CLOSING THE NUTRIENT LOOP: A URINE-SEPARATION AND REUSE TRIAL IN THE CURRUMBIN ECOVILLAGE, QLD

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ABSTRACT

Urine-separating toilets (UST) have been used as an effective means of separating the urine from faeces in many parts of Europe for years, but are yet to be adopted as a viable technology in Australia. The purpose of UST is to separate nutrients (N, P, K) at the source. Although up to about 80% of N, 50% of P and 60% of K are contained in urine, its volumetric fraction of total wastewater flow is only around 1%. By first separating the urine, many nutrients can be captured and reused without intensive, expensive and time-consuming treatment required when urine is combined with faeces. Urine can be reused as a concentrated fertiliser with only limited treatment prior to land application. The aims of this paper are to report on the use of UST technologies in Europe and to describe the initial stages of a urine diversion and reuse demonstration project at a high-profile Ecovillage under construction in Currumbin, southeast Queensland.

Keywords: source separation, urine diversion, sustainable development, nutrient recovery, urine reuse

1 INTRODUCTION

Urine-separating toilets (UST) have been used as an effective source control measure in many parts of Europe for years, but are yet to be adopted as a viable technology in Australia. Recent advances in water conservation and recycling technologies have allowed for a greater opportunity to close (*e.g.* recycle) the water balance, particularly with decentralised systems. However, closing the loop on nutrients for these systems has been a much more difficult task, largely due to the existing systems that collect, store and treat nutrients and water in combination. UST separate nutrients (N, P, K) at source to avoid mixing with faecal matter. Urine separation reduces water use and nutrient discharge to treatment systems and the receiving environment, and increases the potential for closing the nutrient cycle. UST technology ranges from single and dual flush systems to dry (composting) toilets. This paper provides a background on UST and the reuse of urine in Europe, then describes the urine separation demonstration project at The Ecovillage at Currumbin.

2 BACKGROUND ON URINE-SEPARATION

2.1 Advantages of Source Separation

Although up to about 80% of N, 50% of P and 60% of K are contained in urine, its fraction of total volumetric wastewater flow is only around 1% (Figure 1). The purpose of UST is to separate nutrients (N, P, K) at the source, to avoid mixing with faecal matter. The urine can then be reused as a concentrated fertiliser with only limited treatment prior to land application. By separating the urine, many nutrients can be captured and reused without intensive, expensive and time-consuming treatment traditionally required when urine is mixed with faeces. Urine separation can reduce the peaks flows of ammonia in sewage treatment plants (STP) by 30% and reduce the impact of sewer overflows on the aquatic environment (Wilsenach and Loosdrecht 2006).

Although N is abundant in the atmosphere, its industrial fixation is energy and resource intensive. Urine provides a ready source of fixed nitrogen that can be recycled back into the system (via land application, crop uptake and crop consumption). The main source of P is via extraction of phosphate rock, of which there is a critical global shortage. The P in urine can be made bioavailable by the relatively simple process of struvite production. Another advantage of UST is their lower water use. Johansson *et al.* (2002) report about 0.1 to 0.3 L of water is required to flush the urine. This is a reduction of over 90 % per flush compared with a half flush from a standard 3/6 dual toilet. For a solids flush, the volume ranges from 2 to 6 L.

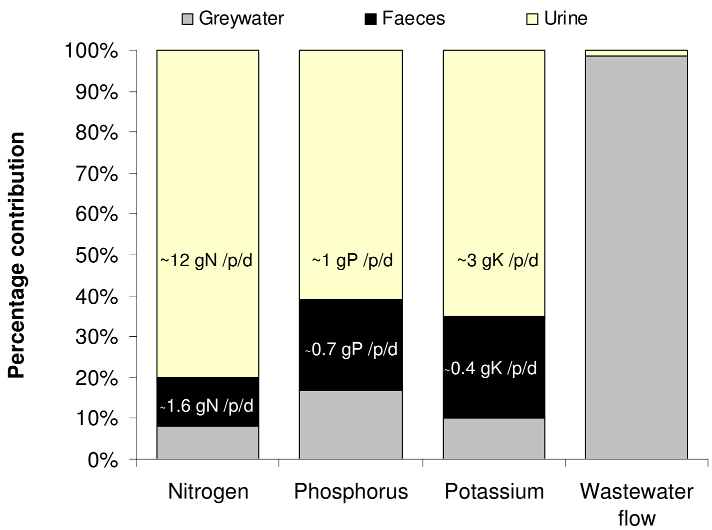

Figure 1. The percentage of nutrients in various wastewater components (Johansson et al. 2002).

Finally, energy consumption required for nutrient removal at STPs can be markedly reduced by source separation technology. The reduction in energy costs at the STP of treating a lower nutrient wastewater can be significant.

One study reported that wastewater having >60% urine separated can result in a net production of energy at a STP (Wilsenach and Loosdrecht 2006). Life cycle analyses of different removal and recovery technologies for nutrients indicated source-separation can be energetically more efficient than either their removal at the STP or new production from natural sources (Maurer *et al*. 2003). For example, specific energy requirements for denitrification and precipitation at a STP are 13 kWh/kg N and 14 kWh/kg P, respectively (Maurer *et al.* 2003). Furthermore, traditional fertiliser production requires specific energies of 13 kWh/kg N and 8 kWh/kg P (Maurer *et al.* 2003). In comparison, the specific energy used for thermal reduction of urine is about 10 kWh/kg (Maurer *et al.* 2003). Struvite production (producing available P for fertiliser use) from separated urine uses only 6 kWh/kg P (Maurer *et al.* 2003).

2.2 Pathogens

In healthy humans, urine is pathogenically sterile in the bladder (Johansson *et al.* 2002; Kvarnström *et al.* 2006). Freshly excreted urine normally contains different dermal bacteria. The most commonly found pathogens excreted in urine of patients are *Salmonella typhi*, *Salmonella paratyphi*, *Mycobacterium tuberculosis*, polyomaviruses, hepatitis B viruses and adenoviruses. If cross-contamination with faecal matter occurs using a UST, bacteria and viruses may be present in the urine. However, such pathogenic microorganisms transported through urine are not considered a public health risk as research on separated urine demonstrates that optimal storage conditions of high pH, high temperature (e.g. >20ºC) for ≥ 6 months will effectively render the urine solution sterile (Johansson *et al.* 2002) as shown in Table 1.

TABLE 1. The relationship between storage conditions, the pathogen content of the urine solution and recommendations for crops in larger systems[A] (Source: Johansson *et al*. 2002).

Storage temperature	Storage period	Type of pathogens in the urine mixture[B]	Recommended crops
4°C	≥ 1 month	Viruses, protozoa	Forage and food crops to be processed
4°C	≥ 6 months	Viruses	Food crops to be processed, forage crops[C]
20°C	≥ 1 month	Viruses	Food crops to be processed, forage crops[C]
20°C	≥ 6 months	Probably none	All crops[D]

[A]"Larger systems" in this case means that human urine is used to fertilise crops that are consumed by persons other than the members of the household where urine is collected, [B]Gram-positive and sporulating bacteria are not included, [C]Except grassland for the production of animal feed, [D]In the case of food crops consumed raw it is recommended that fertilisation with urine be discontinued at least one month prior to harvesting and that the urine is incorporated into the soil

Storage conditions (time and temperature) to achieve adequate treatment depend on the type of crops that the urine will be applied to. Johansson *et al*. (2002) developed a general table showing the relationship between storage conditions and pathogen concentration in urine (Table 1). The end use of the urine will affect the potential exposure to humans, and thus determine the degree of disinfection required. These same principles are articulated in the draft Australian Guidelines for Water Recycling Phase 2 (NRMMC, EPHC & AHMC).

The typical concentrations of *E. coli* in collected urine can reduce by > 6 $\log_{10}$ within a week of storage and thus is not a good microbial indicator for assessing faecal cross-contamination (Höglund *et al*. 1998). Large numbers of faecal streptococci can be found in source separated urine because of growth within the collection pipe (Schönning *et al.* 2002).The performance of *C. perfringens* has also been assessed as an alternative faecal indicator but clostridia are not commonly excreted by population. However, quantification of faecal sterols (*e.g.* coprostanol) has been shown to be a viable alternative (Schönning *et al.* 2002), although this will not allow for enumeration of the microbes, *e.g.* obtaining a concentration. Another potential microbial indicator is *Bacteroides* spp., which has several advantages, including short survival rates outside the hosts, exclusivity to the gut of warm-blooded animals, and constitutes a larger portion of faecal bacteria compared to faecal coliforms or enterococci (Sghir *et al.,* 2000).

2.3 Heavy metals

Heavy metals are low in urine solutions from UST (Jönsson *et al*. 1997; Vinnerås *et al.* 2002). Cadmium (Cd) associated with the extraction of P from low-grade phosphate rock can typically result in concentrations of 20 to 50 mg Cd / kg P in fertilisers (Jönsson *et al.* 1997; Larsen *et al.* 2001). This concentration can expected to be substantially reduced when using urine as a fertiliser, *e.g.* < 5 mg Cd / kg P (Jönsson *et al.* 1997). Heavy metal contamination of urine can also occur from the corrosion of metal pipes and storage tanks due to the high pH and high ammonia content. Therefore metal should be avoided anywhere in the urine collection and transport system.

2.4 Pharmaceuticals

A major metabolic pathway for hormones and pharmaceuticals is excretion via urine. Exposure to (natural and synthetic) hormone and pharmaceutical residues from wastewater reuse is a growing concern. There is currently a knowledge gap regarding the risk of exposure from land application of urine, although Johansson *et al.* (2002) suggest that the environmental risk is less than that from traditional STPs (where discharge to waters is common). Kvarnström *et al.* (2006) also point out that urine and fertilisers are mixed into the active topsoil, which has a microbial community comparable to that in STPs where substantial removal or inactivation of residues can occur (*e.g.* Watkinson and Costanzo, *in press*). Additionally, the residues can be retained and degraded for months in the topsoil, further reducing the likelihood of transmission into plant material via plant uptake.

Notwithstanding the above, in complex chemical mixtures such as urine, threshold values are very problematic to set and research indicates that environmental and human toxicological effects of pharmaceuticals may be additive (Maurer *et al.* 2006). Lienert *et al.* (2007) report a > 50% removal of pharmaceuticals from the wastewater stream by separating urine from faeces, thereby reducing the ecotoxicological risks in the aquatic environment. However, the risk from urine application to soil for use as a fertiliser on food crops remains uncertain.

3 URINE SEPARATION & REUSE DEMONSTRATION PROJECT

3.1 Site Description and Project Overview

The Ecovillage at Currumbin (the Ecovillage) is a 144-lot development on a former 110 ha grazing property in the Currumbin Valley, in the Gold Coast region of southeast Queensland (http://www.theecovillage.com.au). A core philosophy behind the design of The Ecovillage is one of sustainable living, where minimal impact on the environment and maximum conservation and/or recycling of resources is achieved. The goal of sustainability extends to all components of the development, including water and nutrient management, road layouts, materials use (*e.g.* recycled materials), energy management, systems management and housing thermal standards. The Ecovillage is intended as an inspirational model to the development industry and the broader community. In line with this, a demonstration project managed by the Queensland Department of Natural Resources and Water (DNRW) is trialling the use of urine-separating toilets as a sustainable and achievable method of nutrient capture and water conservation and on-site reuse. The DNRW will manage the project with close liaison with developers Landmatters Currumbin Valley Pty Ltd and design engineers Bligh Tanner Pty Ltd and. There are two stages to the project: STAGE I – Demonstrating the practicality of the UST principle and STAGE II – Beneficial reuse of urine.

The objectives of the project will be to (1) demonstrate the advantages of separating nutrients such as nitrogen (N), phosphorus (P) and potassium (K) at the source for subsequent reuse as a concentrated form of fertiliser; (2) quantify the water savings and recovery / person of nutrients that are achieved by UST; and (3) demonstrate to the urban development, local authority, and state regulatory sectors that urine-separation and reuse can provide a safe and sustainable alternative to traditional wastewater treatment management solutions. Results from urine monitoring will be used in mass balance calculations for nutrient, water and energy fluxes from the instrumented households. This information is essential in determining the 'ecometabolism' of a house and provides a quantitative assessment of its sustainability and ability to close the loop on nutrient cycling.

3.2 Urine selection and installation

There are several types of UST on the market in Europe, but none currently in Australia. For the project, urine-separating flush toilets rather than urine separating dry composting toilets have been chosen. It is believed that flush toilets will make the concept more appealing to potential participants and any retrofitting of standard toilet units are easier, if required. The common types of flushing UST are shown in Figure 2.

Figure 2 Examples of urine-separating toilets (a) Roediger No Mix; (b) & (e) Gustavsberg Nordic 393U; (c) WC Dubbletten; and (d) Wost Man Ecology WM-DS.

Based on the lessons learnt from Swedish demonstration trials (*e.g.* Johansson *et al*. 2002; Vinnerås *et al.* 2002) and the desired outcomes from this trial, the UST was selected based on the following criteria:

- Easy to clean and low flush for urine;
- Urine u-bend accessible and allow for 'mechanical snake' to clear any blockages;

- Bowl should allow for men to stand up during urination, otherwise they may avoid using the toilet correctly;
- System should contain no metal (unless stainless steel) in contact with the urine; and
- Comfortable and easy to use with low odour potential.

The UST selected for the project was the Gustavsberg unit (Figure 2b,e) based on expert advice (*e.g.* Nick Ashbolt, Ralf Otterpohl, Håkan Jönsson), cost, and the ability for men to stand up while using this unit without excessive urine loss through splashing. This is an important criterion from both a hygienic (spillage) and nutrient recapture point-of-view. The Gustavsberg toilets were shipped over from Germany through the supplier Berger Biotechnik (www.berger-biotechnik.de).

3.3 Urine Collection and Storage

There are twenty UST available for the trial (assuming one UST installed per household). A reoccurring problem with the UST identified from long-term Swedish research projects is blockages in the u-bend of the urine pipe and toilet seals. It is believed that these blockages are largely due to crystalline precipitates (calcium and magnesium ammonium phosphates) on hair and toilet brush bristles within the toilet seals and on pipe walls. It is important that the pipes be designed to be easily accessible for the use of a 'mechanical snake'.

At each household, the diverted urine will be collected via a separate non-metal pipe from the UST into a 300 to 500 L flexible bladder tank. The volume of urine solution generated will equate to about 350 L per month assuming 3 people per household and 4 L urine solution /p/day.

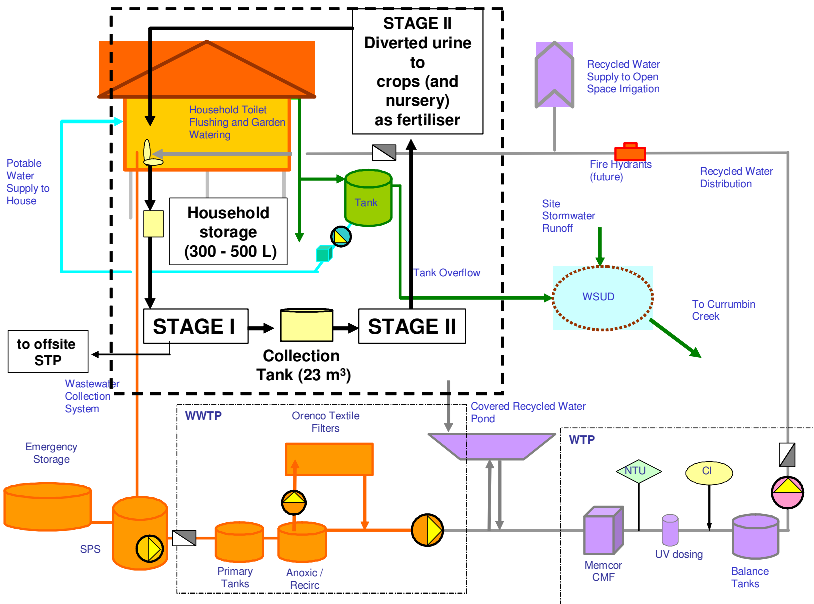

Figure 3 Integrated water management schematic at The Ecovillage with proposed urine separation scheme (adapted from Bligh Tanner Pty Ltd 2005).

The UST generates 0.5 L / flush, by 5 flushes plus 1.5 L of urine / day. Each household storage container will be emptied monthly by a pump-out truck and transferred to a communal storage facility. The communal storage is a 23,000 L polyethylene rainwater tank giving a capacity of at least 2 months urine storage assuming 20 USTs in operation. Disposing of the stored urine during Stage I of the project (no reuse) will involve trucking the urine offsite to a local STP. A schematic of the proposed urine separation scheme is shown in Figure 3, which includes the unique rainwater/recycled water hydraulic circuit at the Ecovillage. Based on the lessons learnt from Swedish demonstration trials (*e.g.* Johansson *et al.* 2002) the following was considered in the design of the collection and storage of urine:

- Watertight pipes and tanks and no metal used for pipes and tanks in contact with urine;
- Horizontal pipes should have a slope of $\geq 1\%$ as sludge continuously precipitates from the urine mixture (although easy to flush away);
- Pipes should be able to be easily inspected; and
- System should not be ventilated (to minimise ammonia loss and odour).

Odour problems have occurred due to poor design and where installations are not watertight. In projects where the UST are properly connected to the pipe system, these problems have not occurred. When connected and operating properly, residents from Swedish studies report that the odour problems in connection with UST do not appear to be greater than with other toilets.

3.4 Urine Monitoring Programme

There will be two main elements to the monitoring programme: biophysical monitoring (*e.g.* water, nutrient and pathogen mass balances) and social monitoring (survey of participant behaviour and attitudes). Both these elements together will provide an overall assessment of the efficiency and applicability of the UST, and the likely adoption of similar projects in the future. Additionally, given the absence of such data in Australia, it is hoped that monitoring results here will provide a baseline database for future urine separation trials. Results from urine quality and quantity monitoring will be used in mass balance calculations for nutrient, water and energy fluxes from the instrumented households. Studies in Sweden suggest that the recovery of nutrients at the source can range from 50 to 100% depending on several factors including correct use of bowl, ammonia losses and leakages during collection and storage. Monitoring components include:

- Monthly collection and analyses of urine solution (flush water plus urine) for N, P, K, and pathogens;
- Field experiments investigating pathogen die-off in urine overtime;
- Social survey of the behaviour and attitudes of users and the likelihood of adopting the technology in the longer-term; and
- Possible analyses of some common pharmaceuticals and their fate in stored urine.

3.5 On-site Reuse of Urine

To maximise the benefits of nutrient capture and close the nutrient loop, the reuse of urine as a plant fertiliser is the most desired outcome. Nitrogen occurs in the form of urea in urine, which will readily hydrolyse to ammonia when diluted in water. In this form, it is quick-acting and can be compared with a high mineral content fertiliser (*e.g*. anhydrous ammonia), as opposed to a slow release manure-type fertiliser where the N is organically bound. The average mass of nutrients excreted in the urine compared with the requirements for grain production is presented in Table 2. The average adult excretes sufficient nutrients in their urine to grow enough wheat to produce a loaf of bread a day, for each day of the year.

TABLE 2 Estimated nutrient loads and crop requirements for wheat (values for nutrients from STOWA, 2002)

Nutrient	Urine kg/p/yr	200 kg grain
N	4.4	4.5
P	0.4	0.6
K	1.0	1.0

The reported barley yield from a urine reuse field study in Sweden using an application of ~ 80 kg N/ha corresponded to 85% of that from yields fertilised with 90 kg of manufactured mineral fertiliser (Johansson *et al.* 2002). The same study found small differences in nitrogen uptake efficiency between urine and mineral fertilisers. Crop N uptake for urine fertiliser (containing 98 kg N/ha) ranged between 44% and 70% of the N applied. In comparison, crop N uptake for mineral fertiliser ranged between 61% and 83% (Johansson *et al.* 2002).

There are several options for urine reuse at the Ecovillage. These include land application on crop area such as food crops (seasonal applications) and forage crops for mulch supply (*i.e.* cut and cart); application on public use land and park (*i.e.* landscape); use in the nursery as a fertiliser; land application on dedicated area, *e.g.* in the Stage 2 of the research project; and off-site reuse as a fertiliser to farmers who directly supply the Ecovillage.

Although the cropping areas have not yet been fully established at The Ecovillage, it is proposed to grow fruit trees and other crop varieties yet to be determined. To determine the initial feasibility of using urine as a fertiliser in the cropping areas, estimates of areas required for uptake of urine fertiliser were calculated (Table 3). The use of 4 L per person/day of urine mix includes a percentage of toilet flush water, which ranges from 0.1 to 2 L for most UST.

TABLE 3 Estimated nutrient loads and crop requirement data assuming 3 people per household and 100% use of UST

Crop	kg N/hh/yr[A]	N uptake (kg/ha)[B]	Area (m^2) required / hh[C]	Area (ha) required for 20 hh
Rice	8.6	150 - 200	≤ 300	≤ 0.60
Corn	8.6	135 - 225	≤ 200	≤ 0.40
Grasslands	8.6	200 - 400	≤ 215	≤ 0.45

[A] Assuming 0.008 kg N per person / day
[B] Based on nutrient uptake rates reported in Reid (1990)
[C] Assuming 50% plant uptake efficiency

The method of applying urine solution to land is important, as significant amounts of ammonia can be lost from the solution due to volatilisation. Spraying is not recommended as it maximises ammonia loss, aerosol production and odour. In Sweden, it is common for tank wagons or tractors, equipped with a pump, to be used to spread urine solution using trailing hoses or tynes. Application times should coincide with crop growth periods and should take into account the potential of some crops to burn easily if ammonia is applied on the plants themselves. Chloride (Cl) and sodium (Na) salts also need to be considered in any urine reuse scheme, as they can be present at typically high concentrations. Nutrient uptake rates in turf and crops can be adversely affected by salinity (*e.g.* EC of urine/water solution ~ 1 to 3 dS/m). *Guidelines for the Use of Urine and Faeces in Crop Production* (Jönsson *et al.* 2004) will be used as a guide for establishing protocols for urine reuse during the project. A urine reuse management plan will be prepared and implemented, in consultation with Queensland Health and the Gold Coast City Council.

3.6 Consultation and Decommissioning

Consultation with Queensland Health, Gold Coast City Council, the Environmental Protection Agency, Department of Local Government, Planning, Recreation and Sport, and Gold Coast Water has been undertaken. All aspects of the project must meet relevant statutory requirements (e.g. EPA regulations) and guidelines, which are listed in the Site Based Management Plan for The Ecovillage (Bligh Tanner Pty Ltd 2005). Implementation of the UST project may require ministerial exemption under the relevant legislation as a temporary research project.

A Heads of Agreement has been drawn up between DNRW, Landmatters Pty Ltd, The Ecovillage Body Corporate and Bligh Tanner Pty Ltd. In essence, this covers the roles and responsibilities for each party both during and after the project lifetime. At the completion of the project, if desired, retrofitting with a standard toilet unit will be at the cost and responsibility of DNRW. At the end of the project any new participants who choose to use UST will do so at the cost and responsibility of themselves and the Body Corporate. On completion of the project, irrespective of the outcomes, the Body Corporate will be responsible for the ongoing maintenance of the UST, storage and urine reuse scheme.

4 CONCLUSIONS

An Australian-first project where twenty urine separation toilets will be trialled at The Ecovillage at Currumbin is underway in southeast Queensland. Urine contains the most concentrated source of N and P in human wastewater and can be reused beneficially as a liquid fertiliser. Life cycle assessment of UST indicates that substantial energy savings at the STP and from reduction in fertiliser manufacture can be gained from separating urine at the source.

The objectives of the Ecovillage project are to quantify the recovery per person of nutrients that are achieved by UST, explore the reuse alternative for urine and gauge the social acceptance of UST. The first stage of the project will look at the practical aspects of UST, such as plumbing challenges (wall mounted v floor mounted), blockages, odour, storage and pumping. The social acceptability of the UST will be closely documented through monthly diaries and quarterly interviews / questionnaires. The project will also explore the safety of urine reuse through pathogen die-off experiments. This will assist in determining the appropriate level of treatment, i.e. disinfection, prior to reuse as a fertiliser. Concentrations of *E. coli* in collected urine can reduce by > 6 $\log_{10}$ within a week of storage and are not recommended as a good microbial indicator for assessing faecal cross-contamination. A potential microbial indicator that may be used is *Bacteroides* spp. Pharmaceutical analyses may also be undertaken to characterise the concentration of pharmaceuticals in the urine and their fate during storage. The second stage of the UST project will focus on the potential crop production on-site from urine fertiliser. Swedish studies have shown that urine fertilisers can achieve at least 85% of that from yields fertilised with manufactured mineral fertiliser. Urine reuse options at the Ecovillage include land application on cropping areas, and use in the nursery as a fertiliser. During the lifetime of the project DNRW will be responsible for the ongoing maintenance of the UST, storage and urine reuse scheme. At the completion of the project, the Ecovillage Body Corporate will assume this responsibility.

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