Sustainable utilisation of human urine in urban areas - practical experiences

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Abstract

After several years of research on utilisation of nutrients in human urine an opportunity to build and use a greenhouse aquaculture demonstration plant appeared in the new science centre Universeum, in Göteborg, Sweden. The challenge for this project is to recycle all the nutrients in urine collected from the staff and the public visiting (over 600 000 visitors after first year) and to demonstrate its value as nutrient with different eco-sanitation technologies on site. The nutrients (N and P) are collected by the use of 26 urine-sorting toilets (estimated 100-300L urine per day, 50% diluted). Part of the urine is treated directly by the aquaculture food chain (algae-zooplankton-fish), another part will be mineralised by chemical precipitation (struvite) and adsorption to minerals (zeolites). The main part of the urine is to be spread in agriculture. This multiple use of the source-separated urine favours a sustainable recycling of nutrients in urban areas and also demonstrates the usefulness of human urine as a nutrient source for the visitors. Furthermore, any eco-toxicological concern by its use can be directly investigated in the aquaculture food chain on site, opening possibilities for interesting research projects in the future. This paper will present a brief description of the site, the ongoing projects, and some practical experiences.

Introduction

The Universeum science centre

Universeum science centre located at Korsvägen in Göteborg, Sweden, was inaugurated in 2001 (Wallin, 2002). The science centre is an educational platform and an excellent forum to tempt youngsters (in ages between 7-19 years old) to develop a better understanding and a direct experiment of sciences by visiting this building (Ervik, 2003).

In the business plan for Universeum, demonstrations of science and technology from an ecological perspective was emphasised and the building was identified as a resource for communicating this perspective. Environmental ambitions were developed into system requirements. During the design process, a reference group of researchers gave advice on goal settings, system design and specific details (Wallin, 2002).

Figure 1: The Universeum exterior autumn 2001, view from the main entrance.
Photo Zsofia Ban.

Ecological engineering and the wastewater system

Ecological engineering was defined in 1971 by Howard T. Odum as the management of nature for human use (Odum, 1971). The synthesis between ecology and technology (eco-technology) requires a combination of basic and applied research as well as interdisciplinary teams for its proper application (Jensen et al, 1992; Mitch, 1991). Because of the complexity of nature a broad professional knowledge is required when creating ecological engineering systems.

After the Brundtland convention (1987), and environmental meetings (e.g. Rio, 1992) fundamental terms as "Agenda 21 ", "life cycle assessment" and "recycling", are stated and widely acknowledged, which has focused the practical local action on new technical developments towards local system for wastewater treatment. This has lifted environmental issues to a higher priority in decision-making processes, and also brought fundamental thinking on local scales to all levels in the society, people are involved. The future work with sustainable development in Sweden is following 15 environmental goals (http://www.environ.se). One of these goals is "A sea in balance and living coast and archipelago" around Sweden. This goal is especially important for urban areas producing enormous amounts of wastewater and discharging large amounts of nutrients to water recipients through wastewater treatment plants operating today as well as leakages of nutrients from agricultural areas, transported by rivers.

The discovery of nitrogen as a major cause of eutrophication, especially in the marine environment, has intensified the research on nitrogen removal from sewage water. Further demands on nutrient removal cause treatment plants to be rebuilt or extended (Mattsson, 1997). More than eighty percent of the nitrogen in sewage water from households originates from human urine (Adamsson, 1999). Therefore, source separating of urine could be a complement to decrease nitrogen discharge to estuaries.

