAF – biological aerated filter. The BAF effectively removes organics but does not substantially disinfect the water (Jefferson et al. 1999).

Treated grey water can be reused in the household, used for irrigation or returned to nature – discharged to surface water or percolated to groundwater. When grey water is used for irrigation special precautions are required when no desinfection step is incorporated: (1) treated grey water should be applied to the soil or sub-surface rather than sprinkled, (2) applied to crops where leaves or stems are not eaten directly (most suitable for trees and bushes and (3) when irrigating edible crops, a certain waiting time between irrigation and harvest is required.

8. "Clean" nutrient production

Direct reuse of anaerobically treated effluent will be often not possible due to a hygienic risk. Post-treatment will be then required to remove pathogenic organisms.

Also because energy prices tend constantly to grow and agriculture is strongly dependent on fossil fuels for production of N and P fertlisers, the reuse of "clean" N and P will become interesting (Helsel 1992; Gajdos 1998; Verstraete, et al. 2004). For clean nutrient production advanced technologies are required. Recovery of "clean" nutrients from anaerobically treated concentrated wastewater is, next to biogas, a potential source of revenue, partially offsetting the costs of treatment. Although both recovery and removal techniques have been investigated or applied in a full scale, limited information is available to decide which route, removal or recovery, should be taken in source separation sanitation concepts.

Industrial ammonia production for fertiliser industry remains fairly inexpensive. Nitrogen is also not a finite mineral and energy required for recovery is often equal to the combined energy required for biological N removal (for instance via a combined SHARON/Anammox process) and industrial ammonia production (Maurer et al. 2003a, b; Wilsenach et al. 2003). Also with a high load of ammonia produced through animal husbandry and the lack of farmland near cities, being a case in many countries, efficient nitrogen removal from separately collected black water could prove to be a more feasible option than recovery.

On the other hand the analysis of different removal and recovery techniques for nutrients in urine shows that in many cases recovery from concentrated streams is energetically more efficient than removal in the traditional wastewater treatment plant and new-production from natural resources (Maurer et al., 2003a, b).

Conventional nitrogen removal processes applied in centralised treatment plants require substantial resources, relative to wastewater treatment as a whole. Nitrification requires aeration which accounts for almost 25% of the total energy demand in wastewater treatment plants. Next to energy requirements for aeration, nitrifiers are slowly growing organisms – requiring long SRT in the aeration reactor, thus large volumes. Denitrification on the other hand requires energy in the form of readily biodegradable organic carbon.

The effluent from anaerobic digesters treating black water will not have an adequate C/N ratio to attain complete denitrification. A COD:N ratio of approximately 2 characterises the effluent of an anaerobic digester treating concentrated black water (Kujawa-Roeleveld et al. 2004). Recently new alternative processes have been studied to remove nitrogen from especially concentrated streams. They were developed mainly to treat reject waters from sludge treatment processes typically characterised by high ammonium concentrations (600–1200 mgN L^{-1}) and usually higher temperatures than domestic wastewater. The alternative nitrogen removal processes are: stripping of ammonia with air or steam, struvite precipitation (MAP), SHARON (single reactor for high activity ammonia removal over nitrite) with denitrification, Anammox process or anaerobic ammonium oxidation (van Dongen 2001a; b), Canon (combined Sharon/anammox), ammonia adsorption to zeolites (Lind et al. 2000).

To apply nutrient recovery/removal techniques, treatment of anaerobic effluent to remove suspended solids and colloidal matter will be often required.

8.1. *Nutrient recovery*

Stripping. Nitrogen in the effluent of an anaerobic reactor treating black water is mainly present as ammonium. By raising the pH the ammonium is converted to readily soluble ammonia. In contact with the gaseous phase ammonia will be transferred from the water to the gas phase. In stripping towers applied for ammonia stripping, the water and gas flow count-currently and a high contact surface is ensured by presence of packing material. Two types of processes are distinguished: air- and steam stripping, differing in the end treatment of the ammonia rich gas. In the air stripping, process the ammonia rich air is either scrubbed with acid or combusted. During the steam stripping aqueous ammonia (salt) is produced, which can be concentrated by reflux (Janus & van de Roest 1997).

