Resource recovery from source separated domestic waste(water) streams; full scale results
Grietje Zeeman and Katarzyna Kuja-Roeleveld

ABSTRACT
A major fraction of nutrients emitted from households are originally present in only 1% of total wastewater volume. New sanitation concepts enable the recovery and reuse of these nutrients from feces and urine. Two possible sanitation concepts are presented, with varying degree of source separation leading to various recovery products. Separate vacuum collection and transport followed by anaerobic treatment of concentrated black water (BW) demonstrated on a scale of 32 houses preserve 7.6 gN/p/d and 0.63 gP/p/d amounting to respectively 69 and 48% of the theoretically produced N and P in the household, and 95% of the retained P was shown to be recoverable via struvite precipitation. Reuse of the anaerobic sludge in agriculture can substantially increase the P recovery. Energy recovery in the form of biogas from anaerobic digestion of concentrated BW fits well in new concepts of sustainable, zero energy buildings. Nutrient recovery from separately collected urine lowers the percentage of nutrient recovery in comparison with BW but can, on the other hand, often be implemented in existing sanitation concepts. Theoretically 11 gN/p/d and 1.0 g P/p/d are produced with urine, of which 38–63 and 34–61% were recovered in practice on a scale of 8–160 inhabitants in Sweden. New sanitation concepts with resource recovery and reuse are being demonstrated worldwide and more and more experience is being gained.

Key words | energy, new sanitation, nutrients, reuse, wastewater reuse

INTRODUCTION
Household waste water was until recently almost exclusively considered as a hygienically risky, polluting stream, which should be removed and treated as far as possible from the production site. The application of central, water-based, transport and treatment systems was a logical consequence.

The same stream may however be regarded as a source of raw materials, such as energy, fertilizer and water, which can be used locally. With a growing demand for renewable energy and decreasing availability of raw materials such as phosphate (Driver et al. 1999) and (depending on the location) of water, domestic (waste)water is increasingly recognized as a source of raw materials. For an efficient recovery of resources often alternative collection (toilet), transport and treatment systems are needed.

Separation at source and prevention of dilution of concentrated flows are prerequisites when selecting such systems. Otterpohl introduced in 1997, the so called ‘sewer less city’, in Lübeck, Germany, where vacuum collection and transport of black water (BW) has been applied and anaerobic treatment of the BW for energy and nutrient recovery (Otterpohl et al. 1997). The grey water has been separately collected and treated already for many years in vertical flow, constructed wetlands.

Since June 2006 the DeSaR, Decentralised Sanitation and Reuse project, in Sneek, The Netherlands has been demonstrated, in which BW of a community of 32 houses is also collected and transported using vacuum system and subsequently provides energy, via biogas production and nutrients, via struvite precipitation, for future reuse (Zeeman et al. 2008).

Within the ‘Zonneterp’ concept (Mels et al. 2006), the combination of DeSaR with green houses is proposed to achieve a large extent of autarky (Wortmann 2008). A green-house is the core of the ‘Zonneterp’ concept, in which solar heat is harvested and used in the living neighborhood. On the other hand fertilizers present in domestic waste streams are recovered and used for cultivation of plants in the greenhouse. Urine separation from feces is an alternative route.
for recovering a major part of the nutrients from domestic waste(water). The concept is in general applied in combination with central collection and treatment of the remaining wastewater stream (grey water and brown water).

A broad oriented research program on urine separation, treatment and reuse has been executed within the NOVOQUATIS project in Switzerland (Larsen & Lienert 2008). Urine separation is applied in Switzerland in the office building of EAWAG and in a library in Liestal (Larsen & Lienert 2008). Jönsson (2001) reports on the application of urine separation in five housing estates in Sweden with a population varying between 8 and 160 people. In The Netherlands several projects on separate urine collection, in for instance office buildings or nursery houses, and its treatment or reuse as a fertilizer are initiated since 2004.

This paper addresses a number of sanitation concepts, with varying degree of source separation leading to various recovery products. Data reported from demonstrated concepts are used for comparing recovery percentages of nitrogen, phosphate, potassium and energy.

WASTEWATER SEPARATION AT SOURCE

In source-separation based sanitation concepts wastewater streams are separated according to their type and degree of pollution and consequently reuse potential of resources. Different degrees of separation can be applied. Generally three types of wastewater streams are distinguished on a household level: (1) BW, (2) grey water, and (3) storm water. Storm water is not considered within this paper.

