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VACUUM SYSTEMS FOR ORGANIC WASTE IN BUILDINGS AND PRECINCTS

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VACUUM SYSTEMS FOR ORGANIC WASTE IN BUILDINGS AND PRECINCTS

by

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I declare that I am the sole author of this report, and have referenced the incorporated relevant information to their original authors.

Alberto Burgada Ruiz,

19th June 2015

Abstract

Sanitation systems currently used in most developed countries use large volumes of fresh water with 20 to 40% of the water consumption utilized for flushing toilets in sewered cities. This use of water turns increasingly scarce resources into waste but there is the potential to use fresh water more efficiently by the use of vacuum systems and turn wastewater into a valuable resource by recovering energy, recycled water and nutrients.

The proposed sanitation system in this report includes the use of vacuum urine-diverting toilets that separate blackwater into two different streams, urine and faeces, and an on-site treatment of the wastewater. The purpose of using these toilets is to save water, produce energy through anaerobic digestion and in the process recover nutrients. Vacuum toilets have the potential to use 10 times less potable water than conventional gravity toilets, substituting water by air as the main agent of transport. Suction created by a vacuum pump is used to remove faeces from the toilet, that travel through the piping system to a collection tank, where it can be treated in absence of oxygen, resulting into biogas and a sludge that will have the potential to be used as a fertilizer, after appropriate treatment. The separated urine is collected and piped separately to a collection tank through gravity. The nutrient recovery, specially phosphorus, nitrogen and potassium, is of critical importance, as the world is facing a critical problem due to a global limited availability of phosphate, essential for agricultural food production globally.

The collection of household organic waste (kitchen waste) is also included in the proposed system, as mixing of it with blackwater help produce a more efficient biological treatment and biogas production.

As increasing pressure is being exerted in our natural resources, new concepts have to be applied in the world, and sanitation has the potential to be highly improved to recover valuable resources such as water, carbon and nutrients.

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Water and wastewater management and sustainability

The way most people live nowadays requires a lot of systems to meet the needs of our lifestyles, including sanitation, which ensures the cleanliness of our homes and cities and protects public health from hazardous compounds and pathogens that cause disease. Through the development of centralised sanitation systems, sewage is removed from our cities, treated to meet the country's public and environmental health requirements in order to be released to the environment in safe ways.

In most developed countries, the structure of the system includes centralised treatment plants that receive wastewater from a lot of different buildings and houses through gravity sewer pipes. When travelling to a central treatment station, wastewater mixes with different wastes such as industry waste and street runoff that may cause a contaminated wastewater stream. Decentralised on site wastewater treatment facilities are still novel but are increasing in numbers. According to JENSSEN et al. (2004), environmental problems can be minimized by constructing wastewater treatment systems based on a sustainable approach, and optimising phosphorus and nitrogen reuse results in a decrease in water consumption.

Potable water is becoming a scarce resource in many countries, and most of our present sanitary systems are using large amounts of fresh water, turning a valuable resource into a waste product. The main focus of this project is that there is the potential to use lower volumes of fresh water to manage wastewater and the end product has the potential to be considered a resource. As cited in JENSSEN et al. (2004), 20 to 40% of water consumption in sewered cities is used for toilet flushing (GARDNER 1997). As stated by LAMO DE ESPINOSA (2014), in 2007, for the first time in history urban population exceeded the rural population, meaning that there is a tendency for people to migrate and live in cities, and along with the fact that the world's population is rapidly increasing, we can confirm that water demand will increase and more wastewater will be produced. This problem requires solutions, and logically, if the number of people grows, the amount of water consumed by each of us should decrease in order to maintain a similar demand of fresh water, or reduce it if possible.

In order to develop a sustainable systems of water and wastewater management, several factors and effects have to be analysed. There's a tendency to choose the most economical option, but concerning sustainability, local and global and both small and large scales of time are included. Local aspects may include particular local hygiene practices, and global aspects may include global warming, declining availability of resources, depletion of the ozone layer, phosphorus availability, etc. As cited in JENNSEN et al. (2004), LINDHOLM AND NORDEIDE (2000) proposed the following indicators to be considered when comparing two different wastewater treatment alternatives:

- Discharge of pollution to local watercourses. For instance: phosphorus, nitrogen and organic matter (BOD).
- The amount of micro-organic pollutants and heavy metals in the sludge going to agriculture.
- Amount of phosphorus, potassium and nitrogen recirculated for plant production.
- Discharge of climate gases like methane and CO2.
- Use of electric energy and fossil energy.
- Use of products with hazardous components.
- Use of finite or critical resources.
- Costs as present value of investments, operation and maintenance.
- The use of area, influence on the landscape, aesthetic and recreational values.
- The service levels like clogging of sewers and flooding of basements.
- Noise, smell, insects and other disturbances in the operation and construction period.
- Safety for children.

Proposed system of wastewater management: criteria for comparison

If both alternatives have a similar performance in one of the indicators, that indicator can be eliminated. This means that if for example both systems are equally safe for children, the ‘Safety for children’ indicator won’t have an effect on determining which system is better. Through the use of this comparison indicators, not only the cheapest or most commonly utilised system alternative should be adopted, but the option that achieves the greatest sustainability outcomes. By doing an initial assessment of both systems without doing a deep analysis of them, we can obtain the next table.

	TRADITIONAL SYSTEM	VACUUM SYSTEM
Discharge of pollution (phosphorus, nitrogen and organic matter).		
MOP and HM going to agriculture.		
PNK recirculated for plant production.		
Discharge of climate gases		
Use of energy.		
Use of products with hazardous components		
Use of finite or critical resources.		
Cost		
Use of area		
Service levels		
Disturbances in operation and construction		
Safety for children		

Table 1. Initial assessment of traditional system vs. Vacuum system with the criteria proposed by LINDHOLM AND NORDEIDE (2000).

The indicators in which the performance of one of the systems is initially superior are marked in green, and in red if inferior. Marked in yellow are the ones that are unclear or need more analysis. So, we can appreciate that without doing a deep study of the systems, the proposed vacuum urine-diverting system is a more sustainable option.

For the first indicator, phosphorus and nitrogen are recovered through urine-diversion and remain in the sludge after anaerobic treatment, so they are not discharged to the environment. BOD will also be reduced through anaerobic digestion.

Thanks to on-site treatment, wastewater won’t be mixed with industrial waste and street runoff, so less heavy metals and pollutants will be present in the sludge and sent to agriculture or landfill.

Phosphorus, nitrogen and potassium will be recirculated for plant production, as most of these nutrients will be present in our diverted urine, and a small part in the remaining sludge in the anaerobic digesters. Through centralised treatment in a wastewater treatment plant, the cost to remove nutrients is higher with nutrients released to the environment. According to JENSSEN et al. (2004), most of the nitrogen and potassium is lost in the traditional biological-chemical treatment performed in centralized systems.

Discharge of greenhouse gases will be avoided by capturing the biogas that food waste mixed with blackwater will release in the digesters. In other case, organic waste goes to landfill and releases this gases into the air. The use of energy is highly related with this indicator because depending on the way that energy is produced, gases are emitted to the atmosphere, so this is not an indicator that can be easily assessed. Different factors related to energy consumption have to be considered, for instance:

- Through water saving, less water needs to be produced and less wastewater has to be treated, and both processes are energy-consuming. With todays technology pollutants can be removed from wastewater, but the process of first diluting the resource and then reconcentrating and capturing the nutrients is highly inefficient.
- When used as a fertilizer or soil improver, urine and anaerobic sludge have to be trucked away from the building or precinct.
- Less solid waste would be collected by trucks if food is put into the vacuum system instead of put in bins for collection. So, as a result, less trucks would be needed.
- Vacuum toilets save large amounts of water but energy has to be used to generate the vacuum needed to transport blackwater from a toilet to the tank.
- Through reuse of nutrients, less fertilizer has to be produced, which is also energy consuming.

As we can appreciate, there are several different direct and indirect factors that can be taken in account when calculating both the energy use and the gases released to the atmosphere. As cited in JENSSEN et al. (2004), one way of assessing this is comparing the transport of a truckload of urine, blackwater or compost with the energy required to produce an equivalent amount of mineral fertilizer. For the case of urine, the energy needed to produce the same amount of mineral fertilizer would be equivalent to the transport of a truckload 40 to 50 km away (JENSSEN and REFSGAARD 1997) (as cited in JENSSEN et al. 2004). The logistics of the system depend on the toilet type, showed in the following figure:

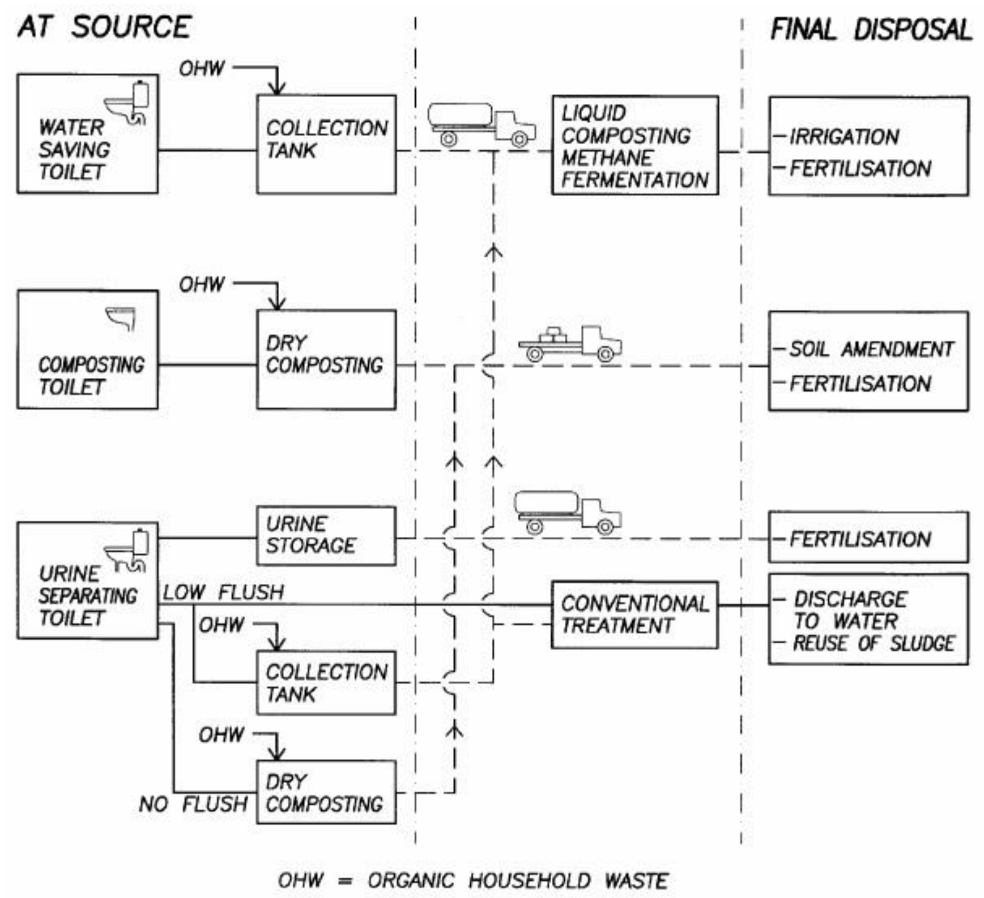

Figure 1. Logistics of blackwater + organic household waste handling dependent of toilet type (JENSSEN and ETNIER 1997). Source: JENSSEN et al. 2004.

Use of finite or critical resources like phosphorus or water would be lowered with the vacuum system. Less phosphate rock would be needed due to nutrient recovery and reuse through urine diversion and anaerobic digestion. Also water would be saved due to lower toilet flushing water demand.

The space area needed for a wastewater treatment plant and the sanitation system itself will be lower with a vacuum system and anaerobic digestion. Through a lower output of wastewater, less treatment is necessary, and so, less space is required for treatment plants. In relation to the system, vacuum piping is more flexible and requires less space thanks to a smaller diameter of pipes compared to traditional gravity piping.

