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Review

# Maximum use of resources present in domestic "used water"

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ABSTRACT

Environmental protection and the sustainable management of natural resources stand at the foreground of economic and technological activities worldwide. Current sewage technologies, however, deal with diluted wastes and do not focus on recovery and are therefore not sustainable. Here, the most promising methods available for the recovery of nutrients (nitrogen, phosphorus), organic material and energy from "used waters" are examined both at the decentralised and centralised level. Novel approaches for water processing, not implementing aerobic biological treatment as a core technology, are conceived and critically evaluated regarding efficiency, diffuse emissions and requisite costs. By implementing up-concentration of dilute wastewaters, the concentrated stream becomes suitable for the waste-to-energy strategy.

The approach of up-concentration of municipal effluent at arrival at the water treatment plant followed by anaerobic digestion of organics and maximal reuse of the mineral nutrients and water is estimated to have a total cost of the order €0.9/m$^3$; the latter is comparable to that of conventional aerobic treatment technologies which has little or no reuse. It is argued that in view of the fact that recovered nutrients will become of increasing economic and ecological value, this new conceptual design for the treatment of "used water" will become feasible in the next decade.

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## 1. Introduction

Throughout the world, water scarcity is being recognized as a present or future threat to human activity and as a consequence water reuse strategies should deserve major attention (Fritzmann et al., 2007).

Water scarcity has become a global issue and not only a problem relevant to arid zones. Continuous population growth, rising standards of living, climate changes, industrialization, agriculture and urbanisation has resulted in water becoming a limiting resource. This scarcity is often the limiting factor for economic and social development (Singh, 2007). According the United Nations predictions, between two and seven billion people will face water shortages by the year 2050. Even today about 80 countries, comprising 20% of the world population are suffering from serious water shortage (United Nations, 2006). Also in countries with the availability of high quality water, industry and agriculture have to compete for these resources with the households. Due to the increasing pressure on the use of groundwater in the last decades, water industries have to look for alternative water resources which have led to the implementation of closed cycle processes in domestic and industrial water supply (Dewettinck et al., 2001; Verdickt et al., 2007; Hoeijmakers et al., 2007). In these industries, wastewater treatment is regarded as an integral part of the production process rather than an end-of-pipe solution.

Effluents, originating from domestic wastewater treatment plants, deserve a special attention because of the availability at the place where water reuse strategies should be adopted, i.e. urbanized regions. This water resource is able to provide up to 80% of the need of freshwater (Qin et al., 2006).

The initial goal of wastewater treatment was to protect downstream users (Wilsenach et al., 2003) and in the last decades environmental protection came into the picture by the stringent effluent standards for nutrients. Yet, one cannot overlook the fact that the conventional approach brings about diffuse emissions such as $CH_4$ (Guisasola et al., 2008) and $H_2S$ (Zhang et al., 2008a) in the sewer and $N_2O$ in the aerobic treatment system (Colliver and Stephenson, 2000). The focus on nutrient removal has as a result that the costs for wastewater treatment in regions with sensitive surface waters is dominated by the conversion and elimination of nitrogen and phosphorus. Since these effluents are the perfect source for the abundant demand of high quality water, domestic wastewater treatment can be seen as a part of the freshwater production. This incorporation has a high impact on the environmental footprint correlated with freshwater production. As an example hereby, the Dow's Benelux site at Terneuzen (The Netherlands) is recently reusing the local community's treated wastewater. The effluent of the sewage treatment plant is subjected to membrane filtration. The product of the latter is implemented by the industry

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to generate steam. By this, three million tons per year of water previously discharged into the North Sea after just one use are now recycled. Reusing this water results in 65% less energy consumed at the facility – compared to desalination of the same amount of seawater. The latter is equivalent with a decrease in $CO_2$ emission of 5000 ton on a yearly basis. Next to $CO_2$, also the chemical demand for the overall water supply process is significantly decreased (Baker, 2008).

Since high quality freshwater can actually be produced form wastewater, an extra effort for harvesting other resources, such as nutrients and energy from wastewater also should be considered in order to make the overall sewage treatment more sustainable. Indeed, besides a freshwater resource, domestic wastewater is also an important carrier medium for nutrients in the nutrients cycle. Nitrogen is an abundant element in the human's diet. This results in a central position of man in the anthropogenic nitrogen cycle (Mulder, 2003). The supply of protein food is largely dependent on the anthropogenic atmospheric nitrogen fixation by the Haber–Bosch process. The generation of ammonia from the air requires 35–50 MJ per kg N in the form of fossil fuel for energy supply (Maurer et al., 2002). The potential of domestic wastewater to decrease the amounts of atmospheric nitrogen that have to be converted to ammonia fertilizer is substantial. Based on an average excretion of 13 g N per capita per day, the annual excretion is 4.75 kg N per capita. Research showed that about 30% fertilizer-N ends up in the domestic wastewater (Bleken and Bakken, 1997; Mulder, 2003). Hence, recovery of nitrogen present in domestic wastewater is able to cover some 30% of the current agricultural N demand. Time has come to recycle the N present in sewage rather than "wasting" it by nitrification and denitrification. This will allow minimizing the anthropogenic production of fertilizer.