BW is a mixture of feces, urine and flush water. A large fraction of the main components of domestic wastewater, viz. organics, nutrients (nitrogen, phosphorus and potassium), pathogens, pharmaceuticals residues and hormones are originally present in a very small volume of feces and urine.

The concentration of BW can be influenced by the choice of the collection system (toilet). Urine separation from BW can result in a low pathogen- and high nutrient-containing stream.

Kitchen waste (KW; food leftovers and rest from food preparation), in The Netherlands currently separately collected in combination with garden waste, is an interesting fraction for combining with BW, considering their potential energy content.

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

COMPOSITION OF DOMESTIC WASTE(WATER) STREAMS

Most of the nutrients present in domestic wastewater originate from feces and urine. By diverting BW plus KW from grey water, 80–95% of the nutrients from households can be recovered. In a healthy adult, the amounts of nutrients are in equilibrium within the body. All nutrients consumed are excreted; normally via the urine or via the feces (Guyton 1992). The nutrient content in urine and feces will vary depending on the food intake, e.g., on protein intake (Drangert 2000; Jönsson et al. 2000). Separate collection of BW plus KW results in a waste stream containing ca. 70% of the potential energy, expressed in COD.

POTENTIAL ENERGY AND FERTILIZERS IN BW AND KW

Human produces about 1.5 L of urine, feces and KW, which contain about 90% of the nitrogen, 80% of the phosphate, 80% of the potassium and 70% of the COD in domestic waste(water) (Kujawa-Roeleveld & Zeeman 2006). Considering The Netherlands with a 16,489,032 population (CBS 2009), and an N, P and K production from BW plus KW of 4.47, 0.58 and 1.41 kg/p/year, respectively (Kujawa-Roeleveld & Zeeman 2006) the potential fertilizer production would be significant (see Table 1). These amounts could cover, respectively, 25, 45 and 59% of the nowadays applied synthetic fertilizer in Dutch agriculture (see Table 1). For urine separation (see Table 2) the potential recovery of N, P and K amounts to, respectively, 19, 23 and 58% coverage of the nowadays applied artificial fertilizer in Dutch agriculture.

<table>
<thead>
<tr>
<th></th>
<th>BW plus KW (tons per year)</th>
<th>Use synthetic fertilizer (tons per year)</th>
<th>Coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N)</td>
<td>73,700</td>
<td>288,000</td>
<td>25</td>
</tr>
<tr>
<td>Phosphate (P)</td>
<td>9,560</td>
<td>21,000</td>
<td>45</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>23,250</td>
<td>35,000</td>
<td>66</td>
</tr>
</tbody>
</table>
considering a production of, respectively, 3.3, 0.3 and 1.0 kg/p/year with urine (Kujawa-Roeleveld & Zeeman 2006).

Phosphate is a finishing fossil resource in small number of countries which availability will be strongly reduced within in the coming 50–100 years (Driver et al. 1999; Smil 2003).

Recovery of phosphate is therefore much more urgent than so far realized. Although nitrogen is a non-limited source, the recovery of nitrogen from the atmosphere via the Haber-Bosch process costs 37–45 kJ/gN (Maurer et al. 2003).

Next to nutrients the mixture of BW and KW contains a considerable amount of COD (Chemical Oxygen Demand), representing potential energy and compost. Considering a COD production from BW plus KW of 40.6 kg/person/year (Kujawa-Roeleveld & Zeeman 2006), the potential CH₄ production amounts to 164 × 10⁶ m³ per year for the whole of The Netherlands. This amount could potentially cover 59% of the nowadays used methane for household cooking (see Table 3). Latter becomes an important fraction when considering sustainably built houses with zero energy used for heating.

### SANITATION CONCEPTS

Sanitation, as defined in this paper, comprises a chain of collection, transport and treatment of domestic wastewater and recovery and reuse of included resources. The collection and transport method for feces and urine (together forming BW) strongly determines the treatment technology that can be applied and finally the possibilities for recovery and reuse of resources.

