Valorisation of Urine Nutrients

Promoting Sanitation & Nutrient Recovery through Urine Separation

Final Project Report 2015

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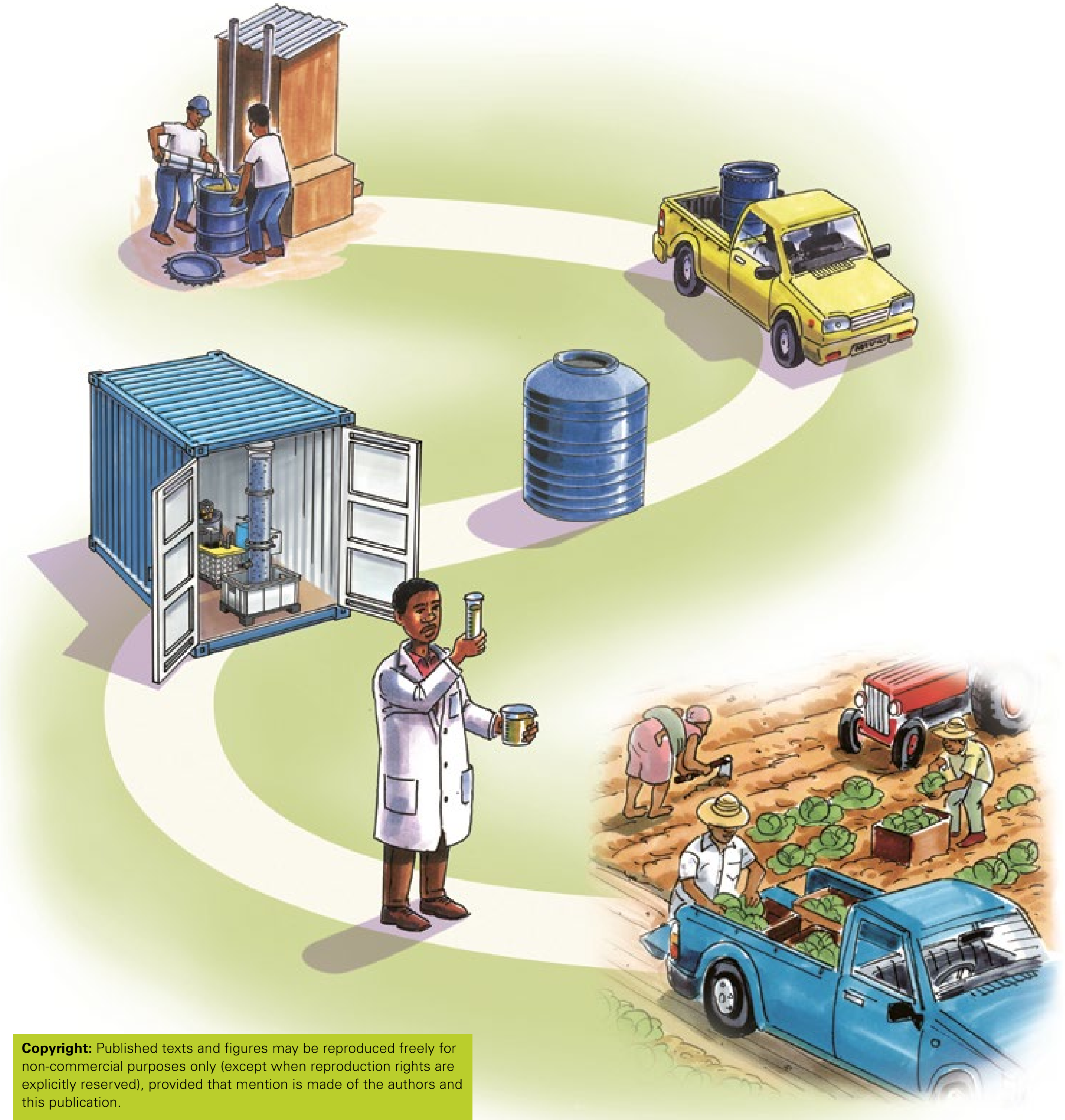

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VUNA—An Introduction

Promoting Sanitation and Nutrient Recovery through Urine Separation

Urine diversion in Durban

In 2002, the eThekwini Municipality–encompassing the greater Durban area–introduced urine-diverting toilets to the under-serviced communities inside the city's recently extended metropolitan boundaries. This was a part of its overall strategy to provide sanitation for all citizens. Urine-diverting dry toilets were chosen because providing a pipe network and a treatment system for enormous supplementary volumes of sewage would have been prohibitively expensive and impractical due to the hilly landscape. At the beginning of the campaign, urine was not collected but instead was infiltrated into the ground directly at the toilet. To date, about 82 000 urine-diverting toilets have been installed in eThekwini. Although urine-diverting toilets met the Municipality's criteria for sanitation and sustainability, many users were not satisfied with the new technology, due to the emptying burden that was placed on the householder. Furthermore, infiltrating urine into the ground risked polluting groundwater, lakes, and rivers.

