Electronic Supplementary Material (ESI) for Environmental Science: Water Research & Technology.


**Supplementary material**

**Assessing the sustainability of on-site sanitation systems using multi-criteria analysis**

**Brenda Vidal [1,*], Annelie Hedström [1], Sylvie Barraud [2], Erik Kärrman [3] and Inga Herrmann [1]**

[1] Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, 971 87 Luleå, Sweden; annelie.hedstrom@ltu.se (A.H.); inga.herrmann@ltu.se (I.H.)
[2] Department of Civil Engineering and Urban Planning, National Institute of Applied Sciences of Lyon, 34 Avenue des Arts Bâtiment J.-C.-A. Coulomb, 69621 Villeurbanne CEDEX, France; sylvie.barraud@insa-lyon.fr
[3] RISE Built Environment, Research Institutes of Sweden, 118 94 Stockholm, Sweden; erik.karrman@ri.se
* Correspondence: Brenda.vidal@ltu.se

## 1. Detailed description of system alternatives

### A1: Septic tank and sand filter

Wastewater from the household is collected in a three-chamber septic tank made of fiberglass-reinforced polyester (FRP) and pumped to a sand filter constructed below ground surface. The wastewater is spread using perforated distribution pipes and treated through a variety of physical, chemical and biochemical reactions and processes as it infiltrates. The effluent is collected at the bottom of the filter by drainage pipes. A conventional sand filter constructed according to the Swedish standard was assumed (Swedish EPA, 2003a), with a layer of filter media of 0.8 m (sand/gravel between 0 to 8 mm in size) and a surface area of 30 $m^2$. Both distribution and drainage pipes are embedded in a 0.2 m coarse gravel layer. The sludge from the septic tank is transported to the nearest WWTP for anaerobic treatment.

### A2. Septic tank and drain field

A design similar to A1 is assumed. However, the wastewater is not collected after the buried infiltrative material, a layer of coarse gravel of 35 cm (Swedish EPA, 2003b), but instead continues infiltrating and percolating through the underlying soil. It was assumed that the properties of the soil allow infiltration of the wastewater.

### A3. Septic tank, sand filter and P-filter

Same design as in alternative A1 with the addition of a polishing step for phosphorus (P) removal (alkaline P-filter), using the filter media Polonite® after the sand filter. The water is transported from the outlet of the sand filter to the P-filter by gravity.

### A4. Septic tank with chemical P removal, sand filter

Wastewater from the house is collected in a three-chamber septic tank. A chemical precipitation unit with polyaluminum chloride is installed inside the household (e.g. under the kitchen sink) and dosed continuously. The flocculation and sedimentation occurs in the septic tank and therefore the tank volume is larger (4 $m^3$) than in alternatives A1-3. The septic sludge is assumed to contain more P than in A1-3. The lifespan of the sand filter was assumed to be higher (25 years instead of 20 years as in A1-3), because some of the suspended solids and the BOD are removed during the flocculation process resulting in a lower load to the sand filter (Palm et al., 2002; Weiss et al., 2008).

### A5. Septic tank with P precipitation and drain field

Same design as in A4 though in this case the wastewater is not collected after the filter media, a layer of gravel (between 12 to 32 mm in size) of 35 cm (Swedish EPA, 2003b), but instead continues infiltrating into the soil. It was assumed that the properties of the soil allow infiltration of the wastewater.

S1. Greywater and blackwater separation

This system is based on the separate collection of greywater (GW) and blackwater (BW). The GW was assumed to be collected in a septic tank followed by a sand filter. The lifespan of the sand filter was assumed to be higher than the conventional one (25 years instead of 20), because most of the nutrients and some BOD are already removed with the BW. The sludge from the GW tank is transported to a WWTP. The BW is collected in a holding tank which is emptied once a year. For collection, storage and treatment reasons it is important that the volume of the WCs' flush is small and therefore the use of a low-flush toilet (about 1 L per flush) was assumed in the analysis. The collected blackwater is transported to a central treatment facility using urea treatment (1% urea) for hygienization.

S2. Greywater and feces, urine diversion (UD).

This system is based on the separate collection of GW, urine and feces fractions from separating toilets. The GW and the feces are collected together in a septic tank and subsequently conveyed to a sand filter. The sludge from the septic tank is transported to a WWTP. The urine is collected in a container and transported to a centralized facility for hygienization (six-month storage).

P1. Package plant 1

This package plant consists of one single unit buried underground to which the wastewater from the household is transported by gravity. The mechanical treatment occurs in the first three chambers of the plant, followed by two bioreactors with aerators that provide oxygen to the water. A fraction of the water is returned to the first chamber. The effluent infiltrates through an alkaline P-filter with Polonite® material placed in a bag in the center of the plant. The sludge is collected from the three chambers that act as septic tanks, and it is transported to the nearest WWTP for anaerobic treatment.

P2. Package plant 2

This package plant consists of one single unit buried underground were the wastewater from the household is transported to by gravity. The plant operates in a 2-phases semi-continuous regime. The main phase corresponds to a continuous process of activated sludge, and the second phase corresponds to the regulation of excess sludge and self-cleaning of the plant when the level of wastewater in the equalization tank is low. The raw wastewater is first collected in an equalization tank and then pumped to an aerated water-processing tank with activated sludge where primary settlement occurs and a chemical dosing equipment is installed. A small sand filter is used as a final polishing step. All the sludge is collected in a separated tank inside the unit and further collected and transported to the nearest WWTP.