There are many alternatives to be discussed when choosing/developing a sanitation concept. These are mainly:

- degree of separation, viz. BW and GW or brown (BrW = only feces), yellow (YW = urine) and GW; incorporation of KW;
- degree of dilution, especially of feces and urine;
- degree of decentralization (house-on-site or community-on-site treatment).

A lower degree of dilution of feces and urine will facilitate the optimal recovery of energy and nutrients and removal of micro-pollutants and pathogens. It will also result in small footprint treatment systems.

Otterpohl (2008) distinguishes, based on source separation, three main lines in nowadays applied and developing sanitation concepts, viz.

- **Vacuum BW collection** and transport connected to biogas-systems. These systems are technically proven and ready for use on a large(r) scale. Applications are established in The Netherlands and Germany;
- **Composting toilets** are applicable in rural areas but are not yet ready for ‘the large scale’ implementations. Development of breakthrough technology that works in Hamburg (the North) and Addis Ababa (the South) is needed;
- **Urine-diversion** with flush sanitation in combination with central treatment of remaining wastewater is demonstrated at several locations. Further development is needed.

In the following sections, these three different sanitation concepts will be discussed in more detail and where possible data on recovery of energy and nutrients are presented and compared with the potentials presented in Tables 1–3.

### CASE STUDIES

**Separation of BW and GW; demonstration 32 houses Sneek, The Netherlands**

In Sneek, a city in the north of The Netherlands, the first treatment system, including nutrient recovery/removal...
from BW collected and transported with vacuum, has been demonstrated for a new housing estate of 32 houses since May 2006 (Elzinga et al. 2009). Each house is equipped with two vacuum toilets (Roediger). A central vacuum station (Roediger), comprising vacuum pump, receiver tank and transfer pump is situated in a cellar outside. BW of all 32 houses is conveyed to the vacuum station receiver tank from where it is pumped to the treatment system. Two UASB-septic tanks of 6 m³ each are installed for the anaerobic treatment of BW and production of biogas. The effluent of the UASB is subjected to a post-treatment where residual COD is removed and phosphate and part of the NH₄⁺-N are recovered (via struvite precipitation) and remaining nitrogen is removed using an OLAND (Oxygen-Limited Autotrophic Nitrification-Denitrification) reactor (Pynaert et al. 2003). Table 4 reveals the recovery of CH₄ and nutrients at anaerobic digestion of concentrated blackwater in a UASB-septic tank as applied for 32 houses in comparison with theoretical values.

Results of the demonstration in Sneek (Elzinga et al. 2009) and laboratory research in Switzerland (Larsen & Lienert 2007) has shown that 95–98% of the total phosphate in the effluent of the UASB and urine, respectively, can be recovered via struvite precipitation by adding sufficient Mg. Latter means that a P recovery via struvite precipitation of 0.22 kg P/p/y can be achieved from BW, which represents 48% of the theoretical potential (see Table 4). When only Mg is added, only a small part of the N is recovered via struvite precipitation. Full nitrogen removal via struvite precipitation is only possible at addition of large quantities of additional phosphate. Latter process might become feasible when phosphate could be recycled, for example at presence of an excess of heat.

A significant part of the P from BW is already precipitated or removed as organic P in the UASB and becomes part of the stabilized sludge (STOWA 2005). Preliminary results of research as described in STOWA (2005) indicate that the anaerobic sludge will meet the Dutch heavy metal standards for agricultural field application (LNV 2005). It has to be emphasized that the amount of excess sludge produced, using a UASB reactor, is very low. Future research will be oriented to quality and use of the UASB-sludge for improved recovery and reuse of P and organic matter.

The amount of nitrogen retained in the effluent of the UASB-septic tank of the housing estate in Sneek amounts to 69% of the theoretically produced amount of N with BW. As feces and urine produced in the 32 houses is completely collected and transferred to the pilot plant, and only a small fraction of the N will be included in the UASB sludge, latter indicates that an important part of the urine is not collected at home.

The elimination of nitrogen via Anammox based processes like OLAND, combined with fertilizer production via the Haber-Bosch process requires 64 MJ kgN⁻¹ (Maurer et al. 2005). The high energy requirements for the N-fixation by the Haber-Bosch pathway makes many recovery and reuse techniques interesting. From an energetic point of view, the evaporation of the water content of urine seems to be competitive (Maurer et al. 2005). For BW more energy is needed as a result of the higher dilution. The mentioned technologies become interesting when excess heat is available. Excess heat can become available when combining greenhouses with a housing estate, as proposed in the Zonneterp project (Mels et al. 2006). Additional profit of such a concept is the direct reuse of produced fertilizers in the greenhouse, reducing transport costs.

