AN AUSTRALIAN FIELD STUDY OF SOURCE SEPARATED URINE.

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ABSTRACT

Urine is rich in plant available nitrogen (N), phosphorus (P) and potassium (K). Urine separating toilets were installed in residences at a new sustainable development in the Gold Coast hinterland. The collected urine solution (urine + flushwater) contained sufficient concentrations of ammonium-N (2,260 mg N /L), P (172 mg/L) and K (484 mg/L) to be a useful liquid fertiliser. About 150 litres/month/person of urine solution was generated. A further benefit of urine separation is the reduction in energy cost at the sewage treatment plant due to the large reduction in N and P loads from the wastewater stream. Issues of concern include the high salinity and sodicity of separated urine, which needs to be carefully managed to prevent plant toxicity in irrigation areas. Microbial loadings and micropollutants will also need careful monitoring to ensure human and environmental safety when using separated urine in cropping systems. Substantial gaseous N loss is also likely to occur unless the application process is carefully managed.

INTRODUCTION

Urine separating toilets (UST) separate solids from the liquid by using a specially designed toilet that has two bowls in the one pan (Figure 1). The urine is collected and stored separately for later use. UST have been used in Northern Europe for at least a decade, with recent trials demonstrating the value of urine as an important supplement/alternative to liquid fertiliser (Jönsson 2004, Larsen and Lienert, 2007).

Water, energy and nutrients are three key areas that need to be addressed to implement sustainable development in both rural & urban areas. In agriculture, the macronutrients used in greatest quantity are nitrogen (N), phosphorus (P) and potassium (K) and their availability is usually seen as the limiting factor in agricultural production. As the world supply of economically viable sources of P and potassium are dwindling, alternative sources are being sought. Dery and Anderson (2007), argue that world production of phosphate rock has already peaked and reserves are in decline, a situation that is alarming in view of the expected impending spike in global demand for food. Further, global potassium production (from potash mines) is also reaching a peak supply situation as finite geological sources are becoming exhausted over the next 4 to 5 decades. Urea, a widely used N fertiliser, on the other hand is manufactured from fossil fuels such as coal or natural gas (using the Haber-Bosch process) and is usually transported large distances from the point of production, increasing both cost and the contribution to greenhouse gas generation. The manufacture of urea requires at best 37 MJ (10 kWhr) of energy per kg of N utilising natural gas (Wisenbach et al 2003, Beal et al 2008).

Another potential benefit of urine separation is energy saving by removing N and P from the wastewater stream. Significant energy is expended at the sewage treatment plant in removing these nutrients (about 13 kWh/kg, Maurer et al 2003), often in biological nutrient removal (BNR) systems. Moreover, BNR plants often require the inputs of additional chemicals such as methanol or molasses to provide carbon for the denitrification process.

The consumption of food by humans is analogous to intensive rural industry, such as a feedlot, with the nutrients consumed in food being largely excreted unless there is an increase in animal biomass. Mass balance studies in Europe suggest that the average adult excretes about 1.5-3.8 kg N, 0.4 kg P and 1kg K each year, which is equivalent to the same mass of nutrients in 200 kg wheat. The average adult excretes around around 1.25 L of urine each day and this accounts for approximately 80% of the total excretion of N, >50% of P and 70% of the potassium (Johanssen et al.,2000; Maurer et al., 2003). However, the most common N compound in human urine is urea and it is the biologically moderated breakdown products of urea that provides the ammonium ions that can be a valuable substitute for manufactured urea in agricultural production.

$$CO(NH_2)_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^- \quad (1)$$
(*urea*)

$$NH_4^+ + OH^- \leftrightarrow NH_3(aq) + H_2O \quad (2)$$
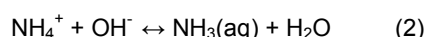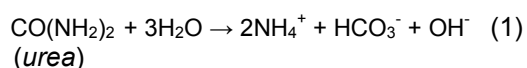
From Jönsson, 2004

This hydrolisation process is dependent on the pH of the solution, with the reaction very much favouring the right hand side of reaction 2 at pH greater than 9, which frequently occurs in urine. However, there is also equilibrium between dissolved and gaseous ammonia that is dependent on temperature and partial pressure of ammonia in the atmosphere above the solution as shown in reaction 3.

$$NH_3(aq) \leftrightarrow NH_3(gas) \quad (3)$$
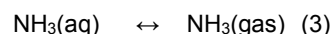
from Jönsson (2004).