Table S1.1 Summary of components included in each alternative.

| ***Components*** | ***Sand filter*** | ***Drain field*** | ***Sand filter + P-filter*** | ***Chemical P removal + sand filter*** | ***Chemical P removal + drain field*** | ***Greywater/ Blackwater separation*** | ***Urine diversion*** | ***P1 (P-filter)*** | ***P2 (chem. precipitation)*** |
|---|---|---|---|---|---|---|---|---|---|
| Abbreviation --> | A1 | A2 | A3 | A4 | A5 | S1 | S2 | P1 | P2 |
| Septic tank 2.2 $m^3$ | x | x | x | | | | x | | |
| Septic tank 4 $m^3$ | | | | x | x | | | | |
| Septic tank 1.2 $m^3$ | | | | | | x | | | |
| Holding tank 6 $m^3$ | | | | | | x | | | |
| Storage tank 3 $m^3$ | | | | | | | x | | |
| Sand filter (20 years lifespan) | x | | x | | | | x | | |
| Sand filter (25 years lifespan) | | | | x | | x | | | |
| Drain field (20 years lifespan) | | x | | | x | | | | |
| Distribution box | x | x | x | x | x | x | x | | |
| Inspection box | x | | x | x | | x | x | | |
| Polonite ® bag | | | x | | | | | x | |
| Tank for Polonite ® bag | | | x | | | | | | |
| Pump | x | x | x | x | x | x | x | x | x |
| Chemical dosing equipment | | | | x | x | | | | |
| Chemicals (PIX) | | | | x | x | | | | x |
| Urea | | | | | | x | | | |
| Vacuum toilet | | | | | | x | | | |
| Urine diversion toilet | | | | | | | x | | |
| Package plant | | | | | | | | x | x |

## 2. Input data and assumptions

Table S2.1 Assumptions for the estimations of the nutrients removal for each alternative.

| ***Alternatives*** | ***P*** | ***N*** | ***Main sources and comments*** |
|---|---|---|---|
| A1. Septic tank + Sand filter | 40% | 30% | 40±20% P and 25±10% N (Olshammar et al., 2015); 50% P and 50% N in sand filters (Urban Water, 2011)*;* 10-80% P and 10-40% N in sand filters (Palm et al., 2002); 8-16% P removal in sand filters (Eveborn et al., 2012) |
| A2. Septic tank + Drain field | 40% | 35% | 50±30% P and 30±10% N (Olshammar et al., 2015); 96% P and 40-60% N in drain fields (Urban Water, 2011) |
| A3. Septic tank + Sand filter + P-filter (Polonite®) | 90% | 30% | 75±20% P in P-filters (Olshammar et al., 2015); 96.7% in column study with Polonite® (Gustafsson et al., 2008); 89-97% P removal in column and full scale systems with Polonite® (Renman and Renman, 2010); 43-99% P reduction in full-scale Polonite® filters (Vidal et al., 2018) |
| A4. Septic tank + chemical P removal + sand filter | 90% | 30% | 90% P removal with chemical precipitation when it functioned (Hellström and Jonsson, 2006); 85% P removal in septic tanks with chemical precipitation |
| A5. Septic tank chemical P removal + drain field | 90% | 35% | Combination of previous assumptions |
| S1. Greywater to sand filter; Blackwater to urea treatment | 90% | 95% | 80% P and 90% N are removed with the BW collection; around 10-20% of remaining N is expected to be reduced in the sand filter (Lennartsson et al., 2009) |
| S2. Greywater + faeces to sand filter, urine diversion to storage | 80% | 85% | A reduction of 35-50% P and 50-70% N is expected when urine is diverted (Palm et al., 2002). Upper values were assumed. |
| P1. Package plant with P-filter Polonite® | 90% | 40% | 80±5% P and 40±5% N for package plants in general (Olshammar et al., 2015). See references in A3 for Polonite® filter material. |
| P2. Package plant with chemical precipitation | 90% | 40% | 80±5% P and 40±5% N for package plants in general (Olshammar et al., 2015). See previous references for chemical precipitation of P. |

Table S2.2 Environmental impacts of basic processes considered in the LCA analysis for indicators GWP and CED.

| # | ***Basic process*** | ***Cumulative Energy Demand (CED)*** | ***Global Warming (GWP)*** | ***Data sources and assumptions*** |
|---|---|---|---|---|
| | | MJ | *$KgCO_2Eq$* | |
| 1 | Excavation of 1m3 of sandy soil with 15 kW excavator | 18,3 | 1,3 | Oekobaudat 2016 database (BMUB, 2016). Process 9.1.01 "Bagger 15kW Aushub". |
| 2 | Transport of 1t of good over 1km by garbage truck (collecting route) | 8,00 | 0,07 | Adjusted from (Sonesson, 1996) |
| 3 | Transport of 1t of good over 1km by medium weight truck | 1,0 | 0,07 | ELCD 3.2 database. Process "Lorry transport" |
| 4 | Transport of 1t of good over 1km by heavy weight truck | 0,7 | 0,05 | ELCD 3.2 database. Process "Articulated lorry transport" |
| 5 | Transport of 1t of good over 1km with sea cargo | 0,2 | 0,01 | ELCD 3.2 database. Process "Container ship ocean" |
| 6 | Production of 1kg of gravel and sand | 0,006 | 0,00007 | Report from the IVL Swedish Environmental Institute (Stripple, 2001), pp 48. |
| 7 | Production of 1kg of macadam (12-24, 16-32mm) | 0,07 | 0,001 | Report from the IVL Swedish Environmental Institute (Stripple, 2001), pp 46, assumed crushed aggregates production. Also used in VeVa (2010) |
| 8 | Production of 1 kg of material-separating layer (macadam 4-8 mm) | 0,02 | 0,0004 | Based on Erlandsson (2010) |
| 9 | Production of 1 MJ of electricity in Sweden | 2,1 | 0,02 | ELCD 3.2 database. Process "Process "Electricity grid mix, consumption mix, at consumer, AC, 230V SE" |
| 10 | Production of 1 MJ of electricity in Poland | 3,4 | 0,3 | ELCD 3.2 database. Process "Electricity grid mix, consumption mix, at consumer, AC, 230V PL" |
| 11 | Production of 1kg of PE (HD) | 77,0 | 1,95 | ELCD 3.2 database. Process "Polyethylene high density granulate (PE-HD), production mix, at plant". |
| 12 | Production of 1kg of PP | 75,0 | 1,98 | ELCD 3.2 database. Process "Polypropylene granulate (PP), production mix, at plant". |
| 13 | Production of 1kg of sheet moulding component: glass-fiber reinforced polyester | 41,3 | 1,8 | Calculated from Duflou et al. (2012) for the polyester resin and ELCD 3.2 database for the glass fiber and filler (calcium carbonate) |
| 14 | Production of 1kg of steel | 13,3 | 1, 6 | ELCD 3.2 database. Process "Steel sections (ILCD), production mix, at plant, blast furnace route / electric arc furnace route, 1 kg". |
| 15 | Production of 1kg of PVC | 60,4 | 2,7 | ELCD 3.2 database. Process "Polyvinylchloride resin (S-PVC), production mix, at plant, suspension polymerisation". |
| 16 | Production of 1m2 of geotextile | 2,33 | 0,11 | (Tillman et al., 1996). Also used in VeVa (2010) |
| 17 | Production of 1kg of PAX | 2,67 | 0,11 | Calculated for PAX 215 (Almemark et al., 2003; Tidåker et al., 2007) |
| 18 | Production of 1kg of urea (production+transport) | 23,51 | 0,91 | Urea assumed to be produced by YARA in Brunsbütel, Germany, and shipped to Helsinborg (325 km by cargo ship) as assumed in Vidal (2014). Energy consumption and $CO_2$ emissions based on (Brentrup and Pallière, 2008) |
| 19 | Production of 1kg of Polonite® | 1,70 | 0,10 | Calculated based on: specific heat capacity of the opoka rock assumed 0.97 kJ/kg*K (Romushkevich et al., |