In terms of operation and construction, as stated before, installation of pipes is really flexible and can be adapted to any building layout, while gravity systems require more space and a specific structure. Also, according to JETSGROUP (2009), a vacuum toilet manufacturer, vacuum toilets are more hygienic and produce less odours, by drawing waste along with large amounts of air into the piping with every single flush. As stated by Vacuum Toilets Australia Pty Ltd, vacuum toilets are remarkably quiet when flushed, as a consequence of a much shorter flushing time.

The purposes of using a vacuum system for sanitation instead of the traditional gravity systems are mainly the following:

- Water saving through the use of vacuum toilets and greywater reuse.
- Energy production through the anaerobic treatment of blackwater and kitchen waste from apartments and commercial establishments.
- Reduce greenhouse such as methane and carbon dioxide in two ways. First, when food waste is disposed to landfill it releases the mentioned gases, while in the proposed system they are captured through anaerobic digestion. Second, indirectly by lowering the energy demand from centralised wastewater treatment plants.
- Reuse of nutrients in blackwater including urine to substitute mineral fertilizers and for soil improvement.

All these characteristics are included in the new approach to sanitation that is being developed and implemented in different projects worldwide, known as Resource Management Sanitation, Ecological Sanitation (EcoSan) or Decentralised Sanitation and Reus (DESAR) (WENDLAND 2008). The following figure illustrates the concept:

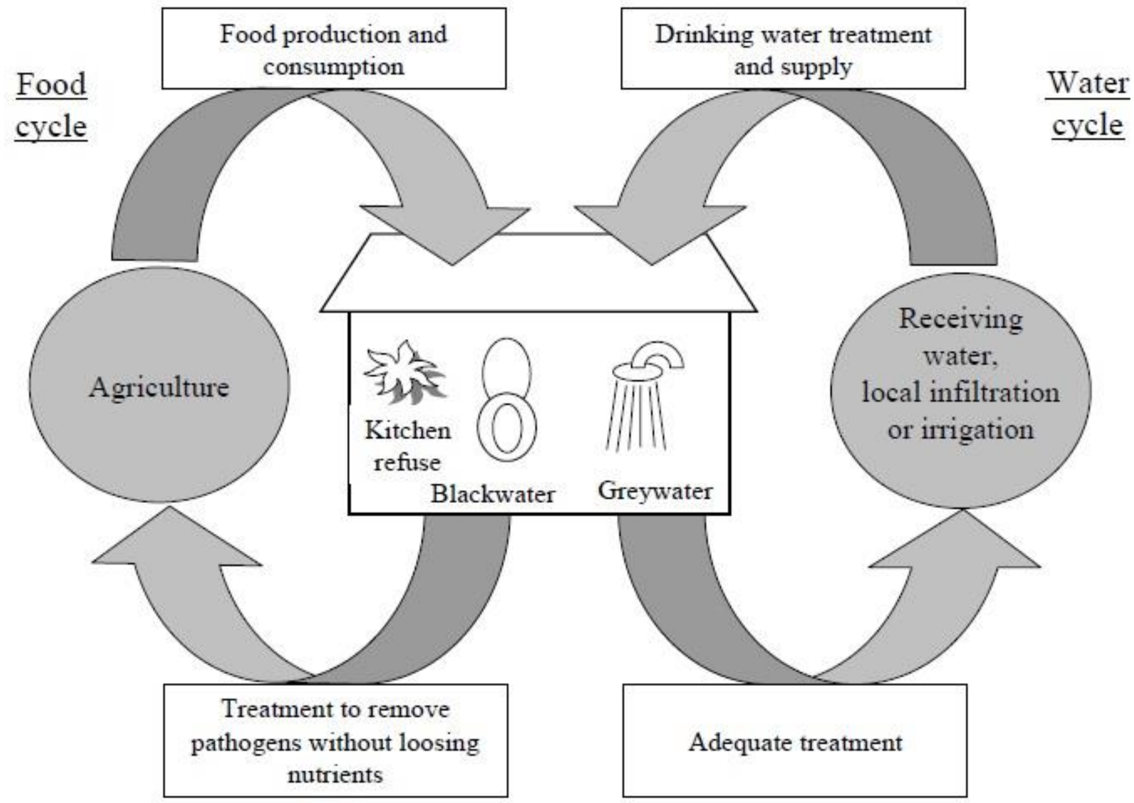

Figure 2. Scheme of the blackwater and greywater flows in resources management sanitation concepts (WENDLAND 2008)

According to JENSSEN et al. (2004), the amount of nutrients discharged from sewage in Norway is equivalent to 15% of the artificial fertilizer input to agriculture, at an economic value of 25 million euros. In addition the energy potential of both waste heat and organic waste in wastewater in Sweden is equivalent to 8% of its total electricity production.

Sanitation systems

Conventional sanitation systems normally involve large sewer systems with centralised treatment plants that perform advanced treatment of wastewater in pursuing a clean and safe environment. This system consumes large volumes of fresh water and requires significant energy and a wide variety of chemicals to treat wastewater. After treated, nutrients that were present in the waste stream are released to the atmosphere or disposed to landfill. These systems are formed by large networks of underground pipes that carry blackwater, greywater, stormwater and industrial wastewater. The system networks are divided into primary (main sewer lines along main roads), secondary and tertiary (the ones in houses and neighbourhoods). Sewer pipes are laid out in straight lines when it's possible and the joints are made with the right angle to ease the flow. Depending on the type of network, pipe diameters go from 3 meters in primary main lines to 1 m in the secondary lateral lines.

These systems involve a significant investment and are challenging to build in urban areas, as they take up significant space and disrupt traffic. A lot of excavation is needed to place the pipes and then refilling. If they are placed under roads, after installing the pipes, roads have to be rebuilt. One of the disadvantages of this method is that ground shifts can cause cracks in pipe joints and wastewater can be exfiltrated to the ground and compromise sewer performance. The sewer design has to be made in a way that permits a minimum flow velocity that doesn't allow particulate accumulation, meaning that it remains clean. Also a constant gradient has to be maintained so that gravity can transport the sewage downwards. When this can't be performed due to an adverse topography, a pumping station is needed to transport the wastewater.

The structure of these systems in urban areas can be appreciated in the following figures, where sewage travels through different branches from houses:

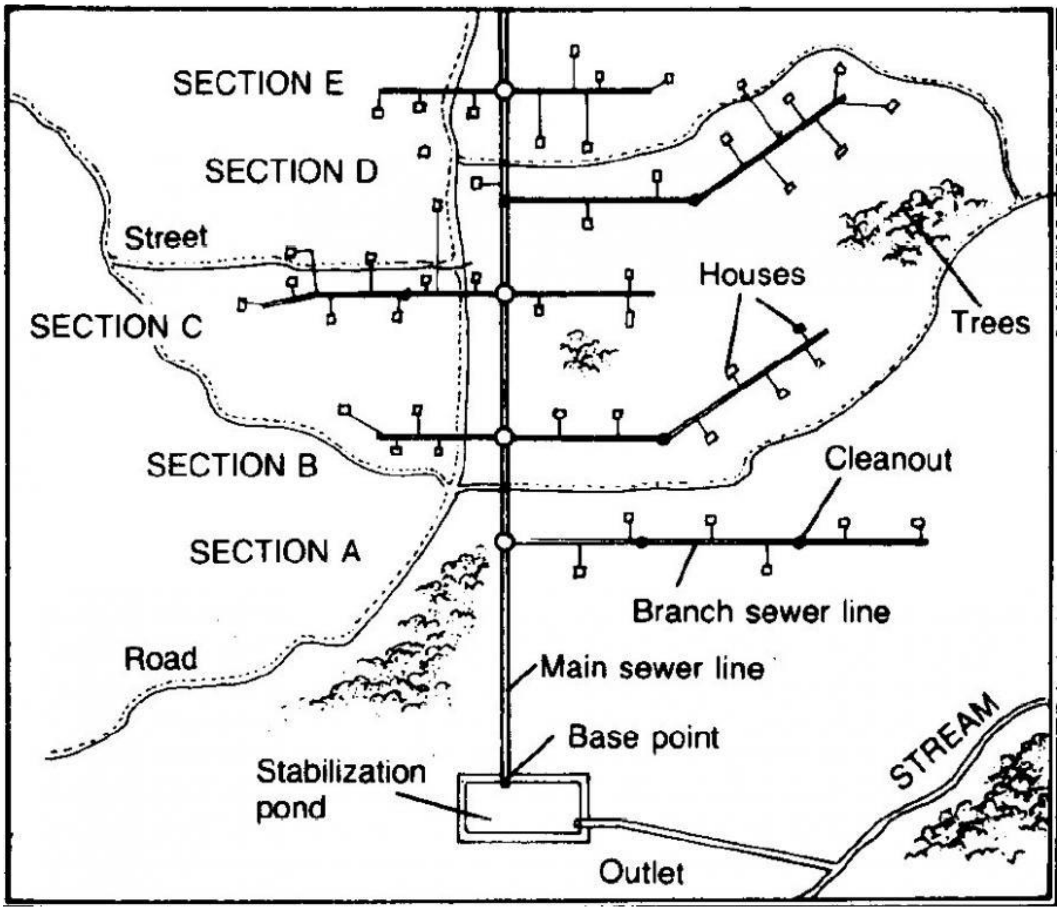

Figure 3. Master sewer system map. Source: USAID (1982)

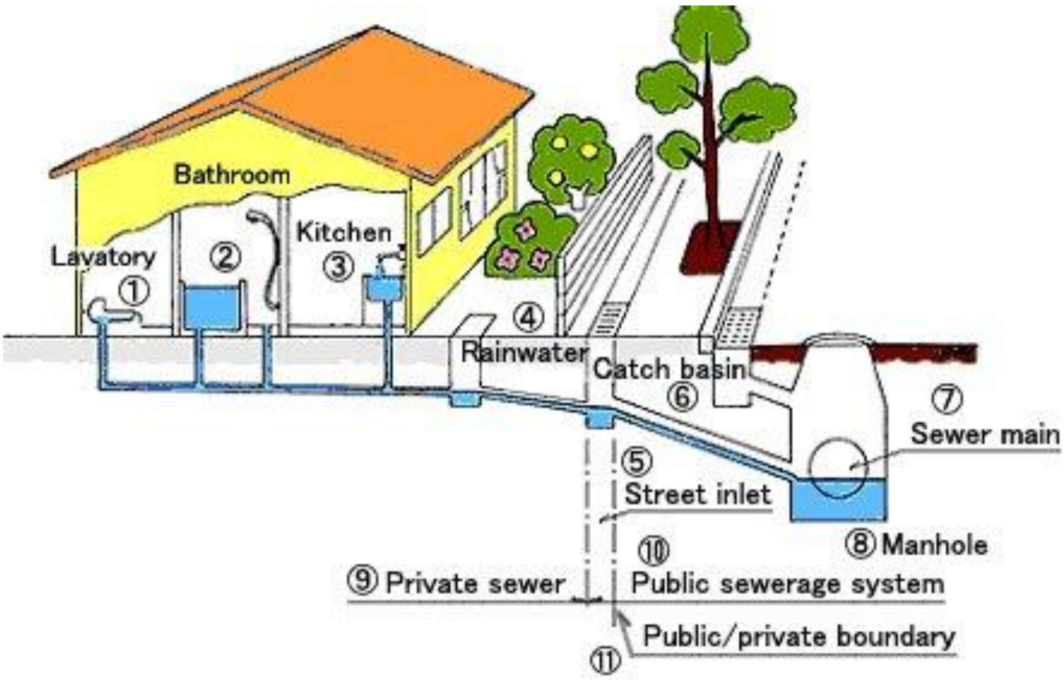

Figure 4. Cross-section of a conventional sewer in an urban area. Source: EAWAG/SANDEC (2008)

Among its main advantages centralised systems have the potential to handle large flow volumes, industrial wastewater can be discharged in them, its low risk to public health and it has low odour or noise related problems. We can also refer to the fact that no previous treatment is needed or on-site storage with conventional sewers, as all the required treatments are performed in the centralised stations.

They come at a high cost, strict construction requirements (such as deep excavations), difficulty to introduce in urban areas or difficulty to identify leakages are included as its main disadvantages. Nutrients are hard to recover and if they are recovered require significant energy needs.

The main benefits of the new type of sanitation system proposed in this report are water and energy savings, potential for nutrient recovery and greenhouse gases emissions reductions. Conventional gravity sewers have been invaluable for cities and society in the past, but they have to be re-thought to help in the development of a more sustainable future.