Ion exchange. Synthetic ion exchanger is a polymer with electrically charged sites at which one ion may replace another. Certain minerals are also quite good exchangers. *Zeolites*, for instance, are hydrated aluminum-silicate minerals, which have an affinity for ammonium ions. Zeolites are effective to remove ammonium (87–98%) from less concentrated influent like domestic wastewaters (up to 150 gN m^{-3}) and also dairy and piggery influents containing up to 1000 mgN L^{-1} (Nguyen & Tanner 1998).

Struvite, phosphate precipitation. Phosphate is a finite resource that should be recovered and recycled where possible. Next to phosphate, domestic wastewater and especially black water contains potassium that could potentially also be recycled. Struvite precipitation is potentially an attractive way to recover two nutrients from anaerobically treated wastes at one time. Struvite forms, magnesium ammonium phosphate hexahydrate $MgNH_4PO_4.6H_2O$ (MAP) or potassium magnesium phosphate hexahydrate $KMgPO_4 \cdot 6H_2O$ (KMP), are minerals, which often precipitate from wastewater, especially during anaerobic digestion when ammonium, phosphate, potassium and magnesium ions are released. Struvite is potentially good, slow-release fertiliser (Salutski et al. 1970) having similar composition as commercial fertiliser (Li et al. 1999).

Formation of struvite forms was observed during biological treatment of hog wastes (Webb & Ho 1992; Wrigley et al. 1992; Maqueda et al. 1994), poultry wastes (Manninen et al., 1989), wine distillery effluents (Lowenthal et al. 1994) and biosolids from biological phosphorus removal processes (Fujimoto et al. 1991). A high degree of ammonia removal via MAP was observed from anaerobic sequencing batch reactor (ASBR) effluent with a molar ratio for NH_3:Mg:(PO_4–P) of 1:1.25:1 and an optimum pH of 9.5 Miles and Ellis (2001). In that study ammonia concentration was reduced from 1500 mg L^{-1} to less than 10 mg L^{-1} by supplying magnesium oxide and potassium phosphate to an effluent waste stream of an operating ASBR.

As the effluent of an anaerobic digester of concentrated black water contains a high concentration of ammonium but significantly lower concentrations of magnesium, phosphate and potassium, these components have to be added if high removal of ammonium is required. For instance, the approximate N:K:P ratio in urine is 27:2:1. Therefore, less than 4% of the ammonia in urine can be potentially recovered with MAP precipitation (STOWA 2005). An additional step to remove ammonia will be therefore needed. Phosphate removal of around 90% was achieved from an influent concentration of 110 mgP L^{-3} (Ueno & Fuji 2001), which is similar to concentrated black water.

A fluidized bed reactor can be used to crystallise struvite. Magnesium hydroxide and other additives (for pH adjustment and/or enhanced nitrogen precipitation) is added with the inflow at the bottom of the fluidized bed, with sodium hydroxide to maintain a pH between 8.2 and 8.8. Struvite granules can be separated by screening. Precipitation in a CSTR is a much simpler technique, after which struvite is separated in a settling tank (Schuiling & Anrade 1999). The transport of struvite particles to liquid/solids separation units is believed to cause operational nuisances due to scaling and resulting pipe blockage. Precipitated particles can be stored instead in a special internal compartment (STOWA, 2005).

Phosphate alone can also be recovered as calcium phosphate in a crystallisation process. In a liquid with high supersaturation, primary nucleation (precipitation) of phosphate minerals will occur in the presence of suitable cations. Supersaturation increases with increasing alkalinity. Calcium phosphate can be formed in a fluidized bed reactor where milk of lime is added in sufficient quantities to maintain pH 8.5 (Eggers et al. 1991). Sulphuric acid is added prior to remove bicarbonate to prevent precipitation of calcium carbonate instead of calcium phosphate. Sand is introduced as seed material and kept in suspension by special flow regulation.

8.2. *Nitrogen removal*

Sharon (Single reactor system for High activity Ammonia Removal Over Nitrite) is a compact biological system for efficient removal of nitrogen from concentrated streams (reject water, black water). Ammonium is first oxidised under aerobic conditions to nitrite (nitritation). With the addition of an external carbon source this nitrite is then converted to dinitrogen gas under anoxic conditions (denitritation). All these conversions take place in a single reactor system (Hellinga et al. 1998). The oxidation of ammonium to nitrite only and not to nitrate leads to a considerable reduction of aeration costs – 25%. An additional cost in the Sharon process is the external carbon source (usually methanol) that needs to be added to the second step. On the other hand because nitrite is directly converted to nitrogen gas, 40% less organic carbon is needed to complete denitrification.