| | | | | |
|---|---|---|---|---|
| | (extraction + heating opoka rock) | | | 2016); opoka rock is heated at 900 ºC (Brogowski and Renman, 2004) in kilns (80% efficiency assumed) fueled with natural gas (Sammeli, personal communication, June 2017). Energy needed (ELCD3.2) to produce 1 kg natural gas= 55.8MJ/kg; natural gas LHV= 44.1MJ/kg and HHV=52.21MJ/kg. Emissions calculated based on ELCD3.2. |
| 20 | Treatment of 1 kg of sludge in average WWTP | 1,0 | 0,01 | Based on energy use and emissions from Hospido et al. (2005) for thickened mixed sludge (including the polymer manufacture) with a dry matter content of 10 g $L^{-1}$, although the sludge from septic tanks is more diluted and normally has lower dry matter content e.g. around 4-6% (Hedström and Hanaeus, 1999). |

Table S2.3 Data and assumptions used for the calculation of the GWP of the storage of BW, urine, and sludge.

| ***Component name*** | ***Comment*** | ***Data sources and assumptions*** |
|---|---|---|
| $N_2O$ emissions from BW (treated with urea 1%) and urine storage | $NH_3$-N emissions: 5% tot-N | as in Karlsson and Rodhe (2002) assuming covered storage. Same factor used for both BW and urine due to their similar low viscosity and dry matter content (Spångberg et al., 2014).<br>95% of $NH_3$-N in the BW (Jönsson et al., 2005) and 100% in the urea (46% N), as the urea is degraded into ammonium by urease-producing bacteria (Nordin, 2010) |
| | Indirect $N_2O$ emissions: 1 % $NH_3$-N emitted to air | (IPCC, 2006) |
| $N_2O$ emissions from sludge storage | $NH_3$-N emissions: 10% tot-N | as for semi-solid manure (Karlsson and Rodhe, 2002) |
| | Indirect $N_2O$ emissions: 1 % $NH_3$-N emitted to air | (IPCC, 2006) |

Table S2.4 Summary of assumptions for the calculation of the indicators *capital cost* (components + man power) and o*peration & maintenance costs.*

| ***Capital cost*** | | ***Prices without VAT*** | ***Comments and references*** |
|---|---|---|---|
| Man power (1 worker + machinery) | | 80 €/ h | 5, 3.5 and 2 days of work (6 hours/day) assumed for installing sand filters/drain fields, package plants, and holding tanks, respectively. Personal communication with Mikael Samuelsson (Sep 2018) http://www.samuelssonmekaniska.se/kontakt.php |
| Man power (1 worker) | | 48 €/ h | |
| Tanks | Septic tank 2.2 $m^3$ | 1384 € | For mixed wastewater or greywater + feces. https://www.avloppscenter.se/vara-produkter/slamavskiljare/1-hushall/baga-slamavskiljare-2-2-m3.html |