Urine diversion and the phosphorus problem

Present agricultural systems depend on continuous input of fertilizer. This fertilizers are derived from phosphate rock, a non-renewable resource of which its reserves are calculated to be consumed over the following decades. According to BØCKMAN et al. (1991), present mineral phosphorus sources will last a hundred to two hundred years, so we can confirm that its availability is limited. As mentioned in Peak Phosphorus, a SSWM publication, when 50% of the resource is still in the ground, a production maximum peak is reached, and prices and international conflicts start to increase due to a production decrement.

Population keeps growing, resulting in increased food production and increased fertilizers requirements. With this scenario in which a resource need will keep rising and its production is expected to decrease over the next decades, two different solutions could be used together to create a big impact on the global food production security. First, according to CORDELL et al. (2009), a vegetarian diet requires 0.6 kg of phosphorus per person and year, as an opposition to 1.6 kg that a meat-based diet, so if more people adopt this type of lifestyle and diet choices, the amount of phosphorus per person utilized would be reduced. On the other hand, alternative sources of phosphorus have to be investigated, and urine is found to be a good option. It contains the majority of nutrients with fertilizing potential among the different types of household waste. Also, it has to be taken into account that energy is required to produce this fertilizers, as for example, producing 1 kg of mineral nitrogen requires 10.5kWh of energy (REFSGAARD 1997).

According to CORDELL et al. (2011), phosphorus has been taken as a pollution concern instead of concerning about its relation with food security. New global challenge is to apply phosphorus recovery measures to substitute phosphate rock, a scarce, and increasingly unaffordable fertilizer.

Through the implementation of urine diversion in sanitation systems, direct collection of urine and associated nutrients is gained by separating streams of faeces and paper in traditional toilets. According to LARSEN et al. (2001), urine diversion has the potential to recover around 80% of nitrogen and 50% of phosphorus in domestic wastewater.

Another positive aspect about urine diversion resides in the fact that it can be directly applied to plants after hygienisation, so phosphorus would be available for crops without involving complicated processes. As mentioned before, urine has to be hygienised prior to its utilization in plants, which according to HÖGLUND (2001), depends on the time and temperature of storage.

Storage temperature	Storage time	Possible pathogens in Urine	Recommended area of use
4 °C	≥1 month	Viruses, protozoa	Food and fodder crops for further processing
4 °C	≥6 months	Viruses	Food crops for further processing and fodder crops
20 °C	≥1 month	Viruses	Food crops for further processing and fodder crops
20 °C	≥6 months	Presumably none	All crops

Table 2. Relation between temperature and time storage, pathogens in urine and recommended area of use (HÖGLUND 2001).

In order to put some numbers to this analysis, we can review different urine diversion related literature and gain data for the amount of urine an average person produces a day and the different nutrients it contains.

In a number of different projects undertaken in Sweden, as mentioned in JENSSEN et al. (2004), the following data was collected about the composition of the collected urine from different apartments. The mean values represent an average result of the different results in collected urine, compared to the Swedish norm. The difference in these values is explained because the Swedish norm refers to undiluted urine, while the various samples that were analysed from apartments contain different quantities of flush water, reducing the nutrient content in the mix.

URINE			
	N (g/l)	P (g/l)	K (g/l)
Mean	3.8	0.3	1
Swedish norm	11	1	2.5

Table 3. Amount of PNK in urine from the data in JENSSEN et al. (2004)

As cited in JENSSEN et al. 2004, according to (HELLSTRØM and KÄRRMAN 1996), an average production of urine of 1.3 litres per capita and day is assumed. Similar numbers are found through other literature. So if we assume the different data collected is correct, we obtain the following amounts of PNK produced per person a year.

	P (kg/cap)	N (kg/cap)	K (kg/cap)
Day	0.001	0.014	0.003
Year	0.475	5.220	1.186

Table 4. Calculated amount of PNK produced per person a year.

If we compare the production of nearly 0.5 kg of phosphorus per person a year according to the Swedish norm with the 0.6 kg of phosphorus stated by CORDELL et al. (2009), we could declare that around 80% of the fertilizer required by a vegetarian based diet could be theoretically provided by the urine produced. In the case of a meat-based diet this numbers would indicate that around 30% of fertilizer could be theoretically provided through urine. These are theoretical values obtained by assuming a correct data source, but understanding that even if there can be small deviations, 80% is a very significant number that should be highlighted.

As cited in CORDELL et al. (2011), the total amount of phosphorus available in excreta, manure, food waste and other sources may vary from country to country depending on: population size, daily food intake, and dietary preferences. Depending on the country, different values are obtained, for instance, if we take data from the estimated excretion of nutrients per capita in (JÖNSSON & VINNERÅS, 2004), we obtain the following table.

	N (kg/cap/y)	P (kg/cap/y)	K (kg/cap/y)
China	3.5	0.4	1.3
Haiti	1.9	0.2	0.9
India	2.3	0.3	1.1
South Africa	3	0.3	1.2
Uganda	2.2	0.3	1

Table 5. PNK per capita and year in different countries, according to JÖNSSON & VINNERÅS (2004).

Comparing this table with the previous 0.6 kg of P required to maintain a vegetarian base diet, we obtain the following table.

	% of P (vegetarian)	% of P (meat-based)
China	67%	25%
Haiti	33%	13%
India	50%	19%
South Africa	50%	19%
Uganda	50%	19%

Table 6. Percentage of phosphorus needed for vegetarian and meat-based diets.

Urine represents a viable substitute for mineral phosphate rock as modelling suggests that approximately 20% to 50% of agricultural fertilizers could be sourced from human urine (DRANGERT 1998; CORDELL, DRANGERT et al. 2009) (as cited in MITCHELL et al. 2013). These numbers have been obtained most probably by assuming a meat based diet as the numbers are close to the ones I obtained.

So by utilizing source separated methods like urine diversion, the energy use could be reduced in the WWTP, as the flow would be lower, and nutrients don't have to be removed, which is a highly energy consuming process. Also nutrients remain in the urine and they are not removed by the different treatment processes. A higher use of urine as fertilizer would have an impact on the production of mineral fertilizer, which would be reduced, and so the energy consumption related to this production.

There are more energy related issues related to urine diversion and its potential to substitute mineral fertilizers. Urine would eventually have to be taken away from storage tanks in buildings for example, and transportation by trucks would consume energy. But also after producing mineral fertilizers requires different stages of transportation. It is not an easy task to assess, but phosphate rock scarcity leaves no other option but to take alternatives into account.

Regarding the use of urine as a fertilizer, according to KVARNSTRÖM et al. (2006) it has not met with any difficult practical problems, as the use of animal urine is common in agriculture. Equipment already exists, so farm practices don't need to be changed. The levels of PNK in urine makes it suitable for fertilizing purposes. One hectare of grain requires around 100 kg of nitrogen per year, which means urine from 20 to 25 people to meet that supply (KVARNSTRÖM et al. 2006). Therefore, if agricultural use of urine is introduced, urine diversion requires large scale implementation.

Vacuum systems

Vacuum systems for sanitation consist basically in substituting water for vacuum as the main agent of transport. Instead of releasing a large volume of water to remove blackwater from our toilets, a vacuum pump creates a pressure difference that creates suction in the toilet. These type of systems are widely used in planes and ships, but its implementation on-shore is still limited. By substituting conventional flushing toilets by vacuum toilets, large amounts of water can be saved. Thanks to the differential air pressure generated in this systems, the piping can be more flexible, as waste can be propelled towards a higher point. That is one of the advantages of these type of systems, that waste can be transported horizontally and vertically upwards, against gravity. According to JENSSEN et al. (2004) the use of vacuum toilets is a feasible and convenient solution for decentralised wastewater treatment.

This flexibility allows room for manoeuvre, as the system can be applied both to new buildings and renovating or rehabilitation of older ones. Pipes can be routed around obstacles, and its installation is faster. Wastewater pipes are of smaller diameter in this type of systems, so less space is required for its installation, which results in a lower impact on infrastructure, for example, the space between floors will be smaller. The fact that gravity is not a limiting factor gives more freedom for designers to position toilets and bathrooms. Vacuum systems use smaller diameter pipes than gravity systems, with a usual diameter of around 50mm, in opposition to 110mm gravity pipes. This helps reduce the space needs, weight and cost considerations.

The main advantage and purpose to use vacuum systems is that large amounts of water can be saved due to a lower amount of flush water needed by vacuum toilets. According to JETSGROUP, the amount of water for flushing toilets can be cut by up to 90%, as well as blackwater will be reduced by the same percentage. According to JETSGROUP (2009), traditional toilets use a minimum of around 6 litres per flush to a maximum of 19 litres for the conventional high-flush toilets, to carry just 0.2 litres of human waste. Vacuum toilets normally use around 1 litre of water for the purpose of maintaining the bowl clean, but it can be even less sometimes. Assuming that a normal person can flush the toilet an average of between one to three times a day (for faeces), 5 to 18 litres can be saved per flush, so 5 to 54 litres can be saved per person an day. This is estimated at between 1800 and 19000 litres of potable water per person per year, depending on the type of toilet used and the times this person flushes the toilet every day. The amount of water used by vacuum toilets could be between 1 to 3 litres a day, up to a maximum of around 1000 litres a year per person. This would represent 5% of the amount of water used by traditional gravity toilets. Considering that toilet flushing represents from 20 to 40% of fresh water use according to JENSSEN et al. (2004), 19 to 38% of our total fresh water demand could be saved. Even more water could be saved by utilizing recycled or greywater for flushing purposes.

The system can be designed in two different ways, the constant vacuum system (CVS) and vacuum on demand system (VOD). Vacuum on demand systems produce vacuum just when it is required as someone flushes the toilet. In the case of larger buildings, constant vacuum systems are a better solution, as flushes will be regular and vacuum will have to be generated constantly. Virtually it is possible to expand the number of toilets without limitations, we would just need to install more vacuum pumps.

With this JETS system, vacuum is generated directly in the pipes, with a vacuum constant level of between 35% and 50% in a CVS. When the toilet is flushed, air and water are sucked into the pipes due to a pressure difference. During the transport from the toilets to the vacuum pump, the slug is affected by gravity and flattens after a time. Slugs are continuously reformed thanks to the 'transport pockets', low points in the pipes. With every next flush, slugs keep moving to the pump direction and other slugs keep reforming.

Depending on the manufacturer, vacuum systems can work in different ways, but normally CVS steps are the following (extracted from JETSGROUP):

1) When you flush the toilet, a valve in the toilet mechanism opens. Air and about 1 liter (1/4 gal.) is sucked into the piping.
2) The liquid waste forms a "slug" which moves at great speed through the pipes, as it is pushed inwards by the outside air. This happens because the air pressure is lower inside the piping than in the room outside (vacuum), and has several benefits - one of which is to allow piping to be laid upwards. The "slug" levels out after a while.
3) In long piping systems and where pipes are to be laid upwards, we collect water in low points in the piping to form new "slugs" as the liquid moves through the piping. These low points are called transport pockets.

4) Inside the pump, toilet waste is ground into tiny particles and discharged to a public sewer, collecting tank or treatment plant.