Urine separation would be expected to be particularly suitable for decentralised

developments such as the Ecovillage at Currumbin which has communal treatment of sewage for around 110 of the 144 detached dwellings. Energy and water saving at this development is particularly important as it aims to achieve near zero draw from the water and electricity grids by using large rainwater tanks for potable supply, recycled water for toilets and external water use, photovoltaic electricity generation, solar hot water systems and thermally efficient houses. To progress the research, the Queensland Department Natural Resources and Water (DNRW) approached the Ecovillage residents, with a proposal for them to participate in a trial of 20 urine separation toilets (Beal *et al.*, 2008).

MATERIALS AND METHODS

The first UST installation occurred in October 2007 and the toilet was in regular use by November 2007. Further installations occurred throughout 2008 as residences were constructed and the second toilet was commissioned in November 2008. Three more toilets were commissioned in December 2008 but insufficient time has elapsed at the time of writing for collection of samples from these installations.

The urine separation toilets were Gustavberg units that were selected on a number of criteria to maximise the benefit of urine separation. These include a low flush volume mixing with the urine, lack of specialised moving parts and compatibility with Australian plumbing fittings (Beal *et al* 2008). The toilets were connected to 300 L polyurethane storage bladders via 50 mm polyethylene pipe (as per figure in Appendix). Polyethylene fittings were used to minimise scaling problems which can occur when using metal pipes, and also to comply with Body Corporate building covenants. Sufficient fall (1:50) was incorporated in the collection pipes to allow the urine solution to drain freely to the storage vessel. The flush is dispersed in a normal manner through a flush rim that encircles the entire pan circumference. The cisterns are dual flush systems of 2/4 litre volume.

Figure 1 A wall mounted Gustavberg urine separating toilet at an Ecovillage home.

The urine solution (urine + flush water) was sampled at intervals that coincided with bladder pump-outs by vacuum truck, usually at 5-6 weeks intervals. Three replicates of the separated urine were collected and taken in refrigerated containers to the DNRW Chemistry Centre laboratories at Indooroopilly, Queensland. Measurements of pH and electrical conductivity were recorded in situ at the time of sampling using calibrated meters. The samples were analysed for total N, total Kjeldahl N (TKN), ammonium, nitrates, nitrites and total P. The urine solution was also analysed for the concentrations of the cations potassium, sodium, calcium and magnesium and this allowed the calculation of the sodium adsorption ratio (SAR). The laboratory is a NATA accredited laboratory and all analyses used standard methods as described in APHA (1998 and 2005). The volume of flush water entering the bladder was calculated by counters that recorded the inputs from two cistern mounted magnetic proximity switches that recorded the number of full and half flushes. The toilet flushes were calibrated to determine the volume of flush water that entered the urine separation plumbing. Volumes were 200 mL for a half flush (2L), and 400 mL for full flush (4L). The volume of flush water and total pump out volume allows the volume of raw urine collected to be calculated which is important to allow nutrient mass balance calculations per capita.