The process is carried out at a relatively high temperature of 30–40 °C, providing high growth rate of biomass impaired with high activity. Nitritation and denitritation take place in one reactor by switching the aeration on and off.

The Sharon process was originally developed to treat the centrate rejected by a direct dewatering of warm digested sludge. In general it is suitable for substantial removal of ammonium from streams containing hundreds to thousands mgN L^{-1}).

If the carbon source is not added to the Sharon process, and there is no internal carbon source present, there is no conversion of nitrite to dinitrogen gas. This would give an effluent from the Sharon reactor, containing both ammonia and nitrite. This effluent can then be used as influent for the *Anammox* reactor. In the Anammox process (ANaerobic AMMonium Oxidation) ammonium is oxidised with nitrite as electron acceptor (Jetten et al. 1999). Dinitrogen gas is the main reaction product. A small amount of nitrate is also formed. Since the Anammox organisms are autotrophic, no addition of an external carbon source is required.

In order to obtain a high removal efficiency, it is essential that ammonium and nitrite are fed to the reactor in molar ratio of one. By combining the Sharon and the Anammox process ammonium can be removed from wastewater with high ammonium content without the addition of an external carbon source and with considerable less aeration costs in comparison with the classical methods. The oxygen demand of the combined SHARON/Anammox process is only 42% of conventional nitrification. Since ammonium provides the energy source no organic electron donor is required. The slow growth rate of *anammox* bacteria is considered as a main disadvantage of this process (STOWA 2005). Biomass retention is therefore crucial.

The CANON system (Completely Autotrophic Nitrogen Removal Over Nitrite) enables to remove ammonium from wastewater in a single, oxygen-limited treatment step. The CANON process relies on the stable interaction between only two bacterial populations: *nitrosomonas*-like aerobic and *planctomycete*-like anaerobic ammonium oxidising bacteria. Effective and stable nitrogen removal to dinitrogen gas of above 90% was reported at N-loading rates above 0.1 kg N_{total} m^{-3} day^{-1} (Third et al. 2001).

For continuous systems nutrient removal or recovery to produce clean products will in general be required. A general scheme involving also final polishing for desinfection and additionally removal of organic micropollutants is given in Figure 12.

9. Discussion

The prime objective of decentralised sanitation concepts is to protect the environment and public health. However, by combining appropriate technologies, efficient treatment and generation of reusable resources can be obtained. The choice of a technological scheme depends on local circumstances and requirements. In a new location to be built or in a situation when there is no sanitation infrastructure at all a maximum recovery and reuse of resources can be achieved when wastewater streams of a different degree of pollution are separately collected and affinitively treated. Black water is then separately collected from grey water. Further separation may involve collection of urine and brown water. The treatment can be house-on-site, community-on-site or combination of both. When reuse is an objective, a minimal amount of transport water should be used for black water. This will make its

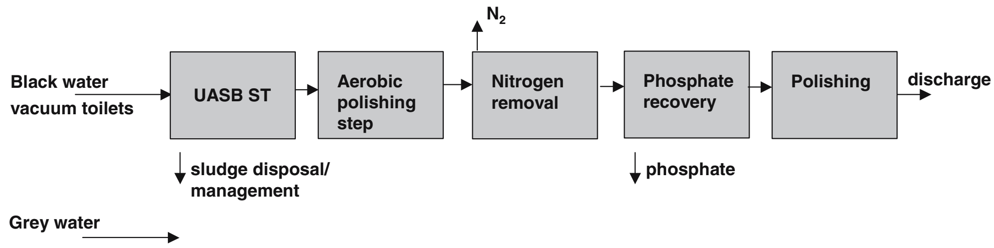

Figure 12. Anaerobic treatment of concentrated domestic wastewater in an UASB septic tank. Nitrogen removal can be accomplished by new removal processes suitable for N-rich streams (Sharon, Anammox, Cannon). Phosphate can be recovered as potassium or ammonium struvite. For excellent reusable effluent quality polishing can be added to remove organic micro-pollutants (estrogens and pharmaceutical residues) and for desinfection.

treatment and reuse less complex and cost-effective. When anaerobic digestion is applied to treat concentrated black water or brown water, addition of kitchen waste can be considered for maximisation of methane recovery.