| | | | |
|---|---|---|---|
| | Septic tank 4 $m^3$ | 2160 € | For mixed wastewater and chemical removal of P. https://www.avloppscenter.se/vara-produkter/slamavskiljare/1-hushall/baga-slamavskiljare-2-hushall.html |
| | Septic tank 1.2 $m^3$ | 920 € | For greywater. https://www.avloppscenter.se/vara-produkter/slamavskiljare/slamavskiljare-bdt/baga-slamavskiljare-bdt-med-integrerad-pumpbrunn.html |
| | Holding tank 6 $m^3$ | 2064 € | For blackwater. https://www.avloppscenter.se/vara-produkter/slutna-tankar/900-storre/under-jord/vpi-6-m3-sluten-tank.html |
| | Storage tank 3$m^3$ | 1080 € | For urine. https://www.avloppscenter.se/vara-produkter/slutna-tankar/900-storre/under-jord/cipax-sluten-tank-3000-l-lagbyggd.html |
| Distribution box | | 536 € | Based on https://www.avloppscenter.se/vara-produkter/pumpbrunnar/brunnar-utan-pumppaket/aq-pumpbrunn-600mm-diam-600-2450mm-hog-utan-pump.html |
| Inspection box | | 240 € | Based on https://www.avloppscenter.se/sv/vara-produkter/infiltrationmarkbadd-med-wc/losa-delar-ror-mm/uppsamlings-och-provtagningsbrunnen.html |
| Pump | | 792 € | Based on https://www.avloppscenter.se/vara-produkter/avloppspumpar/pumpar-for-enklare-smutsat-vatten-bdt/baga-pumppaket-for-slamavskiljare-250.html |
| Equipment for sand filter | | 320 € | Includes distribution, collection and ventilation pipes Assumed based on https://www.avloppscenter.se/vara-produkter/infiltrationmarkbadd-med-wc/markbadd-for-bdt-wc/markbaddspaket-att-kompletera-infiltrationspaketet-32m2.html |
| Equipment for drain field | Basic package | 120 € | Includes distribution and ventilation pipes. https://www.avloppscenter.se/vara-produkter/bdt-och-gravattensystem-utan-wckl/infiltration-bdt/infiltrationspaket-20m2-2-strangar.html |
| | Soil test | 750 € | To check the suitability of the soil for infiltration. Assumed based on https://infiltrationsanlaggning.com/vad-kostar-infiltrationsanlaggning/ |
| Sand and gravel | | 12 € /ton | Assumed based on http://www.nybrogrus.se/produkter-priser/produktprislista/ |
| Filter for P removal | Polonite® bag | 600 € | https://www.avloppscenter.se/vara-produkter/fosforfalla/kemi-och-fosformassa/fosformassa-polonite/polonite-fosforbindande-material-500kg.html |
| | Tank for filter | 1320 € | https://www.avloppscenter.se/vara-produkter/fosforfalla/paket/altech-fosforfalla-2-5m-500kg-polonite.html |
| Components for chemical P removal | Dosing equipment | 776 € | https://www.avloppscenter.se/vara-produkter/fosforfalla/losa-delar/uponor-fosforfalla-clean-easy-pump-1.html |
| | Chemicals | 180 € | 50 L/year based on information from distributors. https://www.avloppscenter.se/vara-produkter/kemi/pax-aluminiumklorid/flockningsmedel-ekotreat-100l-4x25l.html |
| Package plant P1 | | 5832 € | Personal communication Karl-Gustav Niska (Feb 2018) http://www.ecot.se |
| Package plant P2 | | 6150 € | https://www.avloppscenter.se/vara-produkter/reningsverk/reningsverk-ett-hushall/topas-8-1-hushall.html |
| Toilets (only the difference in cost with | Standard | 345 € | Assumed average price based on https://www.avloppscenter.se/en/our-products/toilets-wc/standard-wc/ |

| | | | |
|---|---|---|---|
| respect to standard toilets was included in the calculations) | Vacuum | 1750 € | Assumed based on https://www.avloppscenter.se/en/our-products/toilets-wc/low-flush-wc/eco-flush-the-ultra-low-flush-toilet.html |
| | Urine diversion | 456 € | Assumed based on https://www.avloppscenter.se/en/our-products/toilets-wc/urine-separating-wc/eco-flush-the-ultra-low-flush-toilet.html |
| **Operation & Maintenance cost** | | | |
| Electricity cost | | 0.078 €/ kWh | Electricity network + supplier. https://www.vattenfall.se/elavtal/elpriser/rorligt-elpris/ |
| Annual sampling of effluent | | 76 € | By an external accredited company, for BOD7, Tot-P, Tot-N, *E.coli* and pH. https://www.vattenprovtagning.se/analys/kontrollpaket-enskilt-avlopp |
| Package plant 1 | Service agreements | 176 €/year | Includes one visit per year, change of wear parts and effluent sampling (pH and P concentrations). Personal communication with Karl-Gustav (Feb 2018) http://www.ecot.se |
| | Operation and maintenance | 240 €/year | Change of Polonite® every third year and electricity are included. http://vaguiden.se/marknadsoversikt-2016/ |
| Package plant 2 | Service agreements | 240 €/year | Includes one visit per year, change of wear parts and sludge and effluent sampling (pH and P concentrations). http://vaguiden.se/marknadsoversikt-2016/ |
| | Operation and maintenance | 120 €/year | Electricity, chemicals and consumables included. http://vaguiden.se/marknadsoversikt-2016/ |
| Emptying septic/holding tank | < 3 $m^3$ | 87 € | Prices can vary between 60 – 170 € http://husagare.avloppsguiden.se/sluten-tank-och-kompaktfilter-f%C3%B6r-bdt-.html Assumed values taken from Bollnäs municipality for extractions with hoses up to 10 meters long http://www.bollnas.se/index.php/slamtoemningstaxa |
| | 3.1 – 6 $m^3$ | 121 € | |
| | 6 – 9 $m^3$ | 170 € | |

The capital cost was calculated based on the present value (PV) of the different components, materials and services needed for the installation of the OSS, multiplied by the annuity, which was accounted based on the following formula (Brealey et al., 2012):

$$r\,(1-(1+r)^{-n})^{-1}$$

Where r = interest rate (assumed 4%) and n = amortization time (years) of each component