RESULTS and DISCUSSION

Nutrients

The results obtained to date relate to two USTs with four different sets of residents over a period of twelve months. The storage bladders were emptied prior to each new set of tenants. The variation between the seven sampling events was substantial (Figure 3 and Appendix Table A). The dominant form of N present in the storage was ammonium with an average concentration of 2,260 mg N/L with a range between 1,100 mg N/L and 3,200 mg N/L. Nitrates and nitrites were present at a combined average concentration of 52 mg N/L. The TKN concentration was 2,440 mg N/L (vs 2,260 mg/L of ammonium-N) indicating only a small amount of organic N still present in the solution. These results are as expected as urea is microbologically hydrolysed and promoted by the alkaline conditions that accompany the reaction (eqn. 1). However, anoxic conditions do not favour the conversion of ammonium to nitrate.
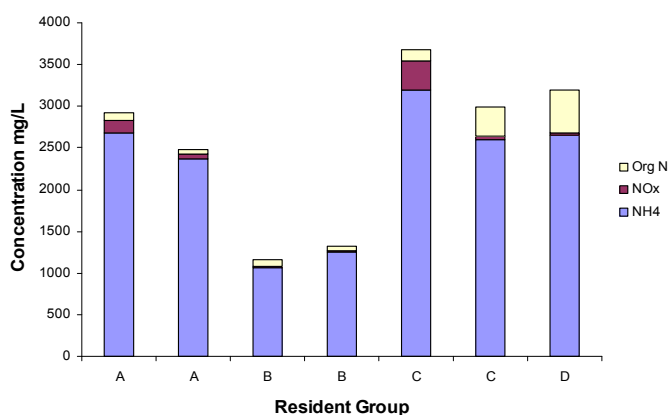

Figure 3 Comparison of the N concentrations of the separated urine at Ecovillage residences.

The average (total) P concentration was 172 mg P/L and varied between 75 and 296 mg P/L. Concentrations of the major cations in fresh urine were included for comparison (Table A in Appendix). Calcium (Ca) (8 mg/L) and magnesium (Mg) (<0.5 mg/L) concentrations are two orders of magnitude less than sodium (Na) (576 mg/L) and K (484 mg/L) concentrations, but display less variation between sampling events. The sodium adsorption ratio (SAR) of 55 was averaged over all sampling events. The pH of the stored urine solution remained strongly alkaline and consistently averaged 9.0, whilst the average electrical conductivity was 15,000 μScm^{-1} (about 9,000mg/L TDS).

Urine as a fertiliser

The N available from the urine solution at the Ecovillage was around 3 kg/person/year based on the average concentrations and the generation of urine solution to date. The comparison between the measured values in urine from the Ecovillage, and the crop requirements for producing 200 kg of grain is shown in Table 2. These values show that while N and K requirements may be adequately supplied by the urine solution, P nutrition for this crop may be deficient.

Table 2 Nutrient loads and crop requirements for wheat. (Beal *et al.* 2008)

Nutrient	Urine solution kg/p/yr	Nutrients (kg) contained in 200 kg grain
N	3.1	4.5
P	0.2	0.6
K	0.7	1.0

In comparison with other commonly used nitrogenous fertilisers such as anhydrous ammonia or urea (Table 3), urine solution may provide a viable alternative whilst limiting N losses through volatilisation. Most of the high concentration fertilisers are applied only once or twice throughout a cropping regime and significant N losses, can occur due to volatilisation, denitrification and leaching below the root zone (CSIRO 2006). Therefore by applying a relatively small quantity of N frequently throughout the growing season will improve the availability of N and better match the N demand of the crop for the whole season. This also more closely matches the generation pattern of the urine solution which is generated constantly. Table 3 illustrates the availability of N for a range of different fertilisers.

Table 3 N percentages of fertilisers and separated urine.

Nitrogen fertiliser	Percentage N
Anhydrous Ammonia	82
Aqua Ammonia	20
Urea	46
Urine solution	0.5-1

From CSIRO 2006

The incorporation of N into the soil for the different fertilisers is dependent on a number of factors including soil conditions, climatic factors and management practices. Anhydrous and aqua ammonia are applied directly to the subsoil through tines and their retention relies on a combination of soil moisture, and cation exchange capacity. However, if conditions are less than optimum, ammonia can be lost readily to the atmosphere. Urea can be applied either to the subsoil or surface broadcast (to pasture) where rapid hydrolisation occurs even with dewfall , leading to substantial volatilisation loss, which

often approaches 50% of total N applied (CSIRO 2006).