The following figures are provided in their website:

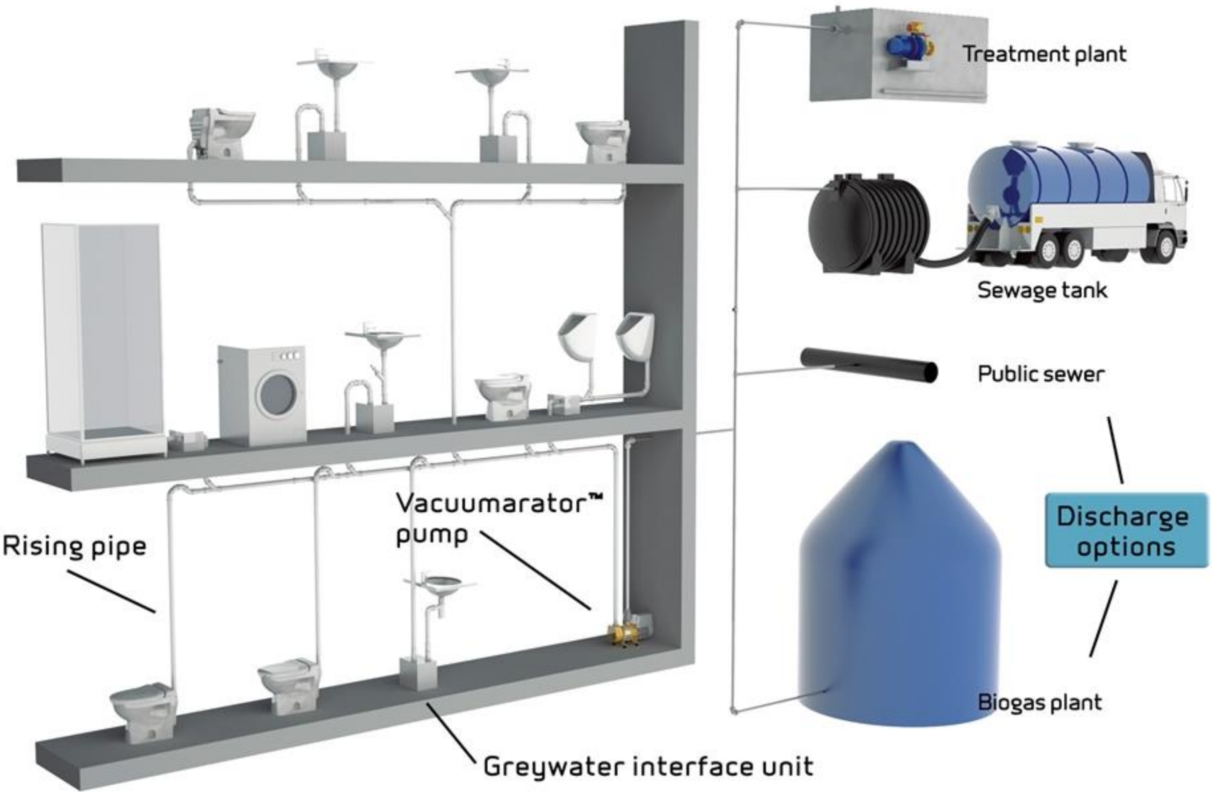

Figure 5. System example with different discharge options. Source: JETSGROUP

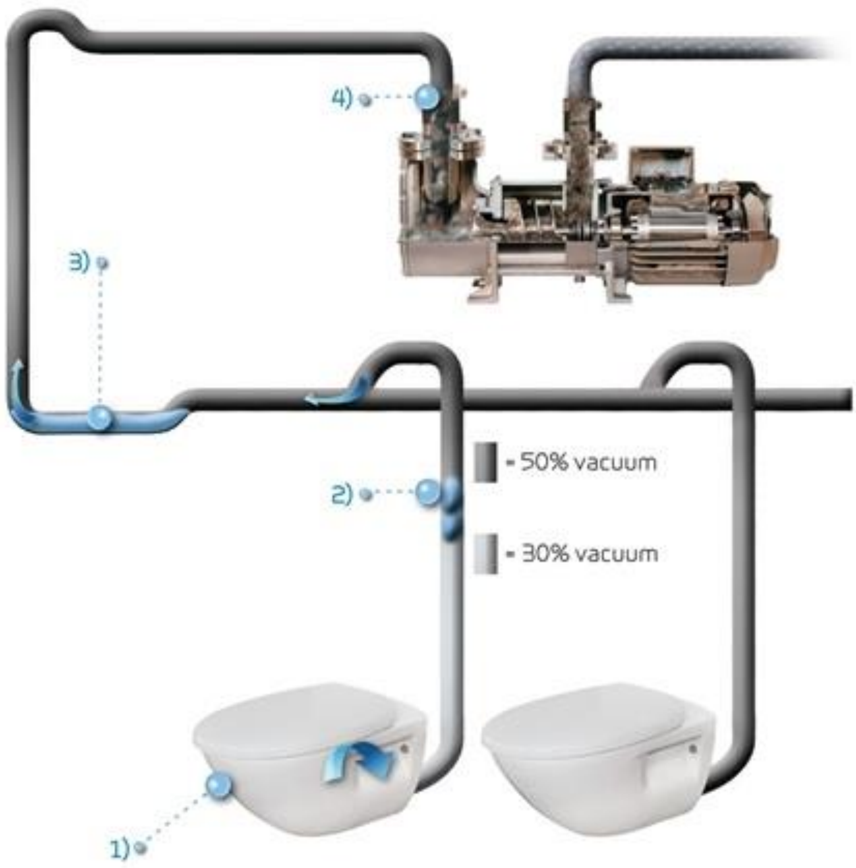

Figure 6. Sewage transport in a vacuum system. Source: JETSGROUP

The most important element on the system is the vacuum pump, and the number of them needed to generate this vacuum depend directly on the number of people in the building, as a higher number of flushes will require a higher vacuum generation rate. A good option in the market are the JETS Vacuumarator pumps, with different sizes and capacities to fit the budget and improve the efficiency of the different vacuum systems. They have different pumps with capacities ranging from 100 to 2600 flushes an hour.

In the JETSGROUP website, a few examples of undertaken projects are shown, which demonstrates that vacuum systems can be applied in buildings successfully. Some of those are:

- São Paulo University: With the system installed in 2007, it paid for itself in 15 months thanks to water related costs. The water consumption from 720 toilets was cut from 420,000 litres per day to about 60,000 litres thanks to JETS vacuum toilets, and the sewage volume was by 90%. The costs of gravity toilets were around 1,800 dollars per day, or 50,000 dollars per month. With a vacuum system and its water savings, the costs were cut to 320 dollars a day, or around 9000 a month. The economic savings were of around 40,000 dollars a month.

- WTorre São Paulo: A 30-storey office block of about 90,000 square metres. It includes more than 400 toilets, although the original design didn't include these vacuum toilets. Due to the water crisis in São Paulo, prices of water are soaring. Just as the university case, the economic savings have been of remarkable importance; the complex is saving 165,000 USD every year.

- Castelão stadium: The world's largest vacuum sanitary installation consists of 906 vacuum toilets and 12 Jets 65MBA Vacuumarator pumps for 70,000 spectators. The stadium, originally built in 1970, had to be renewed for the 2014 FIFA World Cup. The stadium had water tanks that held millions of litres of water, as the public water supply cannot meet such a high demand of water in a specific moment. With the flushing needs cut by 90% the tanks can be considerably reduced. According to JETSGROUP, even with conservative estimates, savings are indicated to be of more than 500,000 litres of fresh water per match.

Proposed system

The proposed sanitation system for buildings and precincts includes a mix of systems described previously in this report. It would include urine diversion, vacuum toilets, and vacuum food waste collection. The main purposes of this would be saving water from vacuum urine diverting toilets, with a lower flush water demand, as seen in the vacuum sanitation part, nutrient recovery for its later reuse as a fertilizer and lower the phosphate rock demand. Also, by treating the vacuum toilets blackwater along with kitchen waste through anaerobic digestion, energy production and a nutrient rich sludge are pursued. If possible, greywater or recycled water reuse are recommendable for water saving purposes.

Main system components would be:

- Vacuum urine-diverting toilets.
- Vacuum food waste disposers.
- Vacuum pump.
- Urine collection tank.
- Anaerobic digestion tank.
- Vacuum pipes (vacuum systems require smaller pipes than conventional ones).
- Urine pipes.
- Electrical devices and control systems.

Vacuum urine diverting toilets

These type of toilets mix the vacuum toilets and urine diversion concepts to benefit from the best features of both, water savings in the case of vacuum toilets and nutrient recovery for urine diversion. Multiple plumbing pipes are required by the system, as blackwater would travel through the vacuum pipes to the anaerobic tank, urine would be collected in a tank through gravity in a different set of pipes, and greywater would be either discharged to the public sewer or treated on-site for further reuse in a third set of pipes.

There are some products already existing in the market, like the EcoVac urine diversion toilet.

Figure 7. EcoVac urine diversion toilet. Source: SuSanA

According to EcoVac manual, it is the lowest flushing toilet on the market, with 0.6 litres for blackwater flushing and 0.1 litres for the urine diversion part bowl rinsing. This small amount of water helps maintaining cleanliness in the bowl. According to MITCHELL et al. (2013), along the recommendations for urine pipework in buildings, it was mentioned that in order to prevent dilution of urine being collected, a diversion valve is needed so that water used in flushing the lines could be directed to the sewer, so a connection between the toilet and the greywater system would be recommendable. This makes sense, because estimating that a human produces 1.3 litres of urine a day in 5 visits to the toilet, 0.5 litres of water would be utilized for flushing every day, which would mean 28% of water in the urine tank, being a high percentage of dilution.

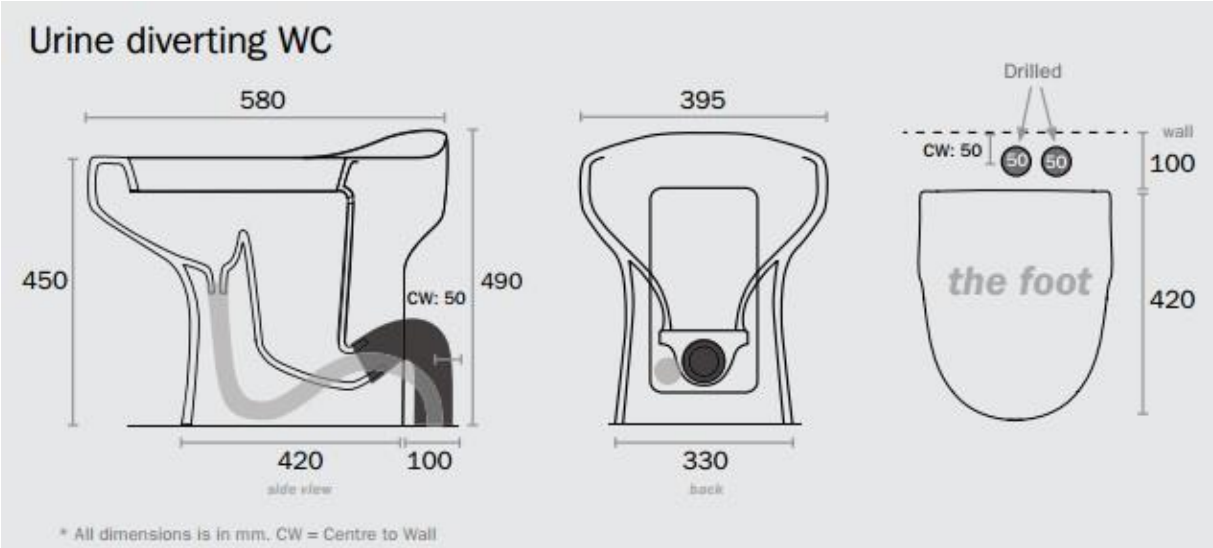

Figure 8. Plans of EcoVac urine diverting toilet. Source: EcoVac manual

According to JOENSSON et al. (2004), urine is very corrosive, so materials that resist corrosiveness should be applied, as plastic or high quality concrete, avoiding metals. The dimensions of the tank have to be calculated accordingly with the amount of people from which is expected to have their urine discharged. Also, the frequency in which it is emptied is a variable in the equation. In order to minimize energy use, the fewer times a truck has to empty the tank and transport it to its reuse or storage location, the less energy in form of petrol will be utilized, and so, the smaller the final emissions will be.

There is a case study of a vacuum urine-diverting sewerage system in Tsinghua University in China. In this case, urine was collected by gravity and faeces were transported through vacuum suction. The building has two symmetrical wings with 9 storeys above ground and 2 underground storeys. The new system coexisted with a traditional sanitation system (one on the east wing and the other one on the west wing), and their differences were studied in terms of design, construction, operation and maintenance. According to WANG and BAO (2007), conventional sewage systems high investments requirements for construction, operation and maintenance, and great demand for flush water has reduced its availability in developing countries, with especial consideration in the arid regions.

In the report it is mentioned that 90% of nitrogen and 60% of phosphorus in conventional municipal wastewater is found in urine and faeces, and according to them, research in sewage systems has been reoriented into more economical and ecological alternatives. The different approaches to it share the same main goals:

- Natural or low energy demanding treatment and disposal of human excreta.
- Complete reclamation of nutrients from human excreta.
- Efficient and safe treatment and reuse of possible dicharged wastewater.