Table S2.5 Assumptions for the assessment of the qualitative indicator s*ocial acceptance*

| ***Alternatives*** | ***Social acceptance*** | ***Notes and references*** |
|---|---|---|
| A1. Septic tank + Sand filter | Very high | It is one of the most common systems in Sweden (Olshammar et al., 2015), it does not require much effort to operate and maintain it |
| A2. Septic tank + Drain field | Very high | It is one of the most common systems in Sweden (Olshammar et al., 2015), it does not require much effort to operate and maintain it |

| | | |
|---|---|---|
| A3. Septic tank + Sand filter + P-filter (Polonite®) | High | The P-filter needs to be changed every 2-4 years (3 years assumed). |
| A4. Septic tank + P precipitation + sand filter | Medium | The dosing equipment for the precipitation of P is placed inside the house, normally under the sink. Re-filling of the chemical must be done regularly, and it has been reported in the literature that often house owners forget to check it up and refill it (Hellström and Jonsson, 2006). |
| A5. Septic tank + P precipitation + drain field | Medium | The dosing equipment for the precipitation of P is placed inside the house, normally under the sink. Re-filling of the chemical must be done regularly, and it has been reported in the literature that often house owners forget to check it up and refill it (Hellström and Jonsson, 2006). |
| S1. Greywater to sand filter; Blackwater to urea treatment | High | The only inconvenience for the house owners is the fact that they have to empty two tanks, the septic tank with GW and the holding tank with BW, instead of only one. But the emptying can be done at the same time, e.g. once a year. This system has generally been more socially accepted than urine-diversion (McConville et al., 2017). |
| S2. Greywater + faeces to sand filter, urine diversion to storage | Low | For the diverting toilet to function properly, individual acceptance and knowledge is required. The diverting toilet could involve more frequent cleaning and maintenance and problems with odors and blockages may arise (Larsen et al., 2009). Moreover, it could be less convenient for visitors or guests. |
| P1. Package plant with P-filter Polonite® | High | It does not have the highest social acceptance because it requires more monitoring than the soil-based systems, as it contains many different components. The risks related to equipment failure (e.g. aeration, sensors, etc.) are higher and will require more attention from the owner (e.g. call the technicians to come). |
| P2. Package plant with chemical precipitation | High | It does not have the highest social acceptance because it requires more monitoring than the soil-based systems, as it contains many different components. The risks related to equipment failure (e.g. aeration, sensors, etc.) are higher and will require more attention from the owner (e.g. call the technicians to come). |

Table S2.6 Assumptions for the assessment of the qualitative indicator *robustness.* Definition of robustness was based on previous descriptions from Spiller et al. (2015).

| ***Alternatives*** | ***Robustness*** | ***Notes and references*** |
|---|---|---|
| A1. Septic tank + Sand filter | High | These systems work well if they are correctly designed and loaded, but they often lack good design and construction from the start, which influences their initial and long term performance (Palm et al., 2002; Vidal et al., 2018). The P-removal decreases with time as the sand gest exhausted (Wilson et al., 2011). |
| A2. Septic tank + Drain field | High | These systems work well if they are correctly designed and loaded, but they often lack good design and construction from the start, which influences their initial and long term performance (Palm et al., 2002; Vidal et al., 2018). The P-removal decreases with time as the sand gest exhausted (Wilson et al., 2011). |
| A3. Septic tank + Sand filter + P-filter (Polonite®) | Medium | If the preceding sand filter is clogged It will affect the subsequent P-filter by clogging it. However, The P-adsorbing compounds are part of the filter media in contrast to the chemical precipitation options where it needs to be added (Jenssen et al., 2010). |
| A4. Septic tank + P precipitation + sand filter | Medium | The dosing equipment often presents problems e.g., precipitants are not refilled and hinders the P removal, hence frequent monitoring is necessary for it to be reliable (Hellström and Jonsson, 2003). If the correct dose of the coagulants and the pH are not sufficient at all times, the high removal of P will not be consistent (Jenssen et al., 2010), and the performance could be unstable. |
| A5. Septic tank + P precipitation + drain field | Medium | The dosing equipment often presents problems (e.g., precipitants are not refilled) and hinders the P removal, hence frequent monitoring is necessary for it to be reliable (Hellström and Jonsson, 2003) |
| S1. Greywater to sand filter; Blackwater to urea treatment | Medium | The low flush toilets might cause problems (e.g., clogging) as compared to normal toilets |
| S2. Greywater + faeces to sand filter, urine diversion to storage | Low | The urine diverting toilet might cause problems (e.g. clogging, odors) |
| P1. Package plant with P-filter Polonite® | Low | The P-adsorbing compounds are part of the filter media in contrast to the chemical precipitation options where it needs to be added (Jenssen et al., 2010). |
| P2. Package plant with chemical precipitation | Low | The dosing equipment often presents problems (e.g., precipitants are not refilled) and hinders the P removal, hence frequent monitoring is necessary for it to be reliable (Hellström and |

| | | |
|---|---|---|
| | | Jonsson, 2003). If the correct dose of the coagulants and the pH are not sufficient at all times, the high removal of P will not be consistent (Jenssen et al., 2010), hence the performance could be unstable. |

Table S2.7 Assumptions for the assessment of the qualitative indicator *risk of pathogen discharge.* Estimations based on the number of barriers present in each system alternative and considering previous research on pathogens removal in sand filters (Herrmann et al., 2017; Kauppinen et al., 2014), P-filters (Herrmann et al., 2017; Jenssen et al., 2010; Nilsson et al., 2013), source separation systems (Larsen and Maurer, 2011; Palm et al., 2002) and package plants.

| ***Alternatives*** | ***Risk of pathogen discharge*** | ***Notes and references*** |
|---|---|---|
| A1. Septic tank + Sand filter | Medium | 1 barrier (sand filter) (Herrmann et al., 2017; Kauppinen et al., 2014) reported great variability in the quality of the effluent of the sand filters investigated. |
| A2. Septic tank + Drain field | High | 1 barrier (soil) but the treated water infiltrates directly into the groundwater, which increases the risk of affecting it negatively as it is often the local source of drinking water (Palm et al., 2002). |
| A3. Septic tank + Sand filter + P-filter (Polonite) | Low | 2 barriers: the sand filter and P-filter; (Jenssen et al., 2010) reported good results in saturated filter beds with Filtralite®P, a light-weight expanded clay aggregate with high P sorption capacity. (Nilsson et al., 2013) reported high reduction rate of Enterococci and E.coli, although it decreased with time. The bacteria reduction in Polonite® could be attributed to the high pH, ”followed by straining in smaller pores created by clogging”. |
| A4. Septic tank + P precipitation + sand filter | Low | By removing particulate matter with the chemical precipitation the pathogen removal also increases as they are often associated to particles (Jiménez et al., 2009). |
| A5. Septic tank + P precipitation + drain field | Medium | 1 barrier (soil) but the treated water infiltrates directly into the groundwater, which increases the risk of affecting it negatively as it is often the local source of drinking water (Palm et al., 2002). By removing particulate matter with the chemical precipitation the pathogen removal also increases as they are often associated to particles (Jiménez et al., 2009). |
| S1. Greywater to sand filter; Blackwater to urea treatment | Very low | The only discharge of wastewater is from GW, which does contain pathogens (Larsen and Maurer, 2011); however most of the pathogen load is contained in the BW which is collected and taken for centralized sanitation somewhere else. |
| S2. Greywater + faeces to sand | Medium | 1 barrier (sand filter) as in A1. Most of the pathogens are contained in the feces as the urine is |

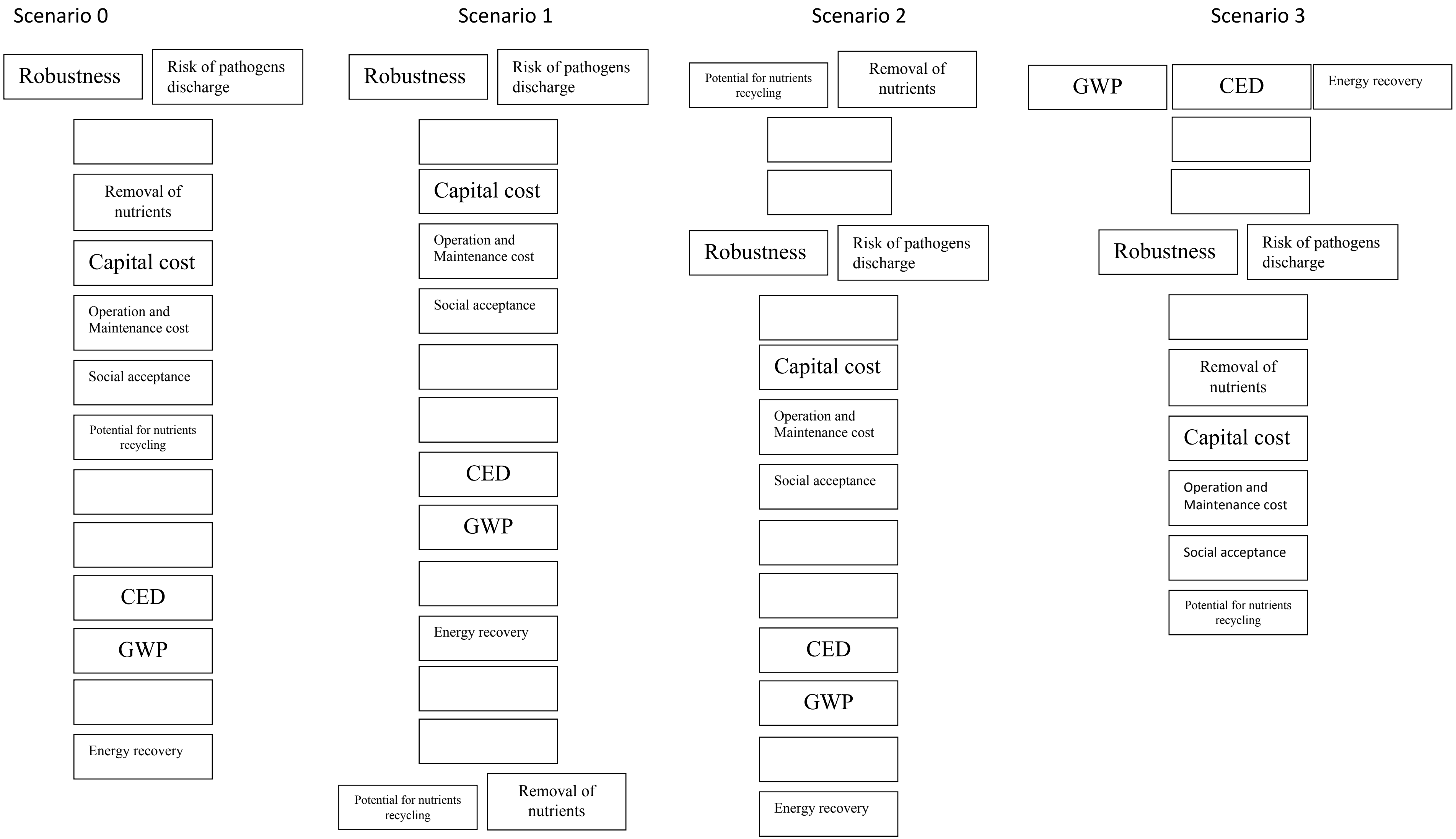
| | | |
|---|---|---|
| filter, urine diversion to storage | | considered almost sterile |
| P1. Package plant with P-filter Polonite ® | Low | 2 barriers, the biological step (with aeration) and the P-filter |
| P2. Package plant with chemical precipitation | Low | 1 barrier, the biological step (with aeration) but also the P-precipitation |

## 3. Summary of input data for the assignation of weights

Table S3.1 Weights given by the different members of the reference group for each indicator and arithmetic mean for each indicator (normalized weight).

| Indicators | Members of the reference group | | | | | | Normalized weight |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | W |
| Robustness | 75 | 85 | 100 | 80 | 100 | 90 | 15.5 |
| Risk of pathogen discharge | 100 | 100 | 70 | 50 | 100 | 100 | 15.5 |
| Nutrients removal (N and P) | 65 | 85 | 90 | 50 | 70 | 80 | 12.9 |
| Capital cost | 30 | 40 | 90 | 100 | 80 | 55 | 11.4 |
| O & M cost | 35 | 40 | 90 | 80 | 80 | 60 | 11.1 |
| Potential for nutrients recycling | 55 | 60 | 50 | 40 | 80 | 75 | 10.6 |
| Social Acceptance | 50 | 80 | 60 | 80 | 30 | 50 | 10.4 |
| Cumulative energy demand | 20 | 30 | 70 | 25 | 10 | 40 | 5.5 |
| Global Warming Potential | 25 | 20 | 70 | 10 | 30 | 20 | 4.9 |
| Energy recovery | 10 | 10 | 30 | 10 | 10 | 10 | 2.2 |
| **Total weights** | | | | | | | 100 |

Figure S3.1 Representation of Simos cards method for the assignation of weights for each scenario (1, 2 and 3). The empty white boxes represent blank cards as described in the methodology (Figueira and Roy, 2002; Simos, 1990). The original weights of Scenario 0, the baseline scenario, were given by the stakeholders but were also transformed with the Simos card method for further definition of the scenarios.



## References


Almemark, M., Jansson, Å., Palm, A., 2003. Jämförande miljöbedömning av två fällningskemikalier : PAX-15 och PAX-215 [Comparative environmental assessment of two precipitation chemicals: PAX-15 and PAX-215]. Report U735. Stockholm. (In Swedish).

Brealey, R., Myers, S., Allen, F., Mohanty, P., 2012. Principles of corporate finance, 6th Canadi. ed. Tata McGraw-Hill Education.

Brentrup, F., Pallière, C., 2008. Energy efficiency and greenhouse gas emissions in European nitrogen fertilizer production and use. Brussels, Belgium.

Brogowski, Z., Renman, G., 2004. Characterization of Opoka as a Basis for its Use in Wastewater Wastewater W Treatment Treatment T. Polish J. Environ. Stud. 13, 15–20.

Duflou, J.R., Deng, Y., Van Acker, K., Dewulf, W., 2012. Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. Mater. Res. Soc. Bull. 37, 374–382. doi:10.1557/mrs.2012.33

Erlandsson, M., 2010. Generell byggproduktinformation (BPI) för bygg- och fastighetssektorn: Miljödata för krossprodukter och naturgrus [General building product information (BPI) for the construction and real estate sector: Environmental data of aggregates and gravel], Stockholm. (In Swedish).

Eveborn, D., Kong, D., Gustafsson, J.P., 2012. Wastewater treatment by soil infiltration: Long-term phosphorus removal. J. Contam. Hydrol. 140, 24–33. doi:10.1016/j.jconhyd.2012.08.003

Figueira, J., Roy, B., 2002. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. Eur. J. Oper. Res. 139, 317–326.

Gustafsson, J.P., Renman, A., Renman, G., Poll, K., 2008. Phosphate removal by mineral-based sorbents used in filters for small-scale wastewater treatment. Water Res. 42, 189–197. doi:10.1016/j.watres.2007.06.058

Hedström, A., Hanaeus, J., 1999. Natural freezing, drying, and composting for treatment of septic sludge. J. Cold Reg. Eng. 13, 167–179.

Hellström, D., Jonsson, L., 2006. Evaluation of small on-site wastewater treatment systems. Manag. Environ. Qual. An Int. J. 17, 728–739. doi:10.1108/14777830610702548

Hellström, D., Jonsson, L., 2003. Evaluation of small wastewater treatment systems. Water Sci. Technol. 48, 61–68.

Herrmann, I., Vidal, B., Hedström, A., 2017. Discharge of indicator bacteria from on-site wastewater treatment systems. Desalin. Water Treat. 91, 365–373. doi:10.5004/dwt.2017.21416

Hospido, A., Moreira, T., Martín, M., Rigola, M., Feijoo, G., 2005. Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: anaerobic digestion versus thermal processes. Int. J. Life Cycle Assess. 10, 336–345. doi:10.1065/lca2005.05.210

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, vol. 4, in: Egglesto, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), . IGES, Japan.

Jenssen, P.D., Krogstad, T., Paruch, A.M., Mæhlum, T., Adam, K., Arias, C.A., Heistad, A., Jonsson, L., Hellström, D., Brix, H., Yli-Halla, M., Vråle, L., Valve, M., 2010. Filter bed systems treating domestic wastewater in the Nordic countries – Performance and reuse of filter media. Ecol. Eng. 36, 1651–1659. doi:10.1016/j.ecoleng.2010.07.004

Jiménez, B., Mara, D., Carr, R., Brissaud, F., 2009. Wastewater Treatment for Pathogen Removal and Nutrient Conservation: Suitable Systems for Use in Developing Countries, in: Pay Drechsel, C.A.S., Liqa Raschid-Sally, Mark Redwood, Akiça Bahri (Eds.), Wastewater Irrigation and Health. Earthscan, London, p. 400.

Jönsson, H., Baky, A., Jeppsson, U., Hellström, D., Kärrman, E., 2005. Composition of Urine, Feaces, Greywater and Biowaste for Utilisation in the URWARE Model. Report 2005:6, Urban Water Report. Urban Water, Chalmers University of Technology, Gothenburg, Sweden.

Karlsson, S., Rodhe, L., 2002. Översyn av Statistiska Centralbyråns beräkning av ammoniakavgången i jordbruket – emissionsfaktorer för ammoniak vid lagring och spridning av stallgödsel [Review of the calculations from Statistics Sweden on ammonia emissions in agriculture - Emission fac. Uppsala.

Kauppinen, A., Martikainen, K., Matikka, V., Veijalainen, A.-M., Pitkänen, T., Heinonen-Tanski, H., Miettinen, I.T., 2014. Sand filters for removal of microbes and nutrients from wastewater during a one-year pilot study in a cold temperate climate. J. Environ. Manage. 133, 206–213. doi:10.1016/j.jenvman.2013.12.008

Larsen, T.., Maurer, M., 2011. Source Separation and Decentralization, Treatise on Water Science. Elsevier, Oxford: Academic Press. doi:10.1016/B978-0-444-53199-5.00083-X

Larsen, T.A., Alder, A.C., Eggen, R.I.L., Maurer, M., Lienert, J., 2009. Source separation: will we see a paradigm shift in wastewater handling? Environ. Sci. Technol. 43, 6121–6125.

Lennartsson, M., Kvarnström, E., Lundberg, T., Buenfil, J., Sawyer, R., 2009. Comparing sanitation systems using sustainability criteria - EcoSanRes Series, 2009-1. Stockholm.

McConville, J.R., Kvarnström, E., Jönsson, H., Kärrman, E., Johansson, M., 2017. Source separation: Challenges & opportunities for transition in the Swedish wastewater sector. Resour. Conserv. Recycl. 120, 144–156. doi:10.1016/J.RESCONREC.2016.12.004

Nilsson, C., Lakshmanan, R., Renman, G., Rajarao, G.K., 2013. Efficacy of reactive mineral-based sorbents for phosphate, bacteria, nitrogen and TOC removal-column experiment in recirculation batch mode. Water Res. 47, 5165–5175. doi:10.1016/j.watres.2013.05.056

Nordin, A., 2010. Ammonia Sanitisation of Human Excreta Treatment Technology for Production of Fertiliser. Doctoral Thesis. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Olshammar, M., Ek, M., Rosenquist, L., Ejhed, H., Sidvall, A., Svanström, S., 2015. På uppdrag av Havs-och vattenmyndigheten Uppdatering av kunskapsläget och statistik för små avloppsanläggningar [The state of knowledge and statistics for small sewage plants. Swedish Agency for Marine and Water Management]. Report 166. Norrköping. (In Swedish).

Palm, O., Malmén, L., Jönsson, H., 2002. Robusta, uthålliga små avloppssytem. En kunskapssammanställning [Robust and durable small wastewater systems. A knowledge compilation]. Report 5224. Stockholm. (In Swedish with English summary).

Renman, A., Renman, G., 2010. Long-term phosphate removal by the calcium-silicate material Polonite in wastewater filtration systems. Chemosphere 79, 659–664. doi:10.1016/j.chemosphere.2010.02.035

Romushkevich, R., Popov, E., Popov, Y., Chekhonin, E., Myasnikov, A., Kazak, A., Belenkaya, I., Zagranovskaya, D., 2016. Thermal Properties of West Siberian Sediments in Application to Basin and Petroleum Systems Modeling. Romushkevich R et. Al - Google Search, in: EGU General Assembly 2016. Vienna.

Sammeli, M., 2017. Ecofiltration Nordic AB, Solna, Sweden. Personal communication.

Simos, J., 1990. Évaluer l'impact sur l'environnement. Une approche originale par l'analyse multicritère et la négotiation [Environmental impact assessment. An original approach for multi-criteria analysis and negociation], Géographie physique et Quaternaire. Presses Polytechniques et Universitaires Romandes, Laussane. (In French). doi:10.7202/032939ar

Sonesson, U., 1996. Modelling of the compost and transport process in the ORWARE simulation model. Report 214. Uppsala.

Spångberg, J., Tidåker, P., Jönsson, H., 2014. Environmental impact of recycling nutrients in human excreta to agriculture compared with enhanced wastewater treatment. Sci. Total Environ. 493, 209–219. doi:10.1016/J.SCITOTENV.2014.05.123

Spiller, M., Vreeburg, J.H.G., Leusbrock, I., Zeeman, G., 2015. Flexible design in water and wastewater engineering--definitions, literature and decision guide. J. Environ. Manage. 149, 271–81. doi:10.1016/j.jenvman.2014.09.031

Stripple, H., 2001. Life Cycle Assessment of Road- A Pilot Study for Inventory Analysis. Report B 1210 E. Gothenburg.

Swedish EPA, 2003a. Faktablad om enskilda avlopp: markbäddar [Fact sheet on on-site wastewater treatment: sand filters].

Swedish EPA, 2003b. Faktablad om enskilda avlopp: Infiltrationsanläggningar [Fact sheet on on-site wastewater treatment: drain fields].

Tidåker, P., Sjöberg, C., Jönsson, H., 2007. Local recycling of plant nutrients from small-scale wastewater systems to farmland—A Swedish scenario study. Resour. Conserv. Recycl. 49, 388–405. doi:10.1016/j.resconrec.2006.05.004

Tillman, A.-M., Lundström, H., Svingby, M., 1996. Life cycle analysis of alternative sewage systems in Bergsjön and Hamburgersund. Partial report from the ECOGUIDE project [Livscykelanalys av alternativa avloppssystem i Bergsjön och Hamburgersund. Delrapport från ECOGUIDE-projektet.]. Göteborg. ( In Swedish).

Urban Water, 2011. VeVa model. Available online at http://kunskapscentrum.avloppsguiden.se/planeringsverktyg.html

Vidal, B., 2014. Blackwater sanitization with urea in Sweden. Master thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Vidal, B., Hedström, A., Herrmann, I., 2018. Phosphorus reduction in filters for on-site wastewater treatment. J. Water Process Eng. 22, 210–217. doi:10.1016/j.jwpe.2018.02.005

Weiss, P., Eveborn, D., Kärrman, E., Gustafsson, J.P., 2008. Environmental systems analysis of four on-site wastewater treatment options. Resour. Conserv. Recycl. 52, 1153–1161. doi:10.1016/j.resconrec.2008.06.004

Wilson, J., Boutilier, L., Jamieson, R., Havard, P., Lake, C., 2011. Effects of hydraulic loading rate and filter length on the performance of lateral flow sand filters for on-site wastewater treatment. J. Hydrol. Eng. 16, 639–649. doi:10.1061/(ASCE)HE.1943-5584.0000359