Urine solution, on the other hand, can be applied on the surface or subsurface, as the N is already in solution as ammonium ions and other nutrients are immediately available to the crop. Small applications applied frequently will assist in limiting losses of nutrients through natural processes such as; volatilisation of ammonia gas, denitrification by soil microbes, and leaching of salts and nutrients by rainfall and irrigation. This approach concurs with advice for most crops that frequent small applications of fertilisers during the growing season will improve yields compared to single application of the same total quantity of N fertiliser (CSIRO 2006). Comparison with a range of common commercial liquid fertilisers (Figure 4) demonstrates that the separated urine solution is much higher in total N compounds than the strongest of the liquid fertilisers diluted to their recommended concentrations (Kele *et al*. 2007) although P and K values are similar. Experiences of researchers in Europe using separated urine as a fertiliser have shown that yield from crops fertilised with urine are similar to yields from conventional fertilisers. The practices of fertilising once prior to planting and then harrowing; or fertilising throughout the growth season appear to show similar yield results in grain crops (Johanssen *et al*. 2000).
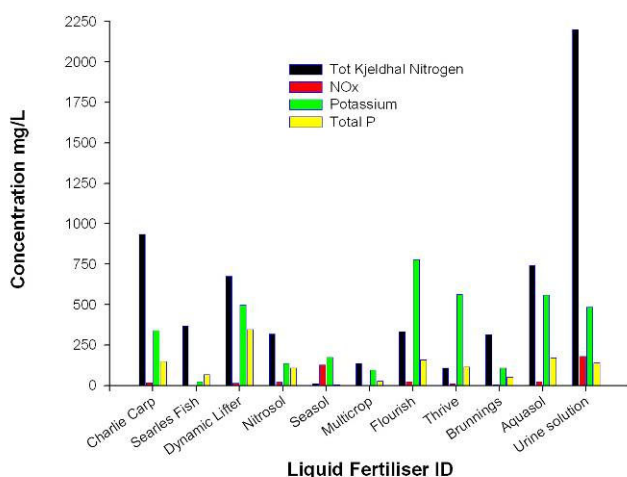

Figure 4 Comparison of urine solution with commercial liquid fertilisers (from Kele *et al.* 2007)

Not withstanding the nutrients available in separated urine, significant challenges exist for widespread reuse of urine solution. For example, the production of urine is the dominant means by which the body excretes excess salts, therefore the salinity of urine is high. The diluted urine in this study (urine and flush water) has an electrical conductivity of 15,000 μScm^{-1}, which is about a third of that of seawater and a sodium concentration of around 575 mg/L. The average

SAR of the stored urine solution was 55, which is much higher that the 5 to 10 value that causes concern in soil aggregate stability in irrigated agriculture. This would be considered too high to use the solution for irrigation, however, the urine is not proposed as the only irrigation source. Small frequent doses followed by adequate irrigation appears to be the most appropriate method to utilise urine as a fertiliser and a pot experiment to test this idea is being setup to begin in the autumn of 2009.

Struvite precipitation

A further challenge in the management of separated of urine is that phosphorus and N in hydrolysed urine can precipitate as struvite, $MgNH_4PO_4.6H_2O$ (Gethke *et al*. 2007), particularly if metal piping is used in the collection system. Precipitates may cause serious blockages in the collection pipe and has been often reported in the European studies (Udert, 2007). In our study, 50 mm polyethylene piping and fittings have been used to transport the urine solution from the toilets to the storage, and this has minimized the adverse flow consequences of precipitation. For example, Figure 5 shows struvite deposits on the internal walls of a collection pipe at the Ecovillage, and no significant reduction of flow was evident after 12 months of use. Solutions that may be employed to clear blocked collection pipes were a 10% citric acid solution or to pour boiling water into the urine well.

Figure 5
Struvite deposits in the urine collection pipe after 12 months of use.

Struvite precipitation also may have occurred in the storage bladders as cloudiness of the solution has been noted on one sampling occasion. Evidence of this was supported by the very low concentrations of Mg and Ca ions (Table A Appendix), when compared to the equivalent values expected for raw urine after its dilution to bladder concentrations (i.e. about 1:1). This suggests that these cations precipitated as phosphorus compounds (struvite and

hydroxyapatite) although the total formation of struvite will be limited by the concentration of Mg and Ca present in the urine and flush water (Udert *et al* 2007). The use of the vacuum pump-out vehicle to empty the bladder will assist in the removal of precipitates. Not withstanding the blockage issues, struvite is considered to be a slow release fertiliser. Hence, provided it is collected with the urine solution, it can be reincorporated into the food production cycle. The commercial analogue of struvite is the common bulk fertiliser, magnesium ammonium phosphate which is the non-hydrated form of the struvite mineral.