Besides nitrogen, phosphorus is also present at substantial levels. Phosphorus is gained from rock phosphates, which are a limited resource concerning quantity and quality. The known rock phosphates deposits in the world are sufficient for 100–1000 years, depending on the efficiency of resource use during P fertilizer production and on the use of fertilizers in the next decades (Tinker, 1977; Smil, 2000; Zhang, 2008). In order to give the phosphate industry and agriculture a sustainable future, it has been advocated that phosphate should be recycled (Driver et al., 1999). Furthermore, mining of phosphate has a heavy environmental impact. The production/mining of 1 kg P fertilizer leads to 2 kg gypsum which is contaminated with heavy metals and radioactive elements and is often not disposed of in an environmental friendly way (Driver et al., 1999; Wilsenach et al., 2003). The sources of phosphate pollution are agriculture (through the use of fertilizer), sewage and industry. Based on an average excretion of 2 g P per capita per day and addition of P originating from detergents, food waste, food additives and other products, a significant amount of the P ends up in the domestic wastewater. The first major concern is to remove the P in order to protect surface waters. By implementing P reuse strategies the need for commercial phosphorus fertilizers can be decreased. However, since wastewater is a heterogeneous and complex matrix of different elements, harvesting phosphorus from this kind of systems poses difficulties (Kvarnström et al., 2003). The poor bio-availability of P for plants and the contamination of the recycled P with heavy metals and organic micropollutants constitute a major challenge (Ito et al., 2008). One should therefore aim at technologies which minimize the level of contaminants associated with the phosphorus fraction.

Based on a series of inquiries with the field of practice, a new concept of dealing with "used water" is proposed, which is in sharp contrast to the one which revolutionized sewage treatment in the past century. Indeed, at current market prices, a potential of €0.35/$m^3$ of resources can be recovered by appropriate techniques (Table 1). The latter value is mainly due to the value of the water as such, followed by the nutrients. The price of phosphate fertilizers has linearly increased during the last 5 years and the current price of processed phosphate rock is expected to be around €0.70/kg P. According the US Geological Survey, the price for unprocessed phosphate rock was €0.54/kg P in 2008 (Jasinski, 2007; US Geological Survey, 2008). The prices of nitrogen fertilizer have recently also become substantial (approximately €0.21/kg N) (US Geological Survey, 2007). Clearly, the time to redesign sewage treatment in a matter to maximize the reuse in the line of the cradle-to-cradle concept (McDonough and Braungart, 2002) has arrived.

**Table 1**
Potential product recovery from municipal "used water".

| Potential recovery | Per $m^3$ sewage | Current market prices | Total per $m^3$ sewage (€) |
|---|---|---|---|
| Water | 1 $m^3$ | €0.250/$m^3$ | 0.25 |
| Nitrogen | 0.05 kg | €0.215/kg | 0.01 |
| Methane[a] | 0.14 $m^3$ | €0.338/$m^3$ $CH_4$ | 0.05 |
| Organic fertilizer[b] | 0.10 kg | €0.20/kg | 0.02 |
| Phosphorus | 0.01 kg | €0.70/kg | 0.01 |
| | | Total | 0.35 |

[a] Methane produced per $m^3$ of sewage was calculated on the basis of 80% organic matter recovery as biogas with 0.35 $m^3CH_4$/kg COD removed.

[b] Organic fertilizer was calculated on the basis of 20% organic matter remaining after anaerobic digestion and the price is based on the agricultural value of organics.

This paper describes the cradle-to-cradle concept for centralised and decentralised systems incorporating the current environmental concerns. Whether or not decentralised systems are part of tomorrow's solution for problems associated with dilute wastestreams and sewerage, focus must be placed on the minimization of diffuse emissions. The degree of valorisation of the present resources in the decentralised wastewater is depending on the scale of the installation, therefore, construction of small decentralised sanitation units should be limited for households for which sewerage connection with the treatment plant is not an option due to the high sewerage costs. In these systems the maximal recovery of resources should be coupled to minimization of diffuse emissions. For larger scale decentral sanitation units, the focus can be fully placed on maximal use of the resources in the form of electricity and heat originating from the anaerobic valorisation of the solids present in the wastewater. For centralised facilities, the implementation of nutrient recovery methods is essential. In this paper, we review the current practices of decentralised (Section 2) and centralised (Section 3) wastewater treatment, and propose new wastewater technologies based on concentrated wastewater, which allow maximum resource recovery.

## 2. Process concepts for decentralised sewage treatment

The current approaches for decentralised treatment of sewage treatment are well known. The often used septic tank represents an investment of about €3000 per family. Due to the anaerobic conditions, it converts a major part of the organic matter to methane gas (estimated at 20–40 $m^3$ per IE per year) which dissipates into the atmosphere and thus contributes to the global warming (Vincke and Verstraete, 1999). Moreover, since decentralised treatments most often release the N and P in the form of soluble minerals to the surface waters, this approach is not at all environmental friendly. Alternatively, the often used small scale aerobic units represent a capital expenditure of some €5000 per family. They consume energy (some 40 kWh/inhabitant equivalent (IE) per year) and also discharge the major part of the nutrients to the environment. Clearly, the current designs for decentralised treatment of sewage are totally insufficient and outdated. New process concepts should aim for a maximal as possible sanitation with minimization of diffuse emissions such as methane, nutrients and pharmaceuticals.