Nutrient recovery to promote sanitation

In 2010, Durban's water utility, eThekwini Water and Sanitation (EWS), teamed up with Eawag to develop a new and improved sanitation system that allows for nutrient recovery from urine in order to promote sanitation. Eawag has a long-standing, successful record of research on nutrient recovery from urine in both low-income contexts (e.g. STUN Project, www.eawag.ch/stun) and in high-income countries (Novaquatis Project, www.novaquatis.eawag.ch).

Figure 1: Urine collectors measure and record the collected urine volume before they pick up the yellow jerry can from a urine-diverting toilet in eThekwini.

Figure 2: Complete nutrient recovery–one of three nutrient recovery plants built by the VUNA Project operates in Eawag's basement. The two other plants recover nutrients from urine in Durban.

The project described in this report had three basic objectives:

- Promote the use of toilets by giving urine a value;
- Produce a valuable fertiliser;
- Protect the environment by reducing pollution.

The project was named VUNA, which means "harvest" in the isiZulu language, but which also stands for "Valorisation of Urine Nutrients in Africa". By bringing together science and practice, the partners aimed to develop the technologies and managements tools necessary for the large-scale implementation of nutrient recovery from urine in Durban and other cities facing similar sanitation challenges.

A trans-disciplinary team for a novel system

In order to cover the many specialist aspects of a novel sanitation system incorporating nutrient recovery, the project team (p. 36) had to involve several research institutes. The Pollution Research Group (PRG) at the University of KwaZulu-Natal (UKZN) provided the scientific resources and expertise for the field studies conducted in Durban. The studies on using incentives to promote urine collection were conducted by the Centre for Development and Cooperation (NADEL) at the Swiss Federal Institute of Technology in Zurich (ETHZ). The Environmental Chemistry Laboratory (LCE) at the Swiss Federal Institute of Technology in Lausanne (EPFL) investigated the pathogens occurring in urine and their inactivation during treatment. During the course of the project, the Plant Nutrition Group at the ETHZ, and the School of Agricultural, Earth and Environmental Sciences at the UKZN, also joined the team in order to investigate how the end products performed as fertilisers. Furthermore, at the UKZN, the School of Agricultural, Earth and Environmental Sciences, and the School of Nursing and Public Health, supported our research on social acceptance and health education.

Figure 3: At the Newlands-Mashu Field Test Site, multiple nutrient recovery technologies can be tested under realistic conditions. Besides the urine treatment plants, the containers host an analytical laboratory and a field office.

Technologies for nutrient recovery from urine

Much of the research in VUNA focused on the treatment processes for recovering nutrients from urine and the quality of their final products. The first of the three basic processes investigated was struvite precipitation (p. 14), a simple procedure for phosphorus recovery. This process had been tested in previous projects and was quickly implemented; however, most of the nitrogen and virtually all other nutrients remain unrecovered. The second process investigated was complete nutrient recovery (p. 6) by combining nitrification (p. 8) and distillation (p. 10). This process is more complex, but it recovers practically all the nutrients in one concentrated solution. The third process was electrolysis (p. 12), which can be used for very small on-site treatment units when nutrient removal, rather than nutrient recovery, is the primary goal of treatment. Efficient treatment processes are crucial for quality fertiliser products. In particular, the treatment must remove any harmful substances, such as pharmaceuticals (p. 18) or pathogens (p. 20), and ensure good availability of the nutrients (p. 22).

More than just technology

Turning urine from waste into a valuable product requires more than just technology. First of all, urine must be sourced and transported. This means that urine-diverting toilets must become accepted by the population, that urine collection is organised in an efficient and reliable way, and that the overall system is economically viable. We tested two basic urine collection schemes in the field. In an institutionalised scheme (p. 24), municipal workers collected urine in jerry cans from households. In the incentivised scheme (p. 32), toilet users were compensated with monetary incentives when they dropped off their urine jerry cans at local collection points. Using computer models (p. 26), we aimed to minimise the costs for both collection schemes. Estimates of urine treatment costs and fertiliser sales revenue became the input data for a business model (p. 34). User surveys assessed the acceptance (p. 28) of the urine diversion concept and, especially, the toilets. An inadequate understanding of the rationale behind urine diversion was often the reason for low acceptance rates for the toilets. Furthermore, we developed interactive health and hygiene education methods (p. 30) to improve the acceptance of urine diversion and of sanitation in general.