I would add saving of resources by a more efficient use of water, as sanitation is mainly related to water by principle.

The SIEEB in Tsinghua University is a 20,000 m^2 and 40 m high building regarded as a model for showing the reduction potential of CO_2 in China. Different approaches of ecological water management have been applied; greywater is collected separately, treated and reused for toilet flushing, car washing and irrigation. Greywater is also mixed with rain collected from the different terraces in each floor.

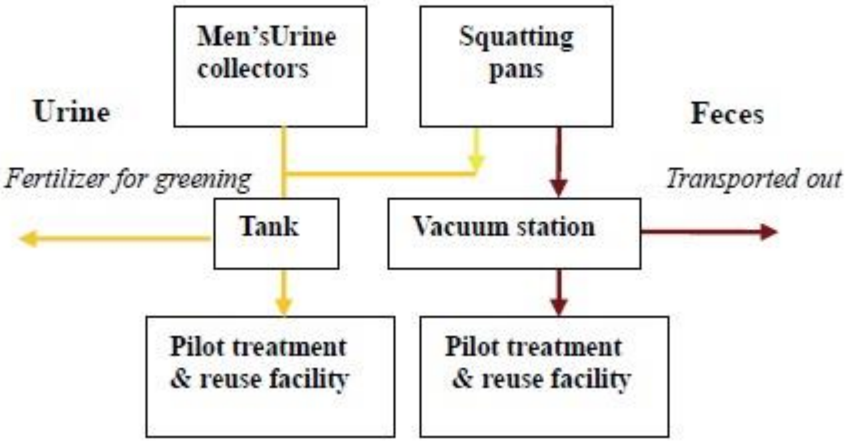

Figure 9. Tsinghua university system diagram. Source: WANG and BAO (2007)

To determine the needs of water, the following data was estimated.

	Number of persons per floor	Number of floors	Flushes per cap/day	Water per flush (L)	Water demand (L/d)
Faeces	25	7	1	0.8	140
Urine	25	7	5	0.1	87.5

Table 7. Tsinghua estimates for design. Source: WANG and BAO (2007)

For collection and storage they used a urine storage tank of D=600mm and H=2m, and a same size storage tank for faeces. Also a buffer tank of the same dimensions for pressure compensation was utilized. The vacuum was generated by 2 pumps in alternate operation and the water levels were monitored by a control system.

In terms of construction and operation and maintenance, the fact that a control system was applied in every toilet and that the pipeline system should be absolutely sealed made the construction stricter and more complicated, as an opposition to the small diameter of the pipes (DN 40 for faeces and DN 10 for urine, compared with DN 1000 for conventional toilets) and the flexible layout of the pipes, which facilitated the construction.

In comparison with the conventional system, 5 to 10 kWh was required to operate the vacuum system, but 2.5 to 4 m^3 of fresh water were saved every day. Taking into account other factors like the reuse of urine, compost of faeces and decrease of wastewater load, they concluded that a vacuum urine-diverting system is an environmentally friendly, economically reasonable and technologically feasible sanitation method with the potential to be applied in modern cities. They also state that with advanced on-site treatment technologies, these type of systems can contribute to close the loop of water and wastewater in our cities.

Finally, some other considerations should be taken in account, as end users behaviour when utilizing these type of toilets. In order to maximize the urine collection, urinating in the back part, designed to hold the faeces and toilet paper, should be avoided, and the best way to do it is to sit down in the toilet instead of urinating while standing up.

Kitchen food disposal system

In addition to blackwater vacuum collection, we can take advantage of the fact that we are implementing the whole structure of the vacuum system and extend it to kitchen waste or kitchen refuse collection. The principle of it would be similar to the toilet collection. We would have a food disposer placed in the kitchen, and by the same principle of toilet flushing, whenever we want to suck the food waste away, we would press a button, the valve opens, and the food is removed from it. By using different images we can imagine a concept for this product, by joining a stainless steel bowl as the place to dispose food, a JETS vacuum valve, and pipes.

Figure 10. Concept idea for food disposal system

The interest of adding food waste to the system resides in the idea that this organic waste improves the performance of anaerobic digestion in terms of COD removal efficiency and methane yield, according to WENDLAND et al. (2006). If the food waste wasn't introduced in the system, it would most likely be sent to landfill. Apart from wasting its anaerobic digestion potential, the same process that occurs in the digester would happen in landfill. The methane released from this waste wouldn't be captured and it would be released to the atmosphere. According to the US Environmental Protection Agency, methane is a 25 times stronger greenhouse gas than carbon dioxide. (EPA Overview of greenhouse gases, http://epa.gov/climatechange/ghgemissions/gases/ch4.html)

A project carried out by the Institute of Wastewater Management in Hamburg University of Technology in Germany, studied the combined anaerobic digestion of blackwater from vacuum toilets and kitchen refuse in a continuous stirred tank reactor (CSTR). According to WENDLAND et al. (2006), the addition of kitchen refuse improved the performance of the process in terms of COD removal efficiency and methane yield. It is also mentioned that kitchen refuse has to be milled in a grinder before being added to the blackwater. This throws a question of how kitchen waste should be grinded in our system, as there will be a high number of kitchens connected, and installing a food grinding system in each house would require a motor for each of the grinders, which would be consuming large amounts of energy. The other option is to grind all the food waste before entering the digester, and the JETS Vacuumarator pump includes an integrated macerator that grinds waste to a fine pulp, resulting in an easier transportation, storage and treatment. The reason to grind food waste to a smaller particle size is to allow a better access to the food for the microbes, resulting in a faster overall process.

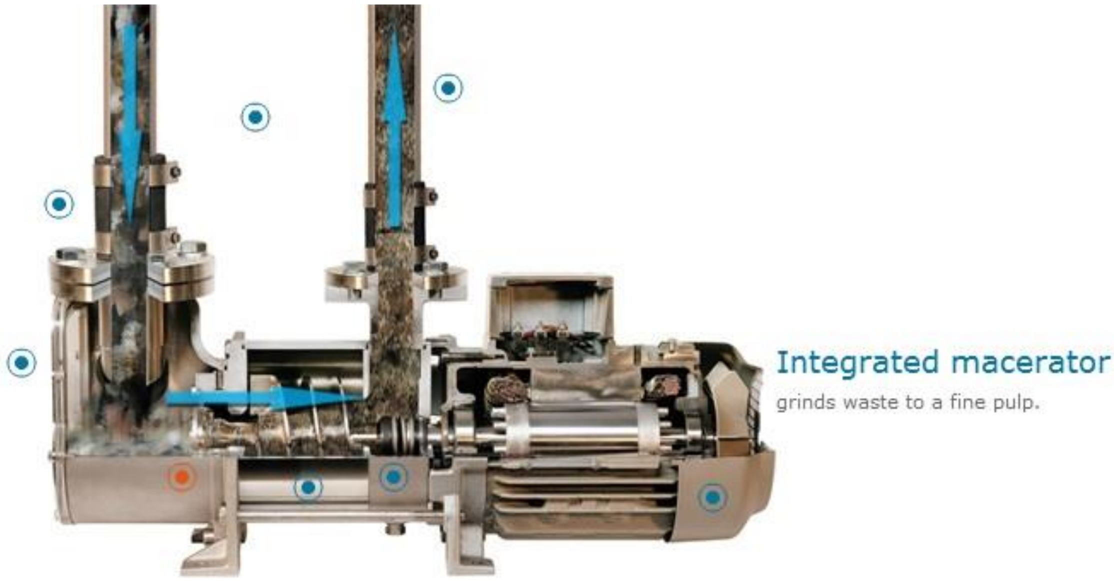

Figure 11. JETS Vacuumarator pump integrated macerator. Source: JETSGROUP

Hard food waste components like bones are an acceptable component to add to the anaerobic digestion. According to WILKIE (2013), if bones are properly grinded can provide pH buffering to the digester and are a source of calcium in the effluent, which is a plant micronutrient. It is also mentioned that meats and oils have a much higher methane production potential than vegetables and carbohydrates. Although meat and bones have a higher methane production potential, and so, more energy can be produced by them, it is known that raising livestock for food production requires a lot more energy, water, and land than producing fruits, vegetables and grains. The question with these hard products like bones would be if they would damage the integrated macerator, and advice should be provided by JETSGROUP whether their macerator is capable of managing bones. Also, smaller food waste would be placed in the vacuum disposer and would be easier to be taken away potentially leading to less blockages or obstruction of the pipes.

So, in conclusion, by adding food waste to the system, methane production is improved, as well as energy production, less greenhouse gases are released to the atmosphere by not sending it to landfill, and a more nutrient rich sludge would result from the anaerobic digestion process.

Greywater treatment and reuse

In case of greywater treatment from showers, sinks, laundry facilities, etc. for reuse, according to JENSSEN et al. (2004), natural systems can be applied, which have small energy requirements and make no use of chemicals. Systems like soil infiltration, constructed wetlands and ponds can be integrated as part of a natural environment. The limiting factor for applying them is the space availability, which is large compared to conventional treatment. According to a case study in Norway, greywater treated by combining a vertical flow bio filter followed by a horizontal flow wetland required 1 m^2 per person (JENSSEN 2005).

Anaerobic digestion of blackwater and kitchen refuse treatment

Anaerobic digestion is a process by which almost any organic waste can be biologically transformed into another form, in the absence of oxygen. The diverse microbial populations degrade organic waste, which results in the production of biogas and other energy-rich organic compounds as end products (LASTELLA et al., 2002). The process lasts over a couple of weeks up to several months. Organic waste releases the gases methane and carbon dioxide in landfills that escape into the atmosphere and pollute the environment, but if the natural process is controlled it has the potential to provide useful outputs as the mentioned biogas and an energy-rich sludge, without oxygen supply. It is considered a viable technology in the competent treatment of organic waste and the simultaneous production of a renewable energy (DE BAERE, 2006; JINGURA and MATENGAIFA, 2009).

Anaerobic digestion is a four-stage process consisting of hydrolysis, fermentation, acidification and finally methane formation. The composition of the biogas, is a mixture of methane (CH4) from around 50 to 75%, carbon dioxide (CO2) from 25 to 50%, 5 to 10% hydrogen, 1 to 2% nitrogen and some traces of hydrogen sulphide.

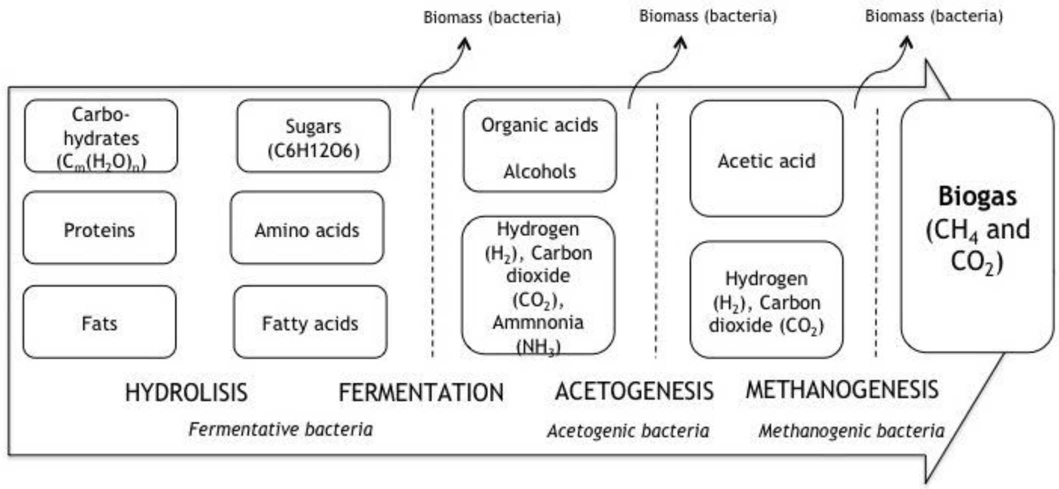

Figure 12. Anaerobic digestion steps. Source: SPUHLER (2010).

Anaerobic digestion of organic waste is also considered an environmentally useful technology. As cited in KHALID et al. (2011), this process reduces environmental pollution in two main ways: the sealed environment of the process prevents exit of methane into the atmosphere, while burning of the methane will release carbon–neutral carbon dioxide (no net effect on atmospheric carbon dioxide and other greenhouse gases). Biogas can be either utilized directly for cooking at household level, or it can be transformed into heat and power in cogeneration plant.