Four aspects need to be considered for wastewater treatment methods (Jenssen et al 1992; Jonasson 1993):

- health aspects,
- recipient aspects,
- cost efficiency aspects and
- recycling aspects

By using separating systems, the nutrients could be used as a resource directly after toilet disposal and appropriate hygienic stabilisation (i.e. storage) and thereby reduce the nitrogen load in incoming water to coastal sewage plants. The value of human urine as fertilizer or soil conditioner in agriculture is well known in Sweden (Jönsson et al., 2000; Johansson, 2000). However, its use can be controversial regarding different stages of urine management (storage, transports, spreading and overall aspects of hygiene). In recent years, research made at Göteborg University have shown that nutrient recovery in crystalline form to obtain a slow-release soil conditioner known as struvite Mg (K, NH4)(PO_4) •6H2O] can be an ecologically and environmentally desirable way (Ban, 1998; Lind, *et al*.,2000). Human urine could also be used in an aquaculture approach (Adamsson, 2000). After several years of research on utilisation of the nutrients in human urine in a constructed food chain (Adamsson, 1999), the possibilities for demonstrating this technique became a reality at Universeum Science centre.

The objectives of this paper are (1) to describe the technique of aquaculture and the initial research on crystallisation based on sorted human urine from Universeum, (2) to share some practical experiences from the operating toilet system at Universeum and (3) to discuss if new techniques like collecting of urine and crystallisation (struvite) could be a solution for sustainable utilisation of human urine in urban areas.

Methods

Collecting urine

The majority of the nutrients (N and P) are collected by the use of 26 urine-sorting toilets (system called "Dubletten", developed by Bibbi Innovation & Co AB, see Figure 2). The front bowl is connected to a separated pipe, which collects urine into two storage tanks (volume of 6 m^3 each). The back bowl is flushed to ordinary sewage system and the sewage plant for Göteborg city, with exception of 7 toilets on the personal floors. The faeces from these 7 toilets are connected to a sludge separator (3 chambers with a total volume of 12 m^3) and this effluent could be used in the aquaculture or be transported to the ordinary sewage system.

The total urine volume collected per year is estimated by number of visitors and a dilution factor of 50% (about 1.2-1.5 dl flushing volume according to the manufacturer of the toilet, see http://www.dubbletten.nu/english-presentation/WCdubbletteneng.htm).
Chemical and microbiological analysis have been made on the urine from the storage tanks by using a water-lifter (small plastic container on a wooden stick) directly placed into the manhole of the tanks, filling a glass bottle (1 L), which were transported in a cool box (+4 C) directly to an accredited laboratory.

Figure 2: The toilet used at Universeum. Picture taken by Marie Adamsson.

The aquaculture-principals

The diluted urine is pumped from storage tanks to a blender (about 50L) in the water treatment centre (aquaculture). From this blender the solution flows by gravity to four cylinders (1 m^3 each) which contain microscopic algae (i.e *Scenedesmus acuminatus*). Using photosynthesis, these algae assimilate the nutrients from the urine. The overflow of algae runs to each of four separated 1 m^3 large concrete aquaria (replicates), were the algae are eaten by zooplankton, water fleas (*Daphnia magna*). The aquaria also contain a plastic microbial substrate (1m * 0,7m * 0.1m) with a pore size of about 0.1-10 mm, which is aerated. The function of this is to be a holder of an attached nitrification bacteria community. The water containing water fleas flows by gravity down to a 6 m^3 (water volume) large tank with small tropical fish (Guppy). These fishes fed on *Daphnia* sp. and are in turn harvested to become food for larger fish in some of the other aquaria in the building. The water runs down to a series of small pools were water plants are cultivated. Not only these plants, but the roots of the rainforest trees are able to take up nutrients which still remain in the water. Then the water is returned to the blender by a pump. In the blender, new urine is added. The water flows round in its own circular system, which is technically operated only by a dosage station of urine and the pump station in the final pool. Biomass production of zooplankton has been recorded as well as pH, dissolved oxygen, total nitrogen, ammonia, nitrate and nitrite to follow and monitor the nutrient flow and locate functional problems within the system during one month the first year (Barone, 2002). Urine from the storage tank in the aquaculture has also been sent to chemical and microbiological analyses.