Scaling-up nutrient recovery programmes

The VUNA Project covered the multiple aspects of developing and implementing a novel sanitation system incorporating nutrient recovery from urine. A first pilot system was set up in eThekwini and today further up-scaling is planned. The challenges of expanding from a pilot scheme to a full-scale programme lie firstly in the collection logistics and management, which strongly influence the system's costs. Secondly, the urine treatment plants require reliable process control (p. 16) to ensure the continuous production of high quality fertilisers. Finally, acceptance by the toilet users themselves must increase. Overall, the project has received a lot of attention from researchers and practitioners in South Africa, Europe and around the world. In fact, the Swiss Federal Office for Agriculture recently granted a license for the fertiliser produced using the VUNA Project's complete nutrient recovery process. This is another valuable endorsement for VUNA's nutrient recovery process–harvesting urine from a sanitation system, reducing environmental pollution and turning waste into a valuable, marketable product.

Figure 4: The fertilisers produced by the VUNA technologies can be directly tested on the fields at the Newlands-Mashu Test Site in eThekwini.

Peter Penicka, Eawag

The nitrification and distillation plant in Eawag's basement is one of three pilot plants producing liquid fertiliser from urine.

Complete Nutrient Recovery

The All Nutrients Solution

- **Three pilot plants produce fertiliser from urine in Switzerland and South Africa.**
- **Careful process control ensures stable nitrification.**
- **Biological nitrification successfully prevents malodour and nitrogen loss.**
- **The combination of nitrification and distillation concentrates all nutrients into one final product.**
- **Besides fertiliser, treatment plants produce distilled water.**

From theory to laboratory testing

The biggest part of the valuable nutrients excreted by the human body is found in urine. Researchers have tested various technologies to extract these nutrients and produce fertiliser. However, most of these technologies aim to recover specific nutrients, meaning that the majority remains in the effluent. Complete recovery is an alternative approach: instead of removing nutrients, water is removed, and nutrient loss is minimised. Distillation is an optimal water removal process (Distillation, p. 10). However, the urine must first be stabilised in order to prevent the most important nitrogen compound–ammonia–from volatilising, which causes environmental pollution and malodour. Biological nitrification is a resource-efficient process used to stabilise nitrogen (Nitrification, p. 8). We previously tested this process in Eawag's laboratory and succeeded in adapting nitrifying bacteria to the high nutrient concentrations found in urine. After this basic proof of concept, we designed and built pilot plants in order to gain practical experience of the process at a realistic scale.

VUNA pilot plants

The first pilot plant was installed in Eawag's main building, near Zurich. Urine was collected using urine-diverting toilets and waterless urinals. Approximately 100 litres of urine were collected per working day for use in fertiliser production. Based on the pilot plant, we built two further plants in eThekwini, South Africa: one at a field test site in Newlands-Mashu and one at the eThekwini Water and Sanitation (EWS) Customer Care Centre in Durban. The pilot nitrification plants consist of one or two plastic columns, each holding 120 litres of liquid. The columns contain suspended plastic biofilm carriers that support the

Figure 1: Plastic biomass carriers provide support for the nitrification bacteria.

Luzius Etter, Adyessa

Figure 2: Bacteria in an aerated column stabilise the urine before the liquid is evaporated in a distiller.

growth of the nitrification bacteria (Figure 1). Stabilised urine from the nitrification columns flows into an intermediate storage tank, from where batches of solution are fed into the distiller. The distillation process concentrates the urine–and its nutrients–into a concentrated nutrient solution. Distilled water leaving the process is the sole by-product: it contains only traces of organic compounds and less than 1 % of the urine's total nitrogen.

Figure 3: eThekwini's Customer Care Centre in Durban produces its own fertiliser from urine.

Table 1: The final fertiliser product contains all necessary nutrients for plant growth. The urine was sourced from the women's urine tank at Eawag's main building. With other urine sources, the nitrogen content can be a factor two higher.