In our case, the digestion of both blackwater and food waste is known as co-digestion. By adding food waste, the load of biodegradable organic matter is increased, and more nutrients are found in the resultant sludge. It also helps, as mentioned before, in the improvement of biogas yield. According to HARTMANN and AHRING (2005), the excess of nutrients provided by co-digestion accelerates biodegradation of solid organic waste through bio stimulation. JINGURA and MATENGAIFA (2009) described the following multiple benefits of co-digestion: the facilitation of a stable and reliable digestion performance and production of a digested product of good quality, and an increase in biogas yield. Nutrients remain in the sludge, which can be composted and used as soil amendment in agriculture. Liquid effluents are either treated and rejected, or reused in fertigation.

A research project was carried out in Lübeck, Germany, about anaerobic co-digestion of blackwater from vacuum toilets and kitchen refuse in a continuous stirred tank reactor. In this project, urine-diversion was not applied, so the flow, even being small, will be bigger than the one in the vacuum urine-diversion toilets proposed. The toilets needed around 0.7 to 1 litre per flush. The flow was of about 5 litres per person and day. Kitchen waste was grinded before adding it to the blackwater. The amount of kitchen waste considered per person was 200 g/day, so the total flow was 5.2 l/day. A scheme of the pilot project is shown:

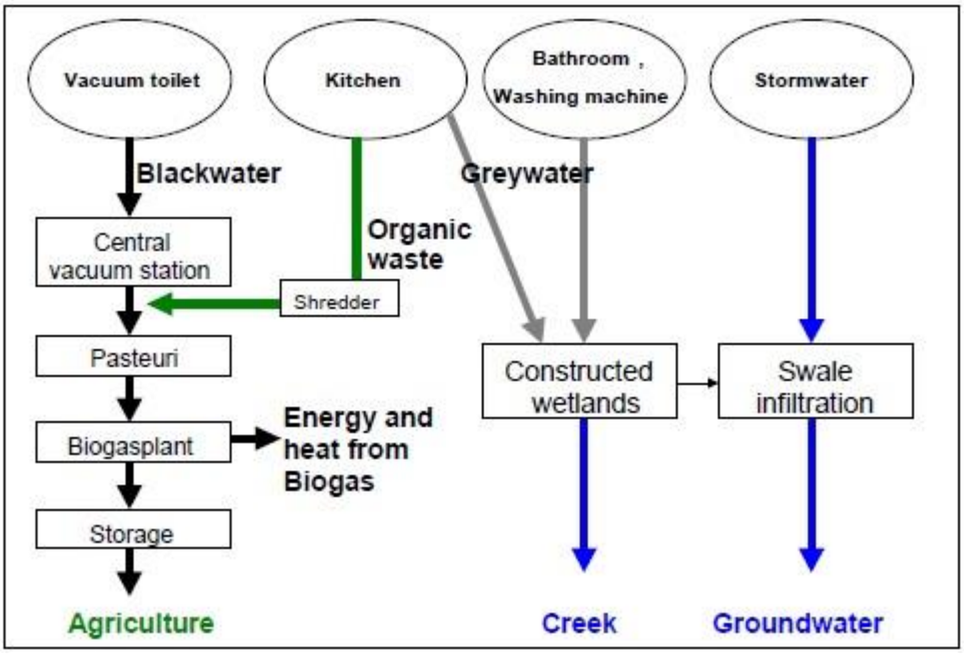

Figure 13. Scheme of the pilot project Flintenbreite. Source: WENDLAND et al. (2006).

Different tests were carried out, specifically:

- Characterisation of blackwater from vacuum toilets.
- COD removal efficiency and methane yield of blackwater digestion for 20 days HRT (hydraulic retention time).
- COD removal efficiency and methane yield of blackwater + kitchen refuse digestion for for 10, 15 and 20 days HRT.

The conclusions of the project state that anaerobic digestion in CSTR is an appropriate way to treat blackwater mixed with kitchen refuse. It is mentioned that the composition of blackwater is not the most appropriate for AD, due to high ammonium concentrations, but the process at 20 days HRT is very stable. The addition of KR improved the process in terms of COD removal and methane yield. At HRT of 15 and 20 days, a stable process was achieved, and even for HRT of 10 days, a steady state process with a decrease of COD removal of 30 to 33% and of methane yield of 19 to 21% can be achieved at a higher level of volatile fatty acids concentration in the effluent. It is stated that nitrogen removal does not take place, but this is of interest in order to use the sludge as fertilizer. As a final conclusion, HRT of 15 days is recommended if the feeding is regular. For fluctuating loads, as for example, different loads of kitchen waste in terms of quantity and quality, a HRT of 20 days is recommended.

The results of the study throw us a number of expected methane yield of 16 litres of CH4/cap/day for blackwater treatment at 20 days HRT, and in case of blackwater with kitchen waste, 32 l/cap/day, 33 l/cap/day and 26 l/cap/day correspond to 20, 15 and 10 days HRT respectively. So it is clear that the addition of food waste improves significantly the methane yield. This data could be taken for the interest of our project, but we would have to take in account that the influent would be different due to urine diversion. 5 litres per person of blackwater were considered, but in our case it will be smaller, because flushing is not needed for urine, and so, the volume of water will be lower.

Nutrients in wastewater and its reuse potential

One of the main purposes of implementing vacuum urine-diverting systems is the recovery and further reuse of nutrients present in wastewater. As cited in JENSSEN et al. (2004), theoretically, nutrients in domestic wastewater and organic waste are nearly sufficient to fertilize the crops to feed the entire world's population, if a vegan diet is followed. Wastewater can be divided in blackwater and greywater, and blackwater can be divided in urine and faeces. Of this fractions, greywater accounts for more than 90% of the total wastewater flow. However, the majority of nutrients are present in the smaller fraction, urine and faeces. This figure illustrates this:

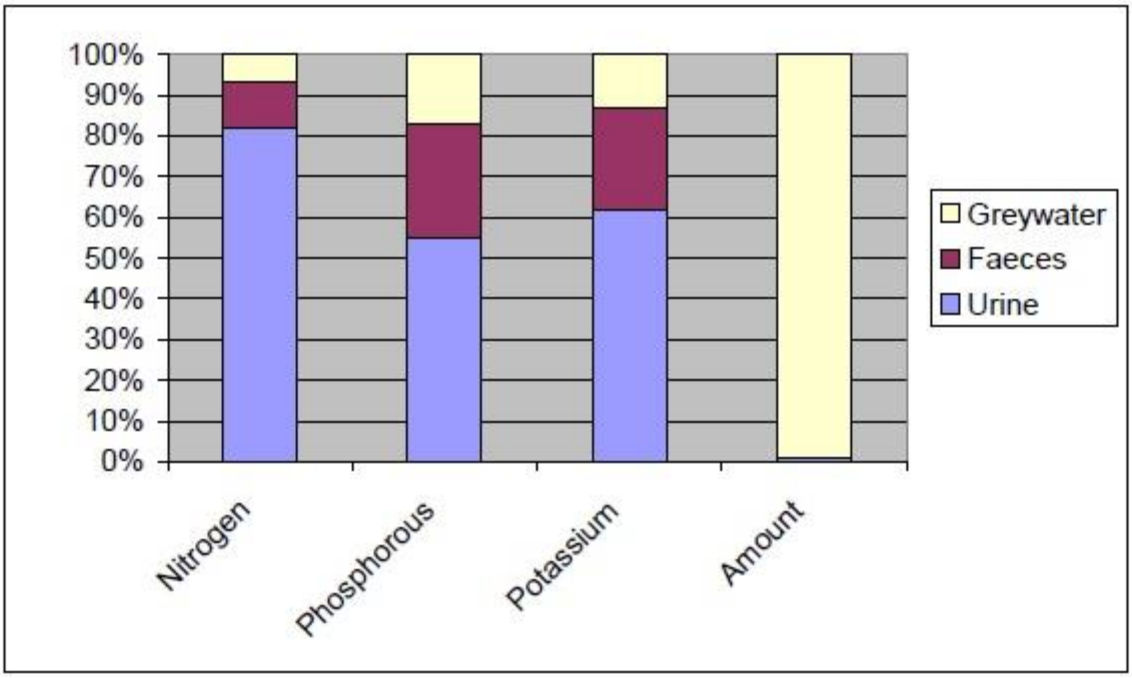

Figure 14. Percentage content of nutrients in domestic wastewater and amounts of wastewater fractions produced (JÖNSSON et al., 1999)

Urine is the most nutrient rich fraction in wastewater as it can be appreciated in the previous figure, but it only accounts for a small percentage, less than 1%, of the total produced wastewater. That's why applying urine diversion systems is the best way to recover this nutrients, otherwise, as mentioned, recovering the nutrients from the diluted urine in the blackwater and greywater mixed is high energy demanding, and in WWTP, nutrient recovery measurements are not performed, while they are considered a pollutant and not a resource in relation to their processes. For example, with actual methods for nitrogen removal of wastewater performed in treatment plants, most is released to the atmosphere. Values of PNK content are shown in the urine-diversion section.

Faeces and organic household waste contain less nutrients than urine, but they may be recycled to soil improvement and plant production as they have a high organic content. According to GARDNER (1997), organic matter accounts for one third of the input to landfills in industrialized countries and as much as two thirds in developing countries. As mentioned in a previous section, when organic waste is disposed to landfill, their methane yield potential for energy production is wasted and as an opposition to having a beneficial impact on the environment, it releases methane and other greenhouse gases.

In relation to concentrations of nutrients in faeces, VINNERÅS (2002) suggested new norm values in Sweden since the existing norms underestimated the amount of water in faeces.

FAECES				
	Dry matter kg/p/y	N g/kg DM	P g/kg DM	K g/kg DM
Swedish norm	12.8	43	14.3	28.5
Suggested norm	11	50	16.6	33.2

Table 8. Concentrations of nutrients in faeces, Swedish norm value vs. suggested norm value.

As shown in JENSSEN et al. (2004), The Agricultural University of Norway undertook a project to study the composition of food waste from 8 different restaurants. The following nutrient content analysis results are shown:

FOOD WASTE							
Dry matter (%)	ph (pH)	Organic matter g/kg	N g/kg	P g/kg	K g/kg	Mg g/kg	Ca g/kg
28.8	4	926	44.5	5	9	1	17

Table 9. Concentration of nutrients in food waste from 8 restaurants in Norway.

So, if we take all the data showed, and merge it in a single table, it results in the following. 0.2 kg of food waste per person and day are considered. Urine data is taken from the Swedish norm, which is considered undiluted, food waste data is taken from the Norwegian 8 restaurants samples, and faeces from the suggested norm values by VINNERÅS (2002).

	P kg/p/y	N kg/p/y	K kg/p/y
Urine	0.475	5.220	1.186
Faeces	0.002	0.005	0.003
Food waste	0.365	3.249	0.657
Total kg/p/y	0.841	8.473	1.846

Table 10. Total nutrients in kg produced per person and year, including food waste.

Presenting it in a 100% stacked column:

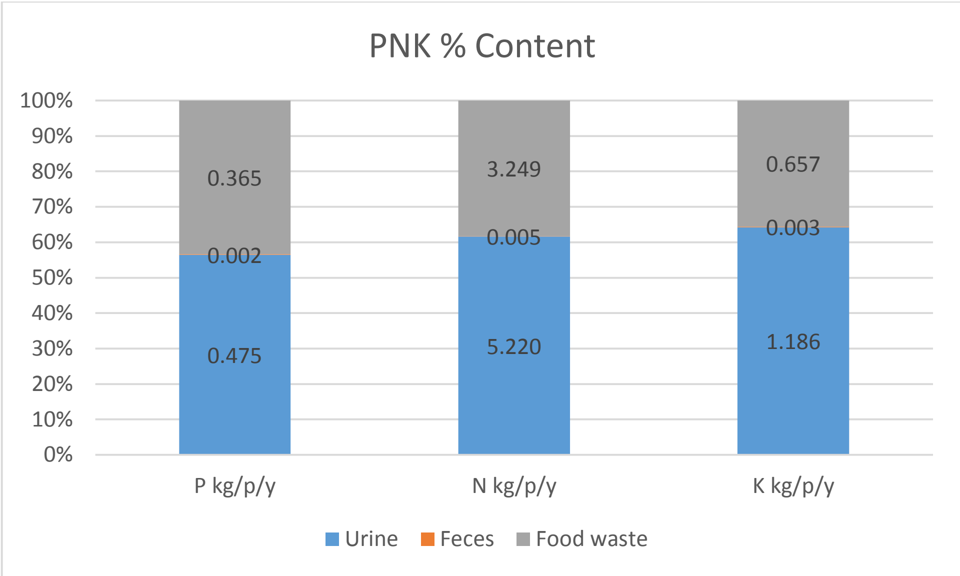

Figure 15. PNK % Content from data.