The struvite process and mineral adsorption

By adding small amounts of magnesium oxide (MgO) to human urine most of the phosphorous (95-99%) and part of the nitrogen (20-50%) can be recovered as a precipitate. Crystalline struvite was the major component of the precipitate, which also contained montgomeryite, brucite and epsonite. Additional mineral adsorption steps improved the nitrogen recovery. Natural zeolites and wollastonite showed excellent adsorbent qualities in contact with ammonia solutions as well as in tests with human urine (Ban, 1998). When struvite crystallisation and mineral adsorption was combined 64-80 % of the nitrogen (as ammonia) was recovered together with 95-99% phosphorus (Lind *et al*., 2000).

The experiments with Universeum urine were based on the combination of two steps:

a) dephosphatisation using different amounts of MgO for struvite crystallisation

b) mineral adsorption using different amounts of zeolite for improved nitrogen removal.

Human urine was collected from the urine tanks at Universeum and transported immediately in closed plastic cans to the laboratory for testing. The urine was directly used for the experiment, without freezing or further storage. The mineral zeolite (with high clinoptilolite content and a grain size of 1,2-2 mm) was used in its natural form. The contact time of the experiment was 72 h at room temperature (20 ^{0}C). A short, manual stirring was made once daily. After 72 hours the supernatant was decanted and analysed for total-P and total-N. (Spectrophotometer DR 4000, Hach-methods 3036 and 2558).

Results

Sorted human urine at Universeum

Collecting system: Since these systems are new, some technical problems could be expected, but there are also some problems related to preliminary construction (compared to traditional water flushing toilets). This has caused problems for the maintainers and cleaning staff at Universeum during the first year. Due to educated and interested staff at Universeum, these toilets have, in spite of non-optimal design, been well maintained and are, in most cases, appreciated by the visitors. There are areas in the building that are more critical than others (i.e. more visited) like the entrance hall, where in high seasons, almost continuous cleaning by staff is necessary. This was not always possible, which has lead to some complains from visitors of odours and blockages of the front bowl (paper jam, etc.).

Nutrients in collected urine: Total N varies between 2-6 g/L in collected urine (see Table 1). The reduction of *E.coli* in stored human urine occurs within a few days. Therefore, also other indicator organism should be used when evaluating hygienic risks from sorted human urine prior to its use as nutrient source (Jönsson, 2000; Höglund, 2001).

Parameters	Method	Unit	1	2
pH	SS 028122-2.Titro		9.2	8.7
BOD (7)	SS 029143-2	mg/l	1200	290
COD (Cr)	Hach	mg/l	2100	1200
Total Phosphorous	TRAACS	mg/l	130	150
Ammonium-N	TRAACS	mg/l	2300	2700
Total Nitrogen	TRAACS	mg/l	2200	2700
Heterotrophic bacteria, 20 C, 2d	SS 028171-1	cfu/ml	>300000	>300000
Coliform bacteria, 35 C	SS 028166-1	cfu/100ml	>160000	<2
E. coli	SS 028166-1	cfu/100ml	>160000	<2
Cadmium	ICP-MS	mg/l	< 0.0004	<0.0004
Potassium	ICP-AES	mg/l	840	930

Table 1: Chemical and microbiological observations from two samples of sorted human urine (about 50% diluted by flush water) at Universeum, Göteborg Sweden. Sample 1 is taken directly from the incoming water to the storage tanks. Sample 2 is taken when the urine enters the blending tank in the aquaculture. This means that the urine in sample 2 has been stored further for at least 1 week at 26 ± 2 ºC.

Research in laboratory scale and small greenhouse system (Adamsson, 1999; Adamsson 2000) showed that *Scenedsmus acuminatus* and *Daphnia magna* can grow and reproduce with human urine as the nutrient source and a reduction of nutrients thorough the aquaculture system is possible with for 36-97% nitrogen and for phosphorous with 67-98%. The initial results from the first 18 month operation of the Universeum system have shown that the critical step is the zooplankton production. This is probably mainly due to high temperature, low food quantity (lack of light for photosynthesis) and ammonia toxicity (Adamsson, not published; Barone 2002). Therefore, a full evaluation of the production and reduction capability in this pilot scale system is yet to be discovered. An initial study based on one month performance of the plant (Barone,2002), indicated that the nitrogen concentration of 1000 mg /L in the sorted urine were reduced to 3 mg/L after the aquaculture steps, and the major part of nitrogen was in form of nitrate, indicating that both nitrification and nitrogen reduction was efficient. One aim is to increase the urine concentration in the blender to produce more algae to improve *Daphnia* production. This must, however, be combined with acceptable pH value in the system to decrease the risk for ammonia toxicity to *Daphnia*.

The struvite process and mineral adsorption

The addition of MgO increased the initial pH value from 8,9 to 9,3. Total-N and total-P reduction after addition of small amounts of MgO respective zeolite to human urine is shown in Figure 3 and 4.

Nitrogen reduction:

a) The tot-N reduction from human urine is highly dependent of the amount of MgO added and of the stoichiometric conditions for *struvite* precipitation. Urea decomposition (availability of ammonium ions) is a pH dependent process. However, the urine used in this experiment was stored in collector tanks for several weeks and most of the urea was already decomposed in ammonium-ammonia form. MgO addition increases the urine pH to 9.0 -9.3 and the availability of nitrogen for struvite formation.

b) The nitrogen uptake by *zeolites* depends on the ion exchange property of the mineral, the amount used, the grain size and contact time. The clinoptilolite type of zeolite used here has good ammonium absorbent capacity. Struvite precipitation itself slightly reduces the pH of the urine and during the adsorption process to the zeolite a competition occurs between H-ions and NH_4-ions for the exchange sites in the mineral structure.

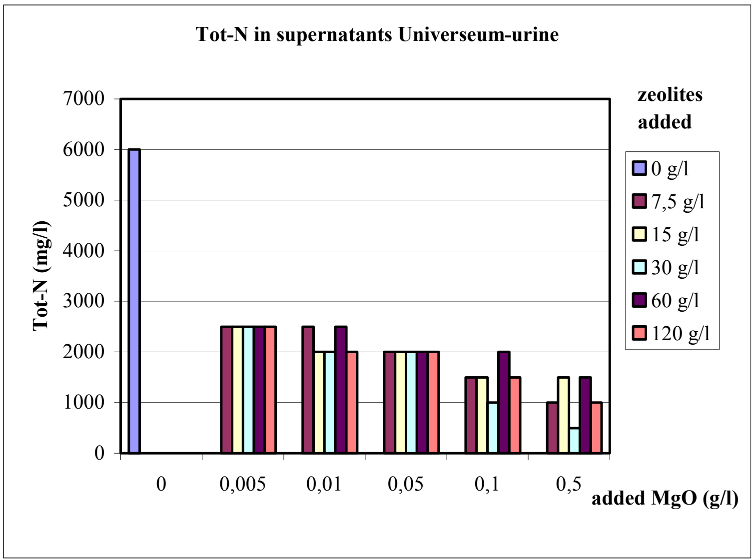

Figure 3: Total-N reduction in urine from Universeum.

Phosphorus reduction:

a) The stoichiometric ratio, Mg:P is 1,71: 2,21 for *struvite* precipitation for urine containing 0,89 g P/l. According to our experiments 0,5 g MgO per litre urine is sufficient to get a tot-P reduction of 95-98%.

b) The natural *clinoptilolite type of zeolite* has also a good tot-P adsorption capacity in contact with human urine. This process is mainly due to the possibilities for chemisorption on the very porous structure of this mineral. The grain size of the mineral and contact time with the liquid is also important.

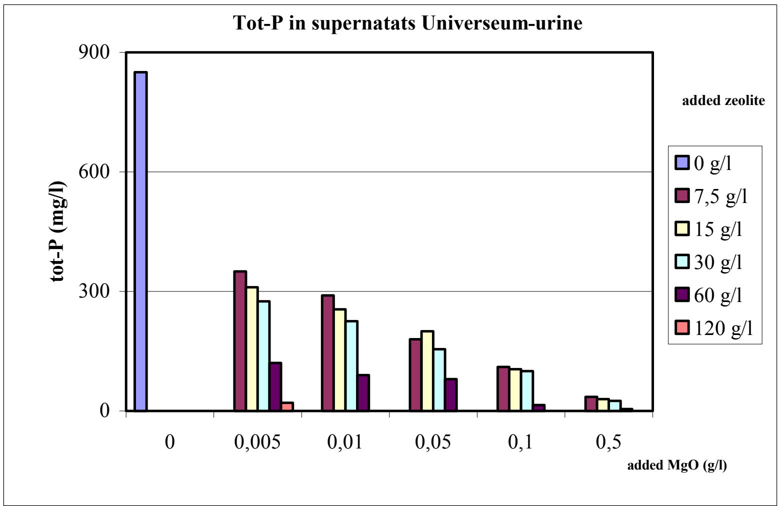

Figure 4: Total-P reduction in urine from Universeum.

Previous test results with combination of struvite precipitation and further ammonium uptake by zeolites have also demonstrated a 64-80% ammonium uptake along with a 98-100 % phosphorus uptake from human urine (Lind *et al*., 2000). Process optimisation at Universeum is in progress.

Discussion

Wastewater is a resource and should therefore be treated as such. However, its use has important hygienic aspects that has to be considered. The aquaculture technique is perfect as a demonstration pilot plant and for educational purposes regarding understanding the scientific background behind eutrophication, and the aquaculture could also be used for research on bioaccumulation and biomagnification of different elements on the organisms living in these aquatic environments. But the aquaculture technique as such has no future as a commonly used wastewater treatment on its own, unless perhaps in combination with other techniques. The most realistic and interesting approach on utilising the nutrients in human urine in urban areas is, therefore, simple collection in storage tanks installed as a complementary to the existing sewer system. The urine fraction can then be transported to farmers to close the loop between farmlands and urban areas. This transport could be environmentally improved by using the struvite process and in this way decreasing the water transport and improving the P transport per km, allowing transports further away from the source. Therefore, we are looking forward to construct a pilot plant of this technique at Universeum in the near future. Cost-efficiency calculation for the struvite precipitation and mineral adsorption method in pilot scale or larger utilisation is not made today. The research is still at an experimental level, mostly at laboratory scale, and a holistic approach including a system evaluation is necessary (life cycle assessment).

Modern society will certainly continue to have large-scale wastewater plants that were constructed during the 70ths and forward for many years to come. This is not a question of either having large, conventional systems or small scale systems, to meet the future demand on sewage treatments. This is about how to use the best technologies in combination to fit the needs and to recycle materials in an as environmentally friendly way as possible in order to reach a sustainable society for coming generations, and also considering aspects of what is accepted from the users point of view.
This multiple use of the source-separated urine from one facility demonstrates a sustainable recycling of nutrients in urban areas and it also demonstrates the usefulness of human urine as a nutrient source for the exhibition visitors. Furthermore, any eco-toxicological concern of its use can be directly investigated in the aquaculture food chain on site, opening possibilities for interesting research projects in the future.

The most important is, therefore, to bring in focus and discuss the question of how we should have built our society today, with our new knowledge of recycling and reuse of materials combined with experiences on wastewater treatment at larger and smaller scales in order to build a sustainable future for coming generations.

Conclusions

- Urine sorting and crystallisation technique could improve the utilisation of human urine in urban areas. Life cycle assessments should be used prior to implementation of this technique in new and existing areas.

- Problems related to preliminary construction of the toilets should be further examined by constructors to improve the system for users and maintainers.

- The Universeum ecological wastewater system is a demonstrating plant and a research site, situated in an educational environment visited by millions of people from all generations. This is a valuable place to initiate discussions and debates on future sustainable utilisation of human urine and wastes from urban areas in general.

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