Ion	Concentration
Nitrogen (N)	50 g/L
Phosphorus (P)	2.1 g/L
Potassium (K)	15 g/L
Sulphur (S)	1.6 g/L
Calcium (Ca)	0.4 g/L
Magnesium (Mg)	0.04 g/L
Iron (Fe)	0.5 mg/L
Copper (Cu)	0.3 mg/L
Zinc (Zn)	15 mg/L
Boron (B)	16 mg/L

Continuous fertiliser production

A nitrification plant takes between 45 and 60 days to start up. During this time, the bacteria–taken from a conventional wastewater treatment plant–must adapt to the very high nitrogen and salt concentration in urine. After this phase, the bacteria in the pilot plant transform between 400 and 800 mg of nitrogen from ammonia into nitrate per litre of plant volume per day. At Eawag, urine typically has an ammonia concentration of 1 800 mg/L (as nitrogen), meaning that 50 litres of urine can be treated each day. After biological treatment, the nitrogen is stable in solution (due to the combined effects of a reduction in pH and nitrate formation). There is no malodour caused by ammonia and organic compounds, and all the nutrients (nitrogen, phosphorus, potassium, sulphur, and numerous micronutrients) remain in the solution. In the ensuing distillation process step, 97 % of water is removed. Potential pathogens are killed because the solution is heated to 80 °C for at least half an hour.

Ensuring high process stability

Three years of pilot plant testing proved that the process was suitable for complete nutrient recovery from urine. Moreover, we were also able to establish all the necessary requirements for stable process operation. Controlling the urine dosage rate and maintaining a constant pH in the nitrification plant proved crucial for stable process performance. Sudden changes in pH can lead to the accumulation of nitrite, which destabilises the biological process and leads to high nitrogen losses during distillation. The final product is a highly concentrated nutrient solution that compares well to commercial liquid fertilisers in terms of nutrient concentrations. Although a supplementary process step could produce a solid fertiliser product, the VUNA Project does not recommend it: not only do solid deposits due to precipitation complicate the drying process, but the solid end product is not thermally stable. Hence, this process has been specifically designed to produce a liquid fertiliser and–as a by-product–distilled water.

Key figures

Nitrogen recovery	> 99 %
Recovery of other nutrients (e.g. P, K)	100 %
Liquid fertiliser produced from 1000 L urine	30 L
Typical ammonia oxidation rate (as NH_4-N)	400 to 800 mg/L/d
Electricity consumption for distillation	80 Wh/L urine
Electricity consumption for nitrification	50 Wh/L urine
Temperature range in the distiller (boiling point at 0.5 bar)	80 to 85 °C

Trough experimentation, we observed how ammonia, nitrite, and pH influence the bacteria in the treatment processes.

Nitrification

Stabilising Nutrients in Urine

- **Biological nitrification prevents nitrogen losses and removes malodour.**
- **Stable nitrification is possible if the pH is kept within a narrow range.**
- **Overloading the nitrification plant with urine generates toxic nitrite.**
- **Underloading the nitrification plant produces acid and harms nitrifying bacteria.**

Bacteria stabilise urine

Urine collected in urine-diverting toilets or urinals contains bacteria that convert urine into a malodourous liquid with high concentrations of volatile ammonia (NH_3). To prevent ammonia from volatilising, and to simplify urine handling, the solution has to be stabilised. One option is a biological process well-known in municipal wastewater treatment: nitrification. In this process, bacteria oxidise half the ammonia into non-volatile nitrate (NO_3^-) and, as the pH drops, the other half is stabilised as non-volatile ammonium (NH_4^+) (Figure 1). Two bacterial groups share the work: ammonia-oxidising bacteria produce nitrite (NO_2^-), and nitrite-oxidising bacteria convert nitrite into nitrate (Figure 2). A third bacterial group (heterotrophs) removes the organic substances that are responsible for the malodour. The process requires a good balance between ammonia-oxidising and nitrite-oxidising bacteria, otherwise nitrite accumulates and inhibits the nitrite-oxidising bacteria. Temperature and pH are the essential parameters in nitrite accumulation.

Learning about urine nitrification

The pilot-scale nitrification plants in Switzerland and South Africa (Complete Nutrient Recovery, p. 6) allowed us to learn more about the functional stability of the nitrification process. Based on these studies, we designed and conducted well-controlled experiments in the laboratory. In short-term experiments, we determined how ammonia, nitrite, and pH influence the activity of ammonia-oxidising and nitrite-oxidising bacteria. The results were integrated into a computer model used to simulate a wide range of operating conditions. Comparing simulated results with actual measurements is a common scientific means to better understand bacterial processes, and such models allow the optimisation of plant operation, for example, during the start-up phase. We also conducted longer-term

Figure 1: Nitrification lowers the pH in urine, preventing ammonia from volatilising.