The major part of the ammonia (60–90%) and the phosphorus (40–70%) in municipal "used water" originates from urine (Butler et al., 1995; Almeida et al., 1999). Thus, separation of the latter may result in more efficient nutrient recovery methodologies. In this context, research has been undertaken in Sweden since the 90s (Hanaeus et al., 1997) at pilot-scale levels with urine separated toilets (17 houses, representing approximately 55 IE). However, this approach requires new infrastructure (both at household and community level) and will be only applicable at special sites.

Toilets employing vacuum collection are well established and they can be implemented more easily. Under optimal conditions they use only 1 L of water for flushing, thus producing 7 L per IE per day of concentrated black water. Under these conditions, water saving amounts to approximately 35 L per IE per day. An important issue in this case is the way of transporting this concentrated sewage to the processing plant.

A process for black water (pre)-treatment with simultaneous energy recovery has been proposed by two research groups i.e. in Finland (Luostarinen and Rintala, 2007) and in the Netherlands (Zeeman et al., 2008). The Upflow Anaerobic Sludge Blanket-Septic Tank (UASB-ST) differs from the conventional septic tank by the upflow mode in which the system is operated (Fig. 1). Consequently, contact between the sludge bed and the water is improved, as well as the removal of suspended solids and the conversion of dissolved organic components. The system requires extra volume for the accumulation and stabilization of sludge. Considering a design value of 100 L per IE, the UASB-ST requires sludge emptying only once per year.

The UASB-ST has several advantages and disadvantages. Results from pilot-scale testing (16 houses with approximately 40 IE) using concentrated blackwater revealed that it was possible to produce approximately 14 L of methane per day (at STP) per IE (Zeeman et al., 2008). The system was capable of converting 40% of the incoming chemical oxygen demand (COD) load to biogas, while 40–50% was accumulated as non- or slowly degradable matter and 10–20% washed out from the system. Therefore, the UASB-ST effluent may still require further processing in ecologically sensitive locations. Evaporation for instance, can minimize the diffuse emissions of recalcitrant pollutants. Alternatively, kitchen wastes can be added to blackwater to increase the biogas yield per site, which has a significant impact on the process economics.

The treatment of grey waters offers significant potential for reuse on-site since they are free from feaces, urine and pathogens and they receive a more positive acceptance by the public. Different options for greywater treatment have been reported previously (e.g. Nolde, 1999; Ramon et al., 2004; Zeeman et al., 2008).

In Table 2, a comparison of the energy requirements by conventional respectively source separated water treatment is given. The anaerobic digestion-based approach is energy positive and offers potential for N, P and water reuse at the local level. Moreover, the diffuse emission of pharmaceuticals is diminished by the use of an anaerobic treatment of the blackwater, which allows a higher degradation of certain pharmaceuticals (Carballa et al., 2007).

By further processing the effluent from the UASB-ST, it is possible to recover phosphorus as struvite (theoretically 0.28 kg P per year and per IE).The ammonium nitrogen is only partially removed from the effluent and needs therefore a further nitrogen removal step which can be performed in an oxygen-limited autotrophic nitrification/denitrification (OLAND) reactor (Vlaeminck et al., in press). This method, based on partial nitritation and anammox, allows a significant decrease of the operational costs compared to conventional nitrification/denitrification process (Fux and Siegriest, 2004).

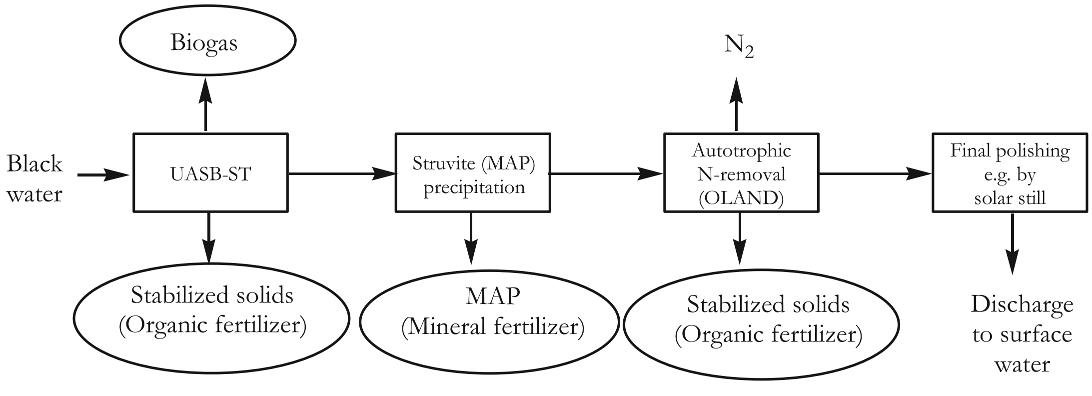
Note that on average, the electricity consumption per IE per year in the industrialized world is of the order of 1000 kWh. Hence, this decentralised approach, making a potential difference of some 30 $kWh_{el}$ per IE per year (Table 2), offers a potential saving of the order of several percentages. Moreover, decentralised heat production can be considered if biogas is valorised in combined heat and power systems.