Pathogens

The popular belief that urine is a sterile fluid is incorrect as both pathogens and benign micro-organisms occur in urine. These organisms can include the normal enteric microflora such as *Escherichia coli* and *enterococci* spp., dermal bacteria like S*taphylococci* spp., and opportunistic pathogens such as Chlamydia and a range of viruses. However, it is more likely that pathogens, including enteric viruses, will occur from cross contamination from faecal matter (Jönsson, 2001). Hence, some form of disinfection will be needed to ensure that the users and the products are protected from microbial infections. Studies conducted in Europe have shown that urine can be effectively sanitised by storage for a period of six months at an average temperature of 10º C. However, there is also evidence that shorter storage treatment periods are possible at higher temperatures (STOWA, 2002). Our study proposes to test this response by conducting a microbial die-off trial using the urine and measuring the survival of a range of spiked bacteria and viral indicators under a range of incubation temperatures and ammonia concentrations. The goal of the study will be to quantify the log reduction of pathogens using a simple storage technique (20 kL tanks) that requires no inputs of chemicals or energy, in line with the environmental aspirations of the community who will both provide and use the raw material.

The experiment has begun and will continue over a number of months to determine the die-off kinetics and log reduction-time relationships for various urine samples spiked with the phage MS-2 (a virus surrogate), a bacterial indicator (*Escherichia coli*) and a protozoan surrogate (*Clostridium perfringens*). This experiment will determine the log reduction needed for a range of end uses to meet the health risk standard (1 micro DALY) specified by the Australian Guidelines for Recycled Water (2006). Early indications (Figure 6) have shown that the *E. coli* populations have completely died off within 7 days at two different temperature regimes that are expected to be

similar to summer average tank temperatures (35º and 25ºC) at the Currumbin Ecovillage. The result of these studies will allow a recommendation on storage protocols which are expected to be a series of 20 kL polyethylene rainwater tanks.
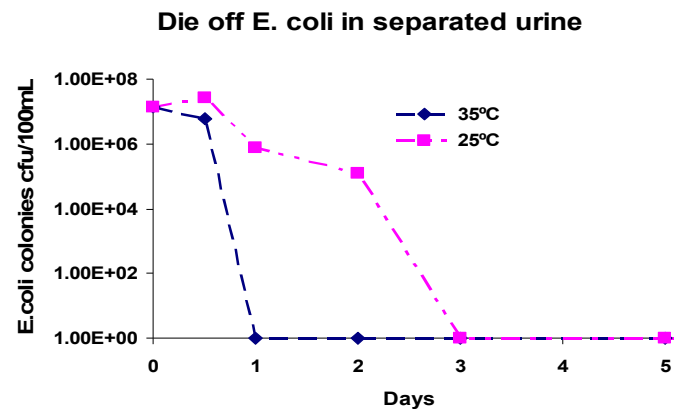

Figure 6 Dieoff of *E. Coli* in separated urine from the Ecovillage at Currumbin (Ahmed, 2008 personal communication)

Micropollutants

Measurement of micropollutants such as pharmaceuticals and endocrine disrupting compounds in the urine solution is another potential component of this study. Lienert and Larsen, (2007), Pronk *et al. (*2006) and Escher *et al.* (2006) have conducted recent studies in Europe on pharmaceuticals in separated urine. They all agree that these chemicals can provide a barrier to the implementation of the reuse of urine unless adequate controls and strategies are in place. For example, Lienert and Larsen (2007), report that up to two thirds of all excreted pharmaceuticals are passed in urine, although the route of excretion (urine vs. faeces) is dependent on the individual compound (Figure 7).
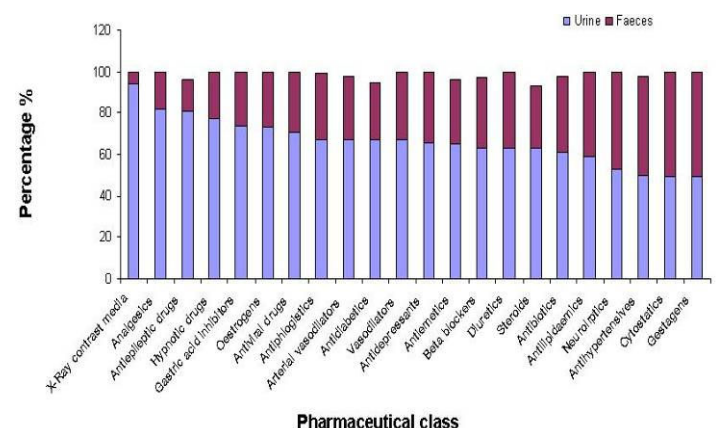

Figure 7 Excretion pathways of the major pharmaceutical groups. From Lienert and Larsen 2007

Common agents such as highly halogenated X-ray contrast media are passed almost entirely in urine while erythromycin, a common antibiotic, is passed mainly in faeces. The effects of these chemicals on the majority of Australian aquatic species are not known, so the authors believe that a precautionary attitude is preferable to responding to an adverse effect. Further treatment of these trace contaminants also occurs in the soil profile through oxidation in aerobic conditions, adherence to soil particles and breakdown by soil microorganisms (Dantas, 2008) limiting their potential for off site impacts.

Social acceptance

The residents at the Ecovillage who have used the toilet have indicated that their acceptance of the urine separating toilet has been very favourable to date. However, recently one user has reported odour problems which appear to occur from ammonia diffusion through the walls of the bladder coinciding with low ambient wind speed. We suspect that at least some of the problem is due to high urea concentration as the toilet is efficient enough to use the half flush to remove solids, and the residents take pride in their frugal water use. We are exploring solutions to this problem, which include changing the type of bladder material, acidifying the bladder to prevent urea hydrolysis, to venting the bladder to atmosphere (which unfortunately will promote ammonia loss).

CONCLUSION

There are several benefits of urine separation and the reuse of the solution. Separated urine is rich in plant available forms of nutrients such as N, phosphorus and potassium. Reusing a product that is normally considered a waste can lead to energy savings in both the production of these nutrients and in their removal from wastewater streams. Careful engineering of urine separation and storage systems can reduce the unpleasant aspects associated with this product (especially odour) and gaseous losses of N. Other barriers, such as microbial contamination requires the users to be aware of the risk of using human physiological wastes, but solutions are being actively sought to enable the safe reuse of separated urine. A remaining challenge is the small but possibly significant amount of micropollutants such as pharmaceuticals and their metabolites.

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Sample	Units	1	2	3	4	5	6	7	Mean	Urine*
Tot N	mg/L	2927	2483	1153	1318	4014	3186	2989	2495	9200
TKN	mg/L	2787	2440	1143	1300	3333	3150	2950	2443	-
NH$_4$	mg/L	2683	2377	1068	1250	3197	2650	2600	2260	581
NOx	mg/L	140	43	10	19	80	36	39	52	-
Total P	mg/L	170	150	75	87	211	296	214	172	720
Ca	mg/L	6	9	10	8	9	8	5	8	170
Mg	mg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	100
Na	mg/L	685	744	393	407	623	700	485	575	2200
K	mg/L	608	456	344	355	656	896	829	484	3300
SAR	nil	72	65	33	37	54	66	56	55	33
pH	nil	8.7	9	9.3	9	9	9	9	9	6.2-8.2
Elec. Cond.	µScm^{-1}	17000	17000	8200	9700	20230	16720	13240	15005	~27,000
Volume	L/pp/day	4.7	2.9	2.4	3.8	1.9	1.6	2.0	2.7	1.25

Figure A. The 300 L urine storage bladder (full) under the residence showing the urine collection pipe and the reinforced vacuum pumpout hose for emptying the bladder.