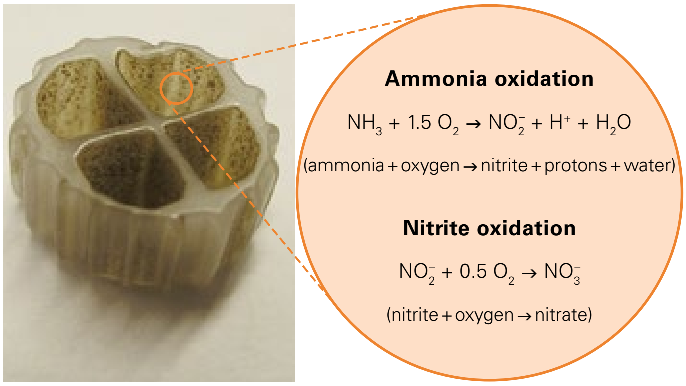


Figure 2: A plastic biofilm carrier used as a support for nitrification bacteria and the biochemical reactions occurring on it. Nitrification is an interplay between ammonia-oxidising bacteria and nitrite-oxidising bacteria (or chemical nitrite oxidation at low pH values).

Towards a robust process

These experiments and simulations showed the importance of stable conditions for nitrification. In practise, this can be achieved with careful process control. The two parameters which have to be kept within narrow ranges are pH and nitrite levels. While pH sensors are common in wastewater treatment plants, real-time nitrite sensors for the high concentrations expected in urine nitrification are not available yet and new technologies will have to be developed (Process Control, p. 16). Two other parameters which can influence the process are urine dosage and aeration. Adequate process control strategies can be tested using the computer model developed for this study, and they will support decision-making on means to avoid both over- and underloading the nitrification plant. Including the continual measurement of the storage tank's urine level into an overall process control strategy would help to ensure that urine volumes never over- or underload the process.

experiments to better understand the causes of another possible process failure: if the nitrification plant receives insufficient urine for an extended period of time, the pH can drop to as low as 2.

Staying steady

Optimal nitrification requires that the bacteria receive a steady supply of urine and that the pH remains within a narrow range. The pH is a critical parameter because it determines the concentration of substrate for the ammonia-oxidising bacteria: they consume ammonia (NH_3) rather than ammonium (NH_4^+). When the influent urine dose rises suddenly, extra ammonia becomes available; ammonia-oxidising bacteria boost their activity and nitrite accumulates. If this is noticed early, the problem can be solved by switching off the dosing pump. Ammonia-oxidising bacteria keep producing nitrite until they are inhibited at a low pH (5.5). Since nitrite-oxidising bacteria are less sensitive to low pH, they will then oxidise surplus nitrite. Conversely, if urine supplies are insufficient over an extended period of time (e.g. holidays), acid-tolerant ammonia-oxidising bacteria may start growing. When this happens, pH can drop to 2, and common ammonia- and nitrite-oxidising bacteria will die off. This situation also produces harmful nitrogen oxide gases due to chemical nitrite oxidation.

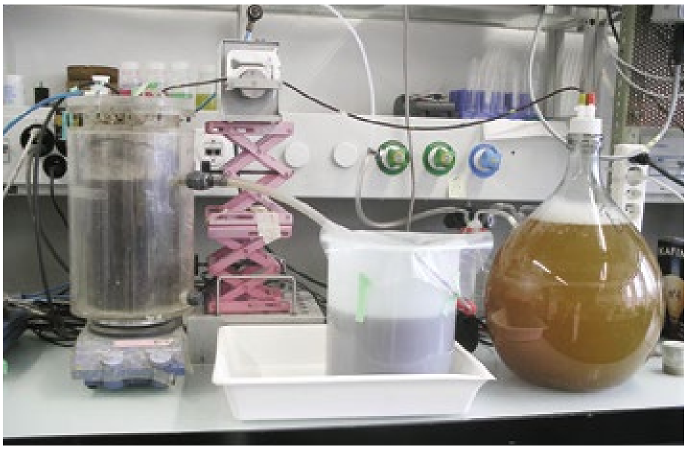


Figure 4: In a laboratory scale nitrification plant, we determined how ammonia, nitrite, and pH influence the activity of ammonia-oxidising and nitrite-oxidising bacteria.