Urine separation

Jönsson (2001) presents 5 (study) locations, where urine separation has been applied. Calculated recovery of N and P based on data presented by Jönsson (2001) are presented in Table 5. Values indicated in Table 5 are calculated based on Equation (1).

\[ R = C \times NP\text{urine} \times H \]

in which: \( R \) (g/p/d) = nutrient recovery; \( C \) (%) = nutrients collected with urine as a percentage of the theoretical production at home (Jönsson 2001); \( NP\text{urine} \) (g/p/d) = Total Nutrient Production with urine according to Jönsson (2001)

The values in Table 5 illustrate that in the considered case studies, respectively, 38–63 and 34–61% of the theoretically, in urine, produced N and P were recovered. Lower than expected minerals recovery could be, except of partial excretion outside the house at offices or public places, due to problems such as leakage, design of toilet or precipitation in pipes.

Table 5 | Recovery (R; g/p/d) of N and P at different locations in Sweden, calculated based on Jönsson (2001) and Equation (1)

<table>
<thead>
<tr>
<th></th>
<th>Understen-höjden</th>
<th>Palster-nackan</th>
<th>Hushagen</th>
<th>Ekoporten</th>
<th>Miljöhuset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhabitants</td>
<td>160</td>
<td>50</td>
<td>8</td>
<td>35</td>
<td>62</td>
</tr>
<tr>
<td>Recovery N (g/p/d)</td>
<td>5.7</td>
<td>4.3</td>
<td>4.8</td>
<td>&gt;0.43</td>
<td>0.41</td>
</tr>
<tr>
<td>Recovery P (g/p/d)</td>
<td>0.49</td>
<td>0.41</td>
<td>&gt;0.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

‘Zonneterp’ concept: coupling sanitation to agriculture

The ‘Zonneterp’ is a design for a neighborhood that generates its own energy, biomass and water supply (Mels et al. 2006). Basic elements of the design are an energy-producing greenhouse, residential area and an anaerobic digester. Greenhouses in The Netherlands receive more solar heat energy than required. Excess heat can be stored in deep aquifers. The stored heat is used for warming the greenhouse during the nights or in winter. The balances show that there is sufficient energy left to heat a block of houses. The BW and KW from neighborhood are anaerobically digested. The produced biogas is burned and the combustion gases are used as CO₂ fertilizer in the greenhouse, while the combustion energy is used for power generation and tap water heating. The grey water of the households is purified and supplemented with nutrients of the BW flows and is used for irrigation purposes within the greenhouse. Greenhouse plants evaporate the irrigation water, while using the nutrients. The vapor condenses and is collected. The collected water is of very high quality and serves as household tap water after a proper quality control.

DISCUSSION AND CONCLUSION

In a small volume of human waste (feces and urine) a major fraction of nutrients emitted from household are present. By application of new sanitation concepts based on source separation, these nutrients can be separated from waste and reused again. A few sanitation concepts are possible, characterized by different degrees of separation. Separate vacuum collection & transport followed by anaerobic treatment of (concentrated) BW is demonstrated on a scale of 32 houses to preserve 7.6 g/N/p d and 0.63 gP/p/d with the UASB effluent, which amounts to respectively 69 and 48% of the theoretically produced N and P in the household. The 95% of the retained P was shown to be recoverable via struvite precipitation. Reuse of the anaerobic UASB sludge in agriculture can substantially increase the P recovery.

Theoretically 11 gN/p/d and 1.0 g P/p/d are produced with urine, of which respectively 38–63 and 34–61% was recovered in practice in five different housing districts with all together 315 inhabitants in Sweden, where urine separation was applied. Recovery (g/p/d) was thus lower in comparison with that at BW separation as applied in Sneek, The Netherlands. At the other hand nutrient concentrations in urine are higher as compared with treated BW, which might favor the possibilities for recovery from the liquid phase, especially for nitrogen.

REFERENCES


Elzinga, N., Gorter, K., de Graaff, M. & Meulman, B. 2009


First received 10 February 2010; accepted in revised form 18 February 2011