System diagram

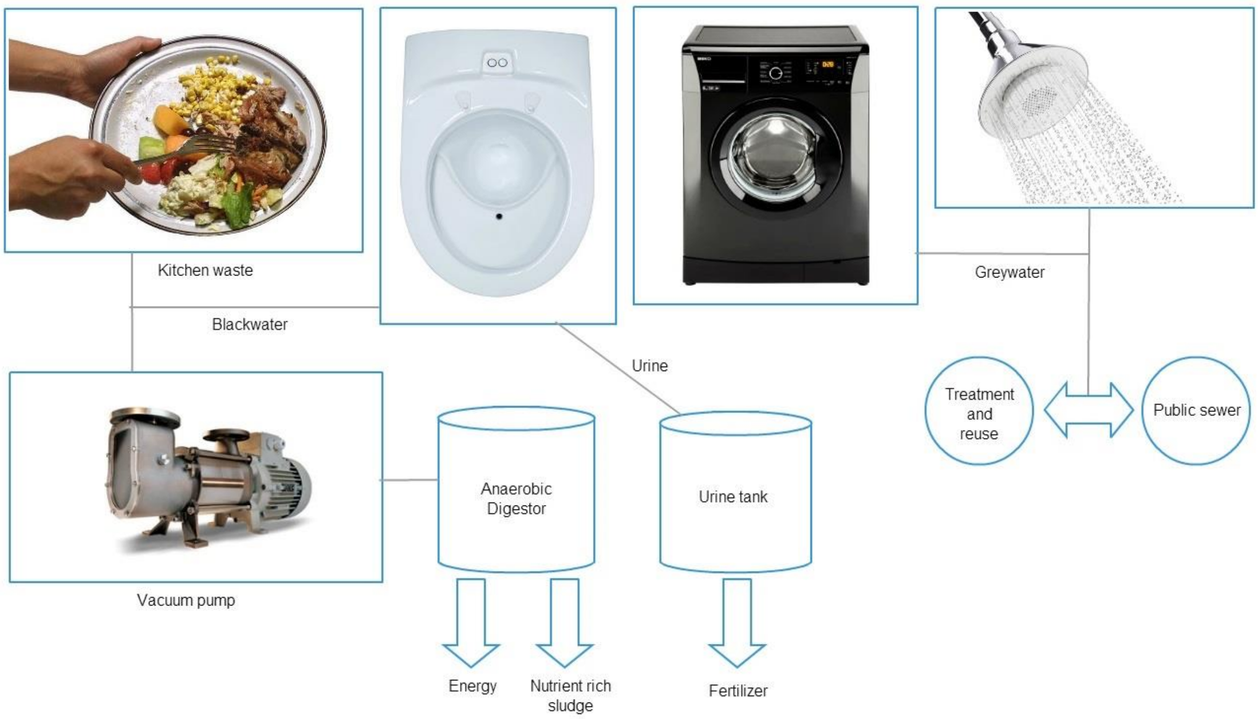

Figure 16. System diagram.

Other concerns

Although this report is focused on the technological and environmental aspects of introducing these type of sanitation systems, such as water savings, nutrient recovery and electricity generation, there are other issues that should be taken in account related to social, economic and political subjects. As it is not the main objective of the project, they won't be deeply investigated, but there are some things that have to be mentioned in the report, for the purpose of understanding the context in which vacuum urine diverting systems would operate, and the relationships between these different factors.

Social and cultural aspects

The system is to be utilized by people, who may use the system in a wrong way due to the fact that they don't know how it works, or who may not be willing to have these type of vacuum sanitation system for a particular reason (cultural, customs…). According to MITCHELL et al. (2013), the personal nature of new sanitation concepts and the high level of intimate end-user interaction make social acceptance of any new toileting technology a critical factor for success.

In order to maximize the efficiency of the system, the collection of urine and food waste should be as high as possible. In relation to the collection of urine, it will be maximum if people use the toilet correctly, letting urine enter the part of the toilet bowl designed for that purpose. This means, as mentioned previously in the report, that people should sit down in the toilet instead of urinating while standing up. To promote the correct use of toilets and explain to the users how people are supposed to behave, visual interaction could help understand the proper use of toilets by using guides in the form of images. Defecation in the urine part of the bowl must be avoided as well, to prevent contamination in the urine tank.

Also, the disposal of food waste in the vacuum food disposers should be encouraged, instead of throwing it in the garbage. People would be willing to collaborate by utilizing these systems correctly if they understand how their practices interfere directly with the environment and sustainability. A way to create awareness of the environmental issues related to the new sanitation system could be creating small guides explaining the connection existing between these problems and the sanitation system. These guides could include brief explanations about phosphorus scarcity, fresh water availability and anaerobic digestion. Also, the mentioned images on how to use the system correctly.

Figure 17. How to use the toilets. Source: MITCHELL et al. (2013).

The guide should also include a brief explanation of good practices in terms of the vacuum food disposers' usage. The smaller the food waste is, the fewer risk of blockage in the pipes would be, so encouraging people to make waste as small as possible should be mentioned. Also, only organic waste should be introduced in the disposers, and not plastics or other things that may cause harm to the system or interfere in the anaerobic digestion.

As a conclusion, these systems are to be used by individuals, and the fact that they are aware of how their practices interfere with the correct functioning of them would be crucial for success. Adapting may take time, because conventional toilets are widely spread and people have coexisted with them for all their lives, but if education is carried out and awareness of the positive effects to the environment of the system is created, people should respond positively and lead to the proper use of the toilets and disposers.

Political issues

The application of a system that deals with public health, electricity generation and waste handling, will have regulations and different laws indicating how or which parameters the different parts of the system should be complying with. The main aspects that may have regulations associated with them are:

- Urine: As explained in the report, urine is to be collected from the different homes through a different set of pipes in a collection tank. The recommended amount of time that urine is stored before it is used for fertilizing purposes is shown in table 2, but there may be a standard stated by the Australian department of agriculture or health department, which must be complied. In case of non-existent regulation due to its lack of implementation, regulations should be developed and guidelines for the safety of public health should be created. Also, the fact that the collection tank can be accessible to people may have some security guidelines to follow as for example the location of the tank, stating that it must be situated in a place only accessible by a person or team responsible for maintenance and by the professional transporters that empty the tank and take the collected urine away from the building.

- Sludge: A similar case to the urine would be anaerobic digestion and the sludge resultant from this process. A nutrient rich sludge derived from anaerobic digestion is to be utilized in agriculture for fertilizing crops, or for soil improvement. In case it is used for crops, regulations about its pathogens content and other sludge characteristics such as heavy metals content can exist. According to REILLY (2001), The Environmental Protection Agency in the United States acknowledged that pathogens risk form land application of sewage sludge have not been adequately evaluated. The final product of agriculture, food, will be determinant for a good health in society, so the use of this sludge and its associated risks to the public health must be assessed. The sludge produced may have to undergo further treatment if it doesn't comply with the regulations in the condition in which it leaves the digesters.
- Energy production: Methane gas is a product of the anaerobic digestion, and it can be used for electricity generation or directly in the building for cooking or heating purposes. If electricity is generated, the generated power should be introduced in the Australian electrical grid. The main bodies for the regulation of the Australian electricity market are the Australian Energy Market Commission, the Australian Energy Regulator and the Australian Energy Market Operator. The Australian Energy Market Commission determines rules and policy for the energy market. Characteristics and parameters about the production of energy to sell to the grid must be followed. In the US, for example, the Public Utility Regulatory Policy Act dictates that the excess electricity that renewable energy systems generate must be purchased by electric companies, as a way of encouraging renewable energy production. (http://science.howstuffworks.com/environmental/energy/sell-electricity-back-grid.htm).

Economics and marketing

The implementation of these new type of sanitation systems will have costs and benefits associated to it. Vacuum toilets and urine diversion toilets already exist, but their presence in buildings and large residential networks is still very limited. If they become more common and are adopted by new building promotions, potential business opportunities can appear due to a new concept of sanitation. For example, the removal of urine and sludge should be performed by a truck company, creating a new activity related to these systems that may lead to job creation. Also, the production of vacuum urine diverting toilets itself would be incremented, and new manufacturers could enter the market, leading to a higher competition and a decrease in the final prices of the toilets.

Costs of the system:

- Installation of the system: The same as a conventional sanitation system for a new building, the pipes have to be installed and that requires a workforce, but as stated previously in the report, the fact that the piping can be more flexible as the waste can travel upwards, makes the installation of the pipes faster and that could lead to fewer hours of human work, making the installation cheaper. In case of the tanks, that would be an additional cost that conventional systems don't have associated to it.
- Emptying the tanks: The decentralised nature of the system requires that the urine and anaerobic sludge are removed frequently, because they are not connected to a public sewer that takes it away from the building or precinct. This task should be performed by trucks that would obviously have a cost associated to it.
- Energy required by the system: The energy required by the vacuum pump and the anaerobic digester should be paid by the whole community of users in the form of a community fee.

Potential benefits:

- Water savings: The lower water demand generated by the vacuum toilets would be reflected in a smaller water bill.
- Energy generation: The power generated by the anaerobic digestion could be sold to the grid, generating an income for the community. The introduction of

power to the grid will have regulations associated with it as mentioned before, so that would determine how this task is to be performed.

- Urine and sludge: There's uncertainty about the potential value of urine and sludge, and who the customers for this products would be. The same as renewable energy is promoted by the government, an economic compensation could be given to the farmers that utilize fertilizers derived from these systems. This would be a measure to promote sustainability and to assure the global food production, as less mineral fertilizers would be utilized.

As the implementation of these systems is studied for large buildings and not for single houses, the main clients would be real estate developers. They should be the ones that choose whether to implement vacuum urine diverting sanitation systems in a building or not, so they should find associated benefits if they choose the proposed system. With an increasing awareness of environmental protection in society, the fact that the proposed system could contribute to the creation of a greener building could be seen as beneficial for the associated value of the apartments. The demand from society of having greener and more respectful technologies could be an appropriate strong argument to promote choosing our option. People would most likely be attracted by an apartment that respects the environment and makes a more responsible use of resources. Also, the fact that the use of water is lower may attract people by having a cheaper water bill.

Another attractive aspect about the system can be the energy production. The fact that you are contributing to fewer greenhouse gas emissions and the production of electricity with your waste makes it an attractive option.

In conclusion, the beneficial aspects of implementing vacuum urine diverting systems should be promoted among the real estate developers to choose this option to create added value to the new building and apartment developments.

Example case study

We consider a precinct consisting of 1000 units, and a commercial space that holds 20 restaurants and other establishments inside. With some of the data obtained from research of different sources and some approximated figures, we analyse its environmental impact in relation with water savings, wastewater production, energy requirements, methane production and nutrient recovery. Not all data is referenced, as there are some estimations for different parameters that involve uncertainty.

For the purpose of obtaining approximate data outputs, different technologies are included in the system:

- Vacuum urine diverting toilets with flush volumes of 0.5 litres for faeces and 0.1 litres for urine flush.
- Gravity toilets with a 6 litre of water flushing volume. This will be used to estimate the water savings of vacuum urine diverting toilets in comparison with conventional toilets.
- Waterless urinals. For the estimation of water use in restaurants, we consider that this type of urinals are common in public and commercial establishments. The water demand for urinating purposes is cut by a half, by considering that every man that urinates in restaurants uses this toilets, and only women flush when urinating.
- Vacuum food disposers. Food collected from them will be treated through anaerobic digestion along with blackwater.
- Vacuum pump: Used to create the necessary vacuum to collect blackwater and food waste into the anaerobic tanks.

Through the use of this technologies in the system, 5 main system characteristics are involved, and for each of them, a data output is calculated:

- Water savings: Estimated by comparing the water use in vacuum urine diverting toilets vs. conventional toilets.
- Wastewater production and tank sizes: Using the estimated volumes produced by vacuum urine diverting toilets and food disposers, both volumes of anaerobic digestion tanks and urine storage tanks can be calculated. This volumes will also be related to the frequency with which they are emptied.

- Energy requirements for vacuum toilets and food disposers: By estimating the amount of flushes required in the case study from vacuum toilets and vacuum food disposers, we choose an appropriate pump that fits the flush requirements and calculate its energy needs.
- Methane production: Considering the figures obtained in WENDLAND (2008), we will calculate the total amount of methane produced in the system. It is important to mention that we are using the numbers obtained in that project although it did not include urine diversion in the system.
- Nutrient recovery: Using table 10 from our report, the total production of nutrients from the building will be calculated assuming that a 100% is recovered.

The calculated numbers of people in the case study will determine all the results, so a table summarizing them is shown. 2 people per unit are considered, as well as 25 seats per restaurant and 3 rotation times. This means that 75 people visit each restaurant every day.

Number of units	1000
Number of people	2000
Number of restaurants	20
Seats/restaurant	25
Rotation times	3
Total visits	1500

Table 11. Calculated numbers of people in case study.

Water savings:

Two flushes per person and day are estimated in apartments for blackwater and five in the case of urine for vacuum urine diverting toilets. For gravity toilets, 5 flushes a day with a volume of 6 litres per flush is estimated.

For restaurants, it was considered that half of the people that visit them urinate, and 10% defecate. In order to estimate the gravity toilets demand, it was considered that everyone that defecates flushes, but the number of flushes from people that urinate was cut to 50%, because in most public and commercial spaces men use waterless urinals. This resulted in a number of 35% of the people that visit the restaurant flushes.

The result of vacuum urine diverting systems using 5% of the amount of water that conventional toilets use is similar to the estimated by JETSGROUP (2009).

APARTMENTS		
Blackwater	Flushes/person/day	2
	Total flushes/day	4000
	Water/flush	0.5
	Total water/day	2000
Urine	Flushes/person/day	5
	Total flushes/day	10000
	Amount of water/flush	0.1
	Total water/day	1000
Gravity toilet	Flushes/person/day	5
	Total flushes/day	10000
	Water/flush	6
	Total water/day	60000

Table 12. Water use estimation for apartments.

RESTAURANTS		
Blackwater	% of people defecate	10
	Total flushes/day	150
	Water/flush	0.5
	Total water/day	75
Urine	% of people urinate	50
	Total flushes/day	750
	Water/flush	0.1
	Total water/day	75
Gravity toilet	% of people flush	35
	Total flushes/day	525
	Water/flush	6
	Total water/day	3150

Table 13. Water use estimation for restaurants.

Vacuum urine diverting	3150
Traditional	63150
% compared	4.99%

Table 14. Vacuum urine diverting vs. gravity toilets.

With the estimations made, the volume of water saved each day would be equal to 60,000 litres. The amount of water saved each year would be the same as 8.76 Olympic pools, considering a pool volume of 2.5 million litres according to the Australian bureau of meteorology (http://media.bom.gov.au/social/blog/39/when-dam-size-matters/).

Figure 18. Olympic pool. Photograph by Lynton Crabb.

Wastewater production and tank sizes:

To perform this calculation, we estimate the production of blackwater, urine and kitchen waste produced every day, and according to the frequency of collection in the case of urine and in relation to the retention time for blackwater and food waste, the size of the tanks can be calculated. The reason to propose two tanks for anaerobic digestion is to have a good amount of methane yield. In this case, when a tank is filled, the other one is used. In this way, the filled tank can hold the waste for 15 days and ensure the retention time. The waste getting in the tank the first day of use would stay for 30 days, and the one from the last day, 15 days.

	APARTMENTS		RESTAURANTS	
Blackwater	Flushes/person/day	2	% of people defecate	10
	Total flushes/day	4000	Total flushes/day	150
	Water/flush	0.5	Water/flush	0.5
	Total water/day	2000	Total water/day	75
	Faeces/flush	0.2	Faeces/flush	0.2
	Total volume/day	2800	Total volume/day	105
Urine	Flushes/person/day	5	% of people urinate	50
	Total flushes/day	10000	Total flushes/day	750
	Water/flush	0.1	Water/flush	0.1
	Total water/day	1000	Total water/day	75
	Urine/p/d	1.3	Urine/flush	0.3
	Total volume/day	3600	Total volume/day	300
Food waste	Kitchen waste/meal	0.2	Kitchen waste/meal	0.2
	Total kitchen waste	400	Total kitchen waste	300

Table 15. Estimations of waste production.

Anaerobic digester	
Volume/day (L)	3605
Volume/day (m3)	3.605
HRT (days)	15
Volume/15 days (m3)	54.075
Tanks	2
Volume/tank (m3)	27.0375

Table 16. Estimation of anaerobic digester volume.

Urine tank	
Volume/day (L)	3900
Volume/day (m3)	3.9
Frequency of collection	Weekly
Volume of tank	27.3

Table 17. Estimation of urine collection tank

If the frequency of collection if of 7 days for urine, a tank of 27.3 m3 would be required. In case of the anaerobic digester, each of the tanks would be 27 m3, and the frequency of collection would be 30 days.

Urine tank	
Volume/day (L)	2600
Volume/day (m3)	2.6
Frequency of collection	Weekly
Volume of tank	18.2

Table 18. Estimation of urine collection tank (without flush water)

In case that flushing for urine is derived to the greywater system for the purpose of not diluting the urine in the tank, the volume of it should be smaller as shown in the previous table.

Energy requirements for vacuum toilets and food vacuum disposers

Using the same estimations for the amount of flushes, we can calculate the total amount of flushes performed every day, and calculate the amount of flushes per hour. I will take in account 16 hours to calculate the amount of flushes per hour, eliminating an average of 8 hours/day of sleeping time.

APARTMENTS		RESTAURANTS	
Vacuum toilet flushes/person	2	% of people defecate	10
Total flushes	4000	Total flushes	150
Vacuum food flushes/unit	3	Total meals	1500
Total flushes	3000	Total flushes	150
TOTAL FLUSHES		7300	
FLUSHES/HOUR		456.25	

Table 19. Estimation of number of flushes/hour.

The estimations show a possible number of around 450 flushes an hour. A security coefficient should be applied in case a higher amount of flushes happens in peak times. By checking the different options offered by JETS in (http://standard.jetsgroup.com/en/Products/Vacuumarator-pumps.aspx), the Jets 95MB Vacuumarator pump could fit our requirements. It is capable of handling 730 flushes an hour at a frequency of 50Hz, which is the one provided by the Australian electrical grid.

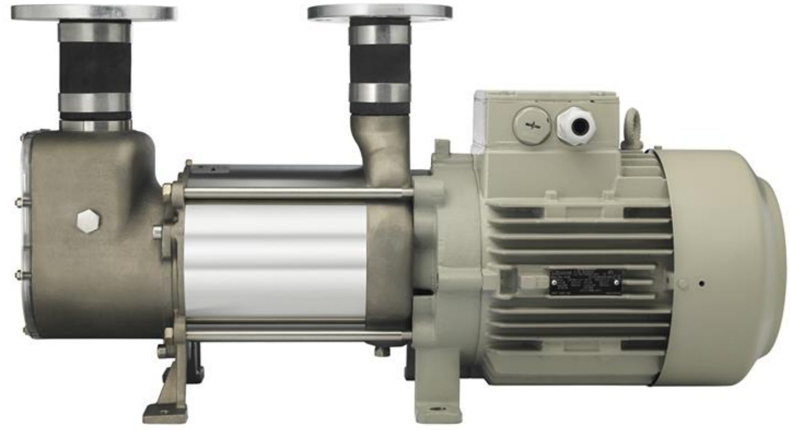

Figure 19. Jets 95MB Vacuumarator pump. Source: JETSGROUP website.

It carries a motor of 5.5 kW. If we divide that amount of power by the number of people living in the building we obtain a value of 2.75 Wh per person. That is the amount of power required by some low consuming light bulbs. The day consumption per person would be 66Wh. That power is comparable to the power consumed by a laptop in one hour.

Methane production

Methane would be produced in the anaerobic digester through the use of blackwater from vacuum toilets and food waste from vacuum food disposers.

By assuming a methane yield of 33 litres per person and day for a retention time of 15 days (WENDLAND et al. 2006), we calculate the total amount of methane produced by the digesters. For 2000 people, 66kL would be produced a day, and in 30 days that makes it around 2 million litres per tank every 30 days. With a density of 0.66 kg/m3 (Wikipedia), the amount of methane in kg produced would be 1300 kg. Assuming an energy content of 55.5 MJ/kg (Ronneau 2004) or 15.4 kWh/kg, the production of each tank for 30 days would be of a total of 20 MWh. That means 335 Wh per person and day, enough energy to run a ceiling fan for 3 hours or a compact fluorescent lamp (100-watt equivalent) for 11 hours. Data of consumption for fan and lamp taken from: http://www.wholesalesolar.com/solar-information/how-to-save-energy/power-table

This estimations may not be very precise as data is collected from WENDLAND (2006), and they didn't include urine diversion in their system, so the inflows to the digester are different. Also, the HRT of 15 days occurs for the waste that gets into the digester on the last day. The rest of the waste will have a retention time of between 16 and 30 days, depending on the day it entered the digester, so a higher methane yield is expected.

ENERGY ESTIMATIONS	
Methane yield for HRT=15 (litres/p/d)	33
Number of days in digester	30
Total methane/day (litres)	66000
Total methane/30 days (m3)	1980
Density of methane (kg/m3)	0.66
Total methane/30 days (kg)	1306.80
Energy content of methane (MJ/kg)	55
Energy content of methane (kWh/kg)	15.4
Total energy produced in 30 days (MWh)	20.12
Energy/p/d (Wh)	335.41

Table 20. Methane and energy estimations.

<u>Nutrient recovery</u>

Using data from table 10, an estimation of the total amount of nutrients (considering 100% recovery) would show the following numbers.

Nutrient	P	N	K
Total kg/p/y	0.84	8.47	1.85
Total T/y	1.68	16.95	3.69

Table 21. Estimated nutrient recovery for 2000 people in tonnes per year.

According to Queensland Government Department of Agriculture and Fisheries, an hectare can yield 7000 kg of irrigated wheat grain, with a nutrient removal of 125 kg of N, 24 kg of P and 35 kg of K per hectare. With the estimated nutrient recovery values obtained in the table, we can determine that taking phosphorus as the limiting nutrient between the three, 70 hectares of crops could be fertilized, producing an amount of 490 tonnes of wheat grain. Assuming that a kg of wheat can produce two packs of whole wheat sliced bread, 490 packs of sliced bread per person and year could be produced. The wheat yield per person would be 245 kg per year or 0.67 kg per day.

Conclusions

Continuous growth of population and its consequent increase in food, water and energy demands require global initiatives to ensure that this demands can be assumed. The increase in food demand requires an enormous input of phosphate rock derived fertilizer, and according to data, the reserves are expected to last for a maximum of between 100 to 200 years. As crops require the input of fertilizer to thrive, alternative sources to phosphorus must be investigated, and human urine has the potential to substitute a portion of it.

Through a literature review of relevant papers, important information and data has been collected to propose an alternative sanitation system involving urine diversion and vacuum collection of blackwater and food waste. Thanks to these systems, water savings, nutrient recovery and energy production are carried out to achieve more sustainable outcomes. An example case study has been performed, and while its results involve a certain level of uncertainty, its conclusions are positive.

This case study was carried out inspired in a precinct that could be similar to Central Park Sydney, as the city of Sydney is expected to suffer a demographic change, with an estimation that its population will grow from 4 to 6 million people in 20 years. This growth can make the city face a struggle to build and expand systems to meet the increased demands, so the efficiency of these systems must be improved. The proposed sanitation system has the potential to save and produce massive amounts of resources.

In the future the trend can be routed towards the implementation of decentralised sanitation and reuse of wastewater for nutrient recovery, water saving and energy production through alternative sanitation concepts.

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