For existing infrastructure several options are available for providing a more sustainable sanitation. Conventional septic tanks to treat black water or all domestic wastewaters can be upgraded to UASB septic tank. Construction of small bore sewer system and transport of the effluent to a post-treatment step is a relatively cheap way to reduce hygienic risks, reduce pollution of ground water or make the wastewater applicable for irrigation and/or fertilisation. When pond systems are used as a main treatment, an anaerobic reactor can be introduced as pre-treatment leading to a substantial reduction of space requirement, water evaporation, methane emission and odour nuisance.

Implementation of source separation based sanitation is a change in a current wastewater management. It is expected that this can form a barrier since consultants, infrastructure constructers, authority policy as well as local water management are used to traditional solutions. Operational and maintenance structures have to be adjusted or new created. Also financing is expected to be different organised than in current situation (if any).

The scale of the treatment system being implemented, house-on-site or community-on-site, determines choice of the optimal sanitation scheme. Some examples are given in Table 7.

An important aspect of the current sanitation infrastructure is its high comfort and majority of users do not really feel the necessity to change it. Introduction of source separated sanitation on the local scale means for the inhabitants installation and use of another type of toilet and location of the facilities for the treatment of black and/or grey water in their close neighborhood. However, when well informed and when change is not associated with their own financial contributions people stand not against new developments. Implementation of kitchen garbage grinders would mean improvement of people's comfort.

Another important aspect in new sanitation concepts is final management of the rest products: e.g. urine, digested black water, sludge, struvite etc.

10. Conclusions

Traditionally anaerobic treatment of domestic wastewater was carried out in decentralised sanitation. Alone, it does not provide a sufficient degree of wastewater purification and resource reuse is not implemented.

Collecting septic tank effluent and transporting it using a small bore sewer system to a semi-central post-treatment unit results in a significant improvement of decentralised sanitation. If an efficient post-treatment is applied, treated wastewater can be used for irrigation or discharged to surface water.

For total domestic wastewater stream more advanced, high rate anaerobic reactors followed by post-treatment can be applied resulting in a demanded effluent quality for irrigation, fertilisation or discharge. The introduction of urine sepa-

Table 7. Some examples of possible treatment scenarios in function to implementation scale (house-on-site or community-on-site)

Wastewater collection and transport system	House on-site	Community-on-site
Total sewage	Septic tank, UASB septic tank, soil/sand filter to polish the effluent, discharge	UASB, post-treatment to remove pathogens, reuse of effluent for irrigation or discharge
Black water, moderate concentration	Septic tank, UASB septic tank, effluent transported with small bore sewer to community-on-site post-treatment	UASB or UASB septic tank, post-treatment to remove pathogens
Black water, highly concentrated (possibly combined with solid kitchen waste)	Accumulation system, additional storage of digested medium, direct reuse	CSTR, post-treatment to remove remaining organics and suspended solids, "clean" nutrient recovery or direct reuse after desinfection
Grey water	Pre-treatment in septic tank, UASB septic tank followed by (sand) filtration system	Pre-treatment to remove solids followed by constructed wetland systems or sand filters. In case no space is available, compact high rate systems, discharge or reuse in household
Urine	Storage, local reuse	Storage, direct reuse or nutrient recovery ("clean" nutrient production)

ration significantly improves the nutrient reuse potential and sustainability of the local sanitation.

Source separation of wastewater streams and their affinitive treatment enables targeted treatment and a maximum recovery of resources. Wastewater containing the highest organic and nutrient load, black water and optionally kitchen waste, is preferably digested in a simple reactor configuration.

Depending on local requirements, anaerobic digestion process efficiency direct reuse of digested medium can be applied. When the reuse standards are stringent, a multi-step advanced treatment process resulting in a clean nutrient production and/or removal will be applied.

A way of wastewater collection and implementation scale (house-on-site or community-on-site) determine type of the treatment system to be selected.

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