## 3. New approach for centralized sewage treatment

### 3.1. Products to recover

### 3.1.1. Water

Due to the presence of micropollutants, direct reuse of effluent from the conventional activated sludge (CAS) as drinking water is



| | |
|---|---|
| UASB-ST | $HRT_{min}$ = 7 d<br>$T_{max}$ = 30°C |
| Struvite | Contact time = 30 min |
| OLAND | $HRT_{min}$ = 3.5 d |

**Fig. 1.** Decentralised black water treatment with biogas and recovery of MAP (after Zeeman et al., 2008). Abbreviations: UASB-ST, upflow anaerobic sludge blanket – septic tank; MAP, magnesium ammonium phosphate; OLAND, oxygen-limited autotrophic nitrification/denitrification; HRT, hydraulic residence time.

**Table 2**
Energy balance for conventional and source separated processing of domestic effluents per inhabitant equivalent (IE) and per year.

| | | | |
|---|---|---|---|
| A | Conventional design | Activated sludge; power consumed | $-25\ \text{kWh}_{el}$ |
| B | New design | Anaerobic digestion; power recovered[a] | |
| | | BW = 5 $m^3$ biogas<br>GW = 0 $m^3$ biogas | ≈ $+10\ \text{kWh}_{el}$[a] |
| | | Aerobic post-treatment, power consumed | |
| | | BW<br>GW — Estimated at 20% of conventional | ≈ $-5\ \text{kWh}_{el}$ |
| | | Total | $+5\ \text{kWh}_{el}$ |
| | | Difference Δ | $30\ \text{kWh}_{el}$ |

Abbreviations: BW, black water; GW, grey water; el, electrical; IE, inhabitant equivalent.
[a] The biogas yields some 10 kWh thermal energy on the side.

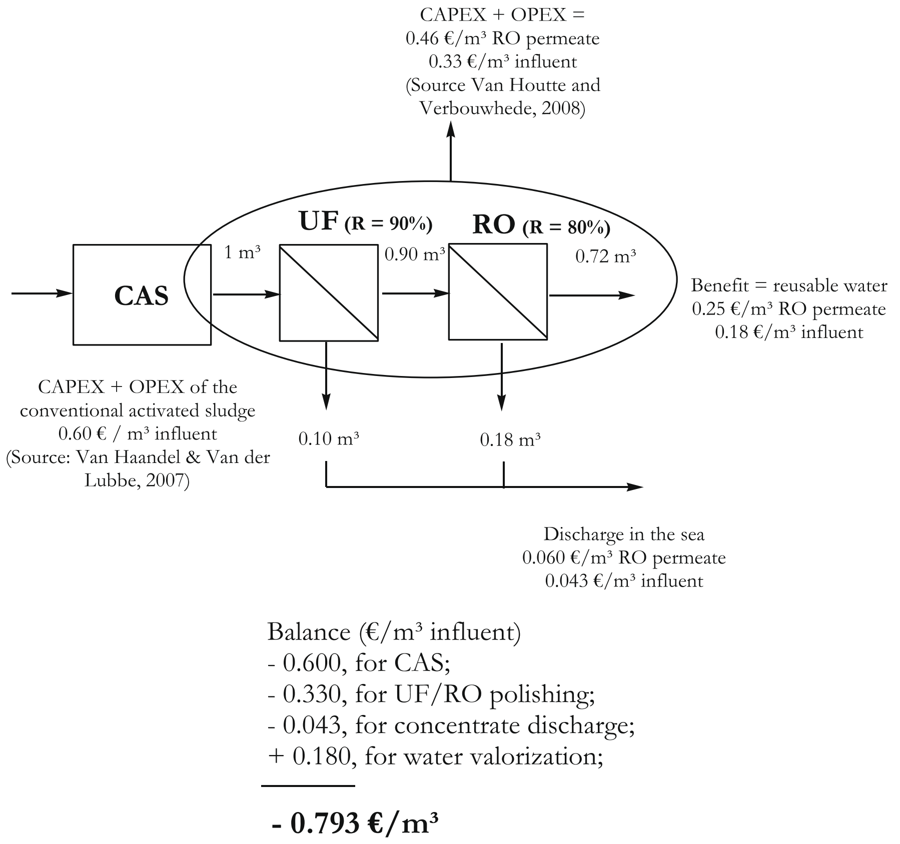


**Fig. 2.** Process and cost overview for conventional activated sludge followed by UF/RO polishing (after Van Haandel and Van der Lubbe, 2007 and Van Houtte and Verbauwhede, 2008). Abbreviations: CAS, conventional activated sludge; UF, ultrafiltration; RO, reverse osmosis; R, recovery, CAPEX, capital expenditure; OPEX, operational expenditure.

not feasible. An extra polishing step by membranes is necessary. After CAS, the effluent is treated by microfiltration (MF) or ultrafiltration (UF) so that a complete retention of the suspended and colloidal particles occurs. At the same time a major part of the pathogens is also removed. To counter the unwanted presence of organic micropollutants in the source waters for fresh- or drinking water production, an advanced polishing step is required. One of the new and advanced techniques is reverse osmosis (RO) polishing in order to counteract the diffuse emissions of persistent compounds such as personal care products and pharmaceuticals (Radjenovic et al., 2008). The process described above is capable to produce high quality water and several large-scale installations are currently in operation (e.g. Water Factory 21, USA; West Basin Plant, USA; Torreele Plant, Belgium). The total costs (Capital Expenses (CAPEX) + Operational Expenses (OPEX)) associated with MF of secondary effluent have been reported to be of the order of €0.35/$m^3$ (Durham et al., 2001). This value was based on actual capital and operational expenses of the West Basin Water Recycling Plant ($Q$ = 11 280 $m^3$/d). The costs for producing freshwater from secondary effluent using RO have been reported to equal €0.44/$m^3$ (Cote et al., 2005) and €0.46/$m^3$ (Dewettinck et al., 2001; Van Houtte and Verbauwhede, 2008). These values include the pre-treatment of the water (by UF). Because of the additional costs of conventional activated sludge (€0.3–0.6/$m^3$) and the reuse treatment, the total process is costly (~€0.8–1.1/$m^3$) and moreover complex. A more detailed cost calculation and process overview of the Torreele plant is given in Fig. 2. The benefit of water reuse is included in the total cost balance.

In the membrane bioreactor (MBR) technology, the activated sludge produced during the aerobic decomposition of organic matter is separated from the treated water by direct membrane filtration. The membrane bioreactor has found numerous applications for wastewater treatment and reuse strategies due to the compatibility with RO systems (Cornel and Krause, 2006; Yang et al., 2006; Lesjean et al., 2004). The total costs (CAPEX and OPEX) for MBR treatment system are slightly higher than those of activated sludge, but in the range of €0.3–0.6/m$^3$ (Cote et al., 2004; Cote et al., 2005). Adding an extra cost of €0.3–0.4/m$^3$ for treating the effluent from the MBR using RO gives a total of €0.6–1.0/m$^3$ of wastewater treated.

### 3.1.2. Energy

The main source of energy at a municipal CAS treatment plant is the biogas produced by the anaerobic sludge digesters during the process of sludge stabilization. During the fermentation process, the biodegradable organics present in the primary and secondary sludge are transformed to methane and carbon dioxide at one hand and new microbial biomass on the other hand. Approximately 0.5 kg per kg of sludge, expressed as COD, is converted to biogas. The residual non-biodegradable matter (0.4 kg) and the new anaerobic biomass (0.1 kg) are exported with the effluent slurry. Thus, only part of the energy can be recovered, i.e. 25% of the incoming raw water COD load. The recovered energy is used for powering gas engines, producing electrical and thermal energy for on-site use. The cost of electricity for a CAS system is about 80% of the energy cost. On the other hand only 40% of electrical energy consumption can currently be covered by power generation on-site (Schwarzenbeck et al., 2008).

An alternative option for energy recovery from domestic effluents is the direct anaerobic digestion. The application of the UASB process directly on sewage has been applied in hot-climate countries and only partial energy recovery is possible, due to the solubility of methane in the effluent. In moderate climates, this approach is not advisable, due to the low ambient temperature. The losses of methane dissolved in the effluent contribute to the climate change. Methane has a ±25 times higher global warming potential than carbon dioxide (Lelieveld et al., 1993). Also the COD removal during direct anaerobic digestion of sewage is at maximum 60–70% (van Haandel and Lettinga, 1994). The main problem is that sewage is too diluted for optimal direct anaerobic digestion and a significant part of the produced methane (up to 40%) is dissolved in the liquid phase and lost with the effluent. As a consequence, only 40–45% of the organic carbon energy content is recovered in practice. Alternative strategies should be applied in order to make anaerobic digestion compatible with wastewater treatment.

### 3.1.3. Nutrients

Nitrogen can be preserved in part by recovering it in the form of magnesium ammonium phosphate (Carballa et al., 2009). Alternatively, it can be released as ammonia and recovered as an ammonium salt by air stripping followed by an acid wash. Moreover, the ammonium can be converted in part or totally to nitrate by nitrification. The challenge for the next decade is to develop methods to produce reliable concentrated nutrient solutions from "used water". If one achieves the latter, they can qualify as "natural stable fertilizer (NSF)" for the regulator and the agronomist.

Phosphorus can be removed directly from the raw wastewater by precipitation with iron, aluminium, lime or magnesium. The iron or aluminium phosphate containing sludge can be chemically processed (alkaline treatment) for releasing the phosphorus content and transform the phosphorus to calcium phosphate, which is the raw material of the phosphorus industry (Morse et al., 1998).

In cases where simultaneous precipitation of phosphates inside the aeration tank is performed or the organic and inorganic sludges are mixed, chemical bound P release requires thermal treatment under acidic or alkaline conditions, e.g. by the Krepro, BioCon and AquaReci process (Levlin et al., 2002). These technologies have been applied in Sweden and operational data have been published by Hansen et al. (2000) and Stendahl and Jafverstrom (2003). However, the consumption of large amounts of chemicals (approximately 0.5–1.0 mol acid or base per mole phosphate) and energy (operational temperature of 100–140 °C) render these methods as yet not cost-effective (Hansen et al., 2000).

Phosphorus recovery as struvite ($MgNH_4PO_4$) requires moderate process conditions (low concentration of suspended solids and water pH above 7.5) but the molecular ratio of $Mg^{2+}$:$NH_4^+$:$PO_4^{3-}$ should be 1:1:1 which often demands the supplementation of magnesium. Approximately 1 kg of struvite can be crystallized from 100 m$^3$ of wastewater (Shu et al., 2006) and the latter material has a potential use as a fertilizer. The struvite pellets, free from toxic impurities, were valued at €250/ton dry matter by fertilizer companies in Japan (Roeleveld et al., 2004). Production costs from sewage sludge supernatant may vary from €220 to 730/ton (Doyle and Parsons, 2002) in Australia and Japan and up to about €2750/ton in the Netherlands (Roeleveld et al., 2004). Due to the limited resource of phosphorus and the demand for fertilizer, the recovery of phosphorus from sewage will have to be practised in the near future.

## 3.2. Technological hardware

### 3.2.1. Up-concentration techniques

A new process layout that enables maximal recovery of water, energy, inorganic and organic fertilizers from domestic discharges is schematised in Fig. 3. The domestic "used water" is initially pretreated by mechanical means (screening, grit removal, microstrainer) to remove large particles and sand. To up-concentrate the water one can use dynamic sand filtration (DSF), dissolved air flotation (DAF), membrane filtration, biological sorption or a combination thereof, and produce an effluent with low levels of suspended and colloidal solids. Simultaneous removal of soluble organic matter by appropriate usage of poly-electrolytes during DSF or DAF can be necessary. The key point is that quality of the effluent must be suitable for UF/RO. Thus, freshwater can be recovered as a first product of the proposed method.

The approach of Primary Enhanced Filtration of sewage was proposed by the group of Tchbanoglous (Jimenez et al., 2000) in the 80s and several study projects (Matsumoto et al., 1982; England et al., 1994) and industrial experiences with the Zimpro Hydro Clean sand filter have been quoted. Direct sand filtration of domestic used water is an interesting option for water pre-treatment and the majority of suspended solids (SS) can be retained. The removal efficiency for SS may vary from 50–90% in accordance to the hydraulic loading rate, filter design and medium characteristics. A significant part of the COD may also be removed but to a lesser extend compared to the suspended solids. The effluent still contains colloidal matter which renders direct reverse osmosis problematic. The use of flocculants however can increase filter performance. The total costs associated for granular media filtration or dynamic sand filtration are in the order of €0.05–0.06/m$^3$ (Asano, 1998), including the cost for alum or iron.

Filtration can be integrated with the design of dissolved air flotation (DAF) facility. DAF is efficient in removing particles and can substantially decrease the particle load to the filters compared to direct filtration. The combination of two-stage DAF and dual media filtration resulted in SS and COD removal of the level of 99% and 75–85% respectively (Krofta et al., 1995). This integration permits designing filters at higher rates. The total costs for dissolved air flotation approximate those for rapid sand filtration (of the order €0.05–0.06/m$^3$).

Alternatively, flocculation of the sewage can be performed as an advanced primary treatment followed by a sedimentation step and stabilisation of the settled organics. In order to avoid the use of

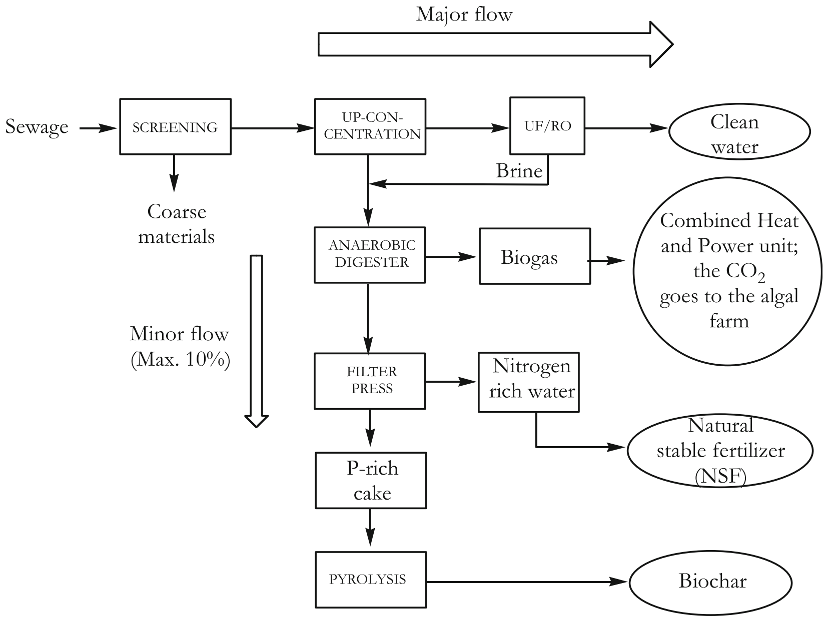


**Fig. 3.** Process scheme based on up-concentration of wastewater at a centralised plant thus allowing maximal recovery of resources from domestic wastewater.

chemical flocculants and the consequent flocculant-associated problems during stabilisation, a two-stage system is known in practise i.e. the Adsorption Bio-Aeration method where the activated sludge acts as a flocculant (Boehnke et al., 1998). In the first phase, adsorption and immobilisation of the organics occurs. The surplus sludge is energy rich and therefore, it can be valorised through anaerobic digestion with an energy self-supporting wastewater treatment as a consequence. In the second phase mineralisation and nitrification take place. The two-stage system permits a decrease of the footprint of the wastewater treatment plant, due to the high organic loading rates in the adsorption stage. A variant of the AB-method is the bioflocculation–adsorption, sedimentation and stabilization process (BSS) where no aeration is performed in the bioflocculation–adsorption step (Zhao et al., 2000).

Membrane filtration is a technology suitable for separation of suspended, colloidal and soluble impurities from water. Despite the evolving performance of membranes, limited publications report on the use of membranes in the primary treatment in order to tackle the environmental footprint issue of wastewater treatment.

Results from a pilot cross-flow microfiltration system on primary effluent revealed surprisingly high fluxes of the level of 100–200 L/m$^2$ h (Bendick et al., 2005). Despite the high quality effluent, the main limits to efficient large-scale application of membrane technology are the fouling phenomena. These phenomena result in a decreasing permeate flux during membrane process exploitation. Membrane fouling is an extremely complex physicochemical phenomenon; usually several mechanisms are involved simultaneously. On the other hand, it is possible to counter severe fouling of the membranes with an increase in operational costs (Bourgeous et al., 2001). Based on understanding the fouling mechanisms, different methods to mitigate membrane fouling are developed. Mitigation strategies can be based on membrane design, operating parameters such as transmembrane pressure, cross-flow velocity and feed characteristics. One of the concepts for a good performing membrane-based treatment system is the multi-stage filtration concept, as the above described UF/RO system for effluent polishing. This approach is based on the premise that no single filtration technology is perfect, so several technologies must be employed in order to protect those membranes sensitive to fouling to optimize their operation, to minimize the number of chemical cleanings, to decrease the energy consumption and guarantee a lower overall cost and environmental footprint of the water treatment process (Lauria, 2008).

In wastewater treatment applications, UF or MF is the RO pretreatment technology of choice due to the highly fouling nature of the feed and on a long-term operation basis the treatment line is economically viable on average to poor water qualities (Bonnelye et al., 2008). Ultrafiltration membranes serve as a clarification pre-treatment removing most of the potential substances responsible for RO fouling such as particles, turbidity, bacteria and large molecular weight molecules. Microbiological fouling of reverse osmosis membranes, for instance through the presence of the so-called TEP (Berman, 2005), is considered to be the main factor for flux decline and loss of salt rejection and clearly needs further in depth exploration.

### 3.2.2. Anaerobic digestion

By implementing up-concentration techniques a high-strength stream is generated. This concentrated stream can be considered as valuable if the waste-to-energy strategy is applied. In this respect anaerobic digestion qualifies in terms of recovery and the possibility to subsequent deal with the residual solids. The anaerobic digester is preferably a completely stirred tank reactor and is operated at thermophilic conditions to ensure a high degree of stabilization of the organics and a high degree of pathogen control. Moreover, it is evident that the anaerobic digester also can be supplemented with other solid organic communal associated wastes such as industrial kitchen waste or road clippings in order to increase the specific biogas production yield which significantly affects the economy of the installation. A diverse feedstock has also a positive impact on the process stability. The anaerobic metabolism takes place in four steps with specific enzymes and bacteria: hydrolysis, acidification, acetogenesis and methanogenesis. Enzymes play an essential role in this metabolism (Sonakya et al., 2001). As enzymes are specialized for a certain degradation process, a lot of different enzymes are necessary. A diverse demand of enzymes requires also a diverse bio-availability of metals like cobalt, nickel, iron and zinc since they are essential cofactors (Noyola and Tinajero, 2005).

### 3.2.3. Biogas valorisation

The biogas produced from the anaerobic digester is treated to remove hydrogen sulphide before valorising the biogas with a cogeneration unit. In this process heat and energy is produced starting from the produced biogas. The energy transformation from biogas towards electricity obeys to the second law of thermodynamics and the yield of electricity is lower than 100%, currently around the 40%. The first law of thermodynamics states the conservation of energy this means that more entropic energy is formed in the form of heat, with a combined efficiency higher than 80%. The heat produced is used to maintain the digester temperature and for post-treatment purposes such as drying and/or evaporation.

In an additional concept aimed at minimizing the $CO_2$ footprint, the $CO_2$ generated from the combined heat and power engine can be fed to an algal farm. The technology of closed photo-bioreactor provides the possibility of control of the algae culture and gas transfer (Gouveia et al., 1996). Additionally, the harvested biomass can be co-digested with the concentrated sewage. Anaerobic digestion of algae has already been found to work well some 50 years ago (Golueke et al., 1957). Anaerobic digestion of the biomass cultivated on a solar algal panel of 1000 $m^2$ results in a power plant with a potential capacity of about 0.4 $kW_{el}$, with prospects of 1 $kW_{el}$ (De Schamphelaire and Verstraete, 2009).

### 3.2.4. Post-treatment

In spite of the major advantages of the anaerobic digestion technology, the produced effluent can never comply with the usual discharge standards. Therefore, the effluent requires a post-treatment in order to adapt the environment legislation.

The effluent from the digester is dewatered by mechanical means such as a filter press, or a centrifuge, producing a humus and P-rich cake. Conditioning of the digester effluent by lime addition can be used to assure enhanced dewatering and to capture the phosphorus content within the humus cake in a biological available form.

The cake fraction is then dried towards a high dry matter content in order to reduce odour problems and to reduce the related transport costs.

After dewatering, next to a solid-rich stream, also a liquid fraction is produced. This contains the major fraction of the nitrogen, which is mainly present as ammonia. This ammonia can be recovered as an ammonia salt through air stripping followed by an acid wash. Alternatively the ammonia is nitrified to nitrate which is up-concentrated by means of an RO and meanwhile producing a high quality water effluent. The concentrated nitrate brine can then be further processed towards a "natural stable fertilizer".

### 3.2.5. Valorisation of the dried cake

Soil amendment of the dried solids is often not allowed due to the presence of recalcitrant xenobiotics. Alternatively the dried solids can serve as an energy source by means of combustion which delivers steam in order to produce electricity. Another technique is gasification, which delivers a fuel gas than can be valorised in a cogeneration unit. Recently, pyrolysis of biomass came into the picture. Pyrolysis is a process where biomass is heated in the absence of oxygen with decomposition of the biomass into vapours, bio-oil and charcoal as a consequence. The latter currently generates a lot of interest because one can sequester carbon in the form of charcoal. Biochar amendment to the soil not only sequesters carbon but also enhances the fertility and vitality of the soil (Lehmann and Joseph, 2009).

## 4. Discussion

The anaerobic digestion of up-concentrated sewage can be self-supporting. Indeed at a COD level of 5 g/L onwards, the biogas produced can cover the overall heat input costs (Thaveesri et al., 1995). In Table 3, the total costs associated with this new design for centralised water treatment are estimated. The approach of up-concentration of municipal effluent at arrival at the water treatment plant, with anaerobic digestion of all organics results in total costs of the order of €0.66–0.95/$m^3$. This total cost value can in the near future benefit from the recovery as depicted in Table 1. This concept permits up-recycling of water, N and P, while there is a potential to be energy and $CO_2$ positive by integrating algal farming. The procedures and the costs involved for further processing the reject water (see Fig. 3 and Table 3) can be minimized by increasing the concentration factor during water pre-treatment. Clearly, the key factor in this new design is the up-concentration of the organics upon arrival at the treatment plant. Undoubtedly, new technologies will be conceived and become economical in the next decade to meet the challenge. If one considers membrane up-concentration as the technology of choice for domestic wastewater up-concentration, some aspects are of prime importance. The first aspect is the long-term stabile operation combined with an acceptable flux, which significantly affects the membrane operational cost. Secondly, the impact of the recovery of the UF pre-treatment, i.e. the amount of permeate produced per unit of influent is of crucial importance. It is worthwhile to investigate strategies and process design in order to reach a recovery as high as possible (preferably more than 90%) in order to reach a stream as concentrated as possible. The COD level of the concentrate stream is not only depending on the recovery but also on the COD retention. Ultrafiltration membranes with a MWCO generally higher than 100 kDa, do not remove the smaller organic matter molecules responsible for the fouling on RO membranes and the COD-concentration of the concentrate will not be high enough (Bonnelye et al., 2008). The lower the MWCO, the higher the COD retention but the process operational costs increase because of the operational pressures.

**Table 3**
Cost considerations for the proposed sewage recycling technology in which the major part of the flow is considered to go directly to reuse while a concentrate is produced at the entry of the plant which is subjected to advanced recovery for energy and fertilizers.

| Processes | Costs (€/$m^3$) | |
|---|---|---|
| *Major flow* | | |
| Dissolved air flotation | 0.02–0.03 | 0.53–1.15 |
| Dynamic sand filtration | 0.05–0.06 | |
| Ultrafiltration and reverse osmosis | 0.46–1.06 | |
| *Minor flow* | | |
| Anaerobic digestion | Break-even | 0.08–0.10 |
| Mechanical separation | 0.08–0.10 | |
| pyrolysis | | |
| | Break-even | |
| | Total costs | 0.61–1.25[a] |

[a] This is the estimated total cost; for the potential recoveries one is referred to Table 1.

## 5. Concluding remarks

The conventional activated sludge process coupled with MF/UF and RO is complex and costs of the order of €0.793/$m^3$ sewage treated (Fig. 2), while N and P are generally "wasted". The key to new sewage treatment is the separation at home respectively the non-dispersion of resources at arrival at the treatment plant. The concept of up-concentration of municipal discharges, either at home or upon arrival at the water processing plant, enables fractionation of different components and recovery of energy and fertilizers. Factors that require further research include the quality of the organic P-rich cake after anaerobic digestion, the quality and stability upon storage of the nutrient solutions, the sanitation risks associated with the various recoveries and the psychological acceptance of the recovered resources. For centralised systems operating according to the process without activated sludge, as outlined in Fig. 3, the costs may soon become competitive with those of the conventional treatment processes. Therefore, this new cradle-to-cradle approach for sewage treatment warrants validation in practice.

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