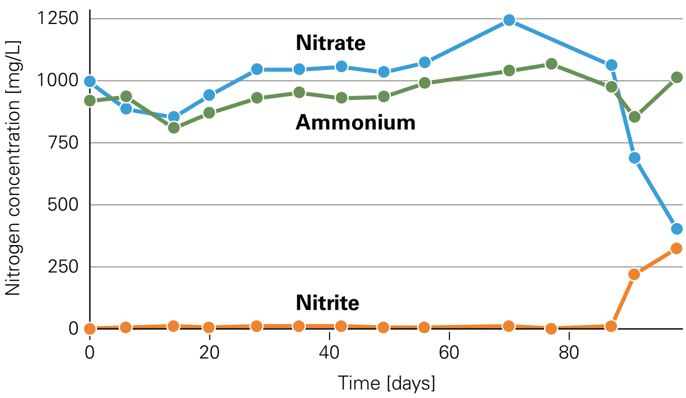


Figure 3: The intermediate nitrite accumulates after a sudden increase in urine dosage.

Key figures

Final ammonium to nitrate ratio	1:1
Substrates and inhibitors of nitrifying bacteria	free ammonia (NH_3), nitrite (NO_2^-)
Optimal pH for urine nitrification	5.8 to 6.5
Lower pH limit for common ammonia-oxidising bacteria (without acid adaptation)	5.5
pH causing release of harmful gases (through chemical nitrite oxidation)	< 4

Distillation experiments in the laboratory investigated how salts precipitate in nitrified urine.

Distillation

Water Removal from Nitrified Urine

- **Distillation efficiently concentrates urine nutrients into a liquid fertiliser.**
- **Nitrogen loss during distillation is very low (below 1.5 %, if the initial pH value is 6).**
- **Producing liquid ammonium nitrate is safe as the maximum operating temperature is far below the critical 165 °C.**
- **Solid ammonium nitrate must not be produced at temperatures above 96 °C, to avoid risk of explosion.**
- **Complete nitrification to nitrate (by adding calcium carbonate) increases thermal stability.**

Converting urine into a concentrated nutrient product

After source-separated urine has been stabilised by the nitrification process (Complete Nutrient Recovery, p. 6; Nitrification, p. 8), the nitrified urine is distilled in order to reduce its volume, thus minimising costs for storage and transportation. There are a number of reasons why we chose distillation as the process for concentrating nitrified urine: nearly all the water can be removed; the energy required is comparatively low in distillers using energy recovery (e.g. vapour compression and heat exchange); distillers are easily available, off-the-shelf products; and the high-temperature process pasteurises the solution. However, at the beginning of this project, there was only a very small body of knowledge on the distillation of nitrified urine, and a number of unanswered questions remained. How much water could be removed before salts precipitate? Could unwanted substances, such as sodium chloride, be removed through stepwise distillation? Would any nutrients be lost to the gas phase? Which safety issues should be considered when distilling an ammonium nitrate solution?

Figure 1: State-of-the-art distiller with vapour compression featuring 90 % energy recovery used in our pilot plants (KMU-LOFT Cleanwater GmbH).

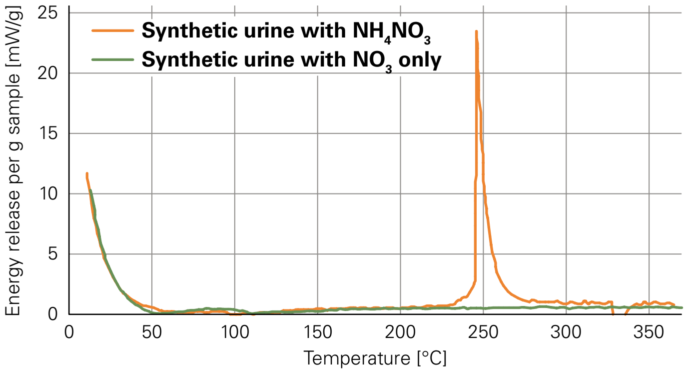


Figure 2: Energy released from solid samples heated in a RADEX device (RApid Detector for EXothermic processes).

ping, thereby producing another valuable product: distilled water. Producing a liquid concentrate, instead of a solid, has substantial advantages: the process is safer and the operation is simpler, given that no scaling occurs. Liquid fertilisers might well also have a higher market value than solid ones (Business Model, p. 34), and they comply with the legal standards for ammonium nitrate fertilisers. The concentrated liquid samples used for the safety assessment had sufficiently low ammonium nitrate concentrations (8.7 % nitrogen) to meet the legal requirements for fertilisers (max. 16 % nitrogen according to European and South African legislation). In the case of the dried product (> 16 % nitrogen), the fertiliser could only be sold to certified professionals in Europe or would have to be mixed with 20 % of ground limestone in South Africa.

In the laboratory, in silico, and at the pilot scale

Laboratory experiments were used to investigate how water content and temperature determine when salts start precipitating in nitrified urine. Further laboratory experiments were used to measure how much volatile ammonia is lost during distillation. In collaboration with Swissi, an institute specialised in safety assessments, we conducted state-of-the-art calorimetric measurements that enabled assessments of the thermal stability of the distillation products. All these laboratory experiments were conducted in parallel, using samples of real nitrified urine, but also using synthetic solutions or solids. Using the latter enabled adjustments to be made to specific critical properties, such as ammonium and chloride content. Additional computer modelling was used to validate certain experimental results and to analyse effects which were not verifiable using laboratory experiments alone. Last but not least, we gained a wealth of experience by operating an industrial-sized distiller for more than three years using real nitrified urine (Complete Nutrient Recovery, p. 6).

Critical operating temperature

Using distillation, 97 % of the water in nitrified urine can be removed, yet all the salts remain in solution. Sodium chloride is the first salt to precipitate and 50 % of it could be removed without losing considerable amounts of nutrients using stepwise distillation. This can be beneficial for the final product's use as a fertiliser, but does not help to improve thermal stability; even at low concentrations, chloride acts as a catalyst for ammonium nitrate decomposition at high temperatures. Measurements also showed that less than 1.5 % of the ammonia present is lost by volatilisation, if the nitrified urine distilled has a pH value of 6. Besides ammonia, only traces of carbon dioxide and organic substances were found in the condensate. Finally, the safety assessment concluded that a maximum operating temperature of 96 °C should be used while producing solid ammonium nitrate. Higher operating temperatures can be used, however, when producing a liquid ammonium nitrate solution (165 °C) or if all or nearly all ammonia is nitrified to nitrate with the help of base dosage (see Key figures).

Keep it liquid

These studies proved that distillation is a feasible technology with which to recover virtually all the nutrients in nitrified urine. They also showed that the distillate contained only small amounts of ammonia and organic compounds. These could be easily removed by strip-

Figure 3: About 800 mL of concentrate or 600 g of dry solids can be produced from 20 L of nitrified urine.

Key figures

Maximum water removal from nitrified urine (ammonium nitrate)	97 %
Maximum sodium chloride removal from nitrified urine (ammonium nitrate)	50 %

Distilled liquid	**Nitrogen loss**
Stored urine (pH 9)	93 %
Nitrified urine (pH 6)	1.5 %

Final product	**Maximum operating temperature**
Solid ammonium nitrate	96 °C
Liquid ammonium nitrate	165 °C
Solid nitrate	> 360 °C

How can electrolysis be used to create specific chemical processes in urine? Experiments on by-product formation.

Electrolysis

Electricity Treats Urine

- **Electrolysis rapidly removes ammonia and organic substances from urine.**
- **Electrolysis is well suited for decentralised urine treatment in compact units.**
- **Phosphorus can be recovered efficiently using electrochemical magnesium dosage.**
- **Biological nitrification becomes more robust when nitrite is controlled electrochemically.**

Electrolysis downsizes treatment units

Many chemical and biological processes involve the transfer of electrons. In electrolysis, the electron transfer occurs at the surface of an electrode as soon as a power source supplies the required energy. When this occurs, the electrical current drives the conversion of certain chemical compounds into new compounds. This has multiple advantages, especially for decentralised urine treatment in compact units: the technology is reliable; the conversion processes can be fast; and the processes can be directly controlled by applying a specified current or voltage. The real challenge, however, is to specifically convert unwanted into wanted substances. This is particularly difficult with urine: because numerous substances are present, defining the exact conditions at which only the desired processes take place is complex. The consequences of unwanted processes may be energy losses or the formation of harmful by-products. Our research investigated how to use electrolysis to create specific chemical conversion processes in urine.

Multiple options to treat urine

In laboratory experiments, we explored three applications of electrolysis for urine treatment. Firstly, we tested the electrochemical oxidation capacity of three different types of electrodes–boron-doped diamonds (BDD), iridium dioxide (IrO_2), and graphite–to degrade ammonia and organic substances. The aim of this process was to prevent environmental pollution and malodour. Secondly, we combined an electrolysis cell, containing graphite electrodes, with a biological nitrification plant. This combination stabilises the nitrification process, as surplus nitrite (Nitrification, p. 8) is degraded

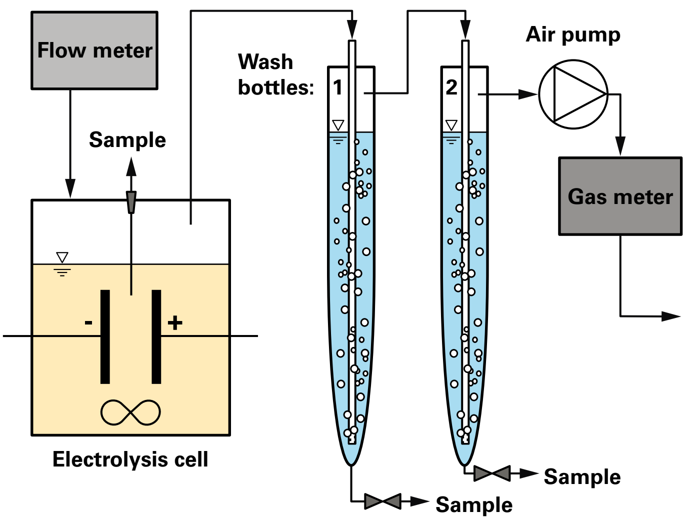


Figure 1: Wash bottles filled with an organic solvent trapped volatile chlorination by-products emitted by an electrolysis cell.

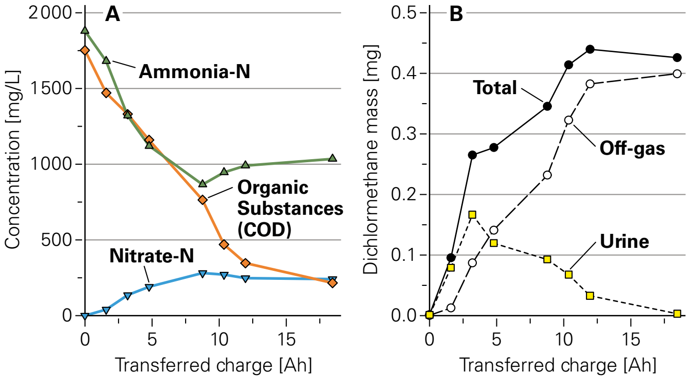


Figure 2: Iridium dioxide (IrO_2) electrodes remove ammonia and organic substances (A), but can also produce harmful chlorination by-products, e.g. dichloromethane (B).

electrochemically. Thirdly, a metallic magnesium electrode was dissolved using electrolysis in order to fine-tune the struvite precipitation process (Struvite Precipitation, p. 14). At a constant electric potential, the electrode dosed the exact amount of magnesium needed by the process. In addition to the positive effects of these three applications, we also investigated their potential drawbacks, e.g. the production of harmful chlorination by-products.

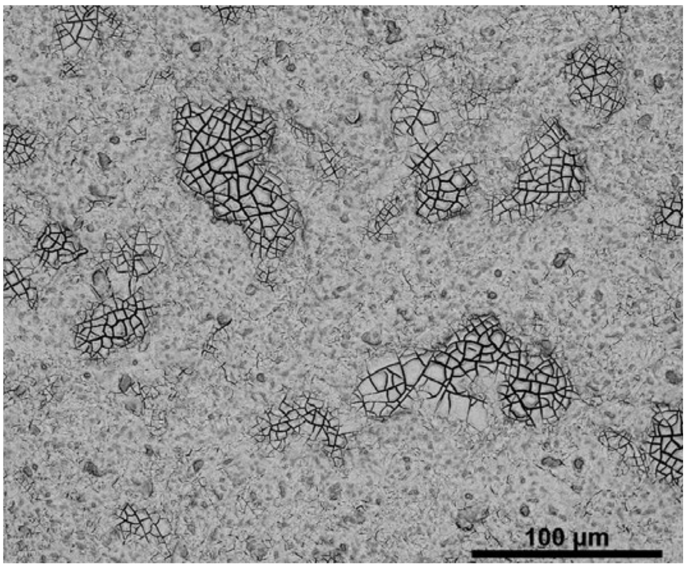


Figure 3: Scanning electron microscope image of an iridium oxide electrode. The surface has a texture comparable to cracked dried mud.

Remove and recover nutrients

Our laboratory experiments showed that ammonia and organic substances can be removed rapidly. Using BDD or IrO_2 electrodes (Key figures), we achieved fast degradation by applying high voltages. This approach could also be used to sanitise urine. The drawbacks, however, were high energy consumption and the formation of large amounts of chlorination by-products. Conversely, graphite electrodes were able to remove ammonia at low voltages. The benefits of this process were low electrode costs, reduced energy demand, and no chlorination by-products. However, ammonia removal was slow. Graphite electrodes were also successful in stabilising nitrification. Electrochemical nitrite oxidation allowed high nitrite concentrations to be brought well below inhibitory levels for nitrifying bacteria. Last but not least, electrochemical dissolution of magnesium for struvite precipitation proved to be a process which can be used to dose magnesium.

The future of urine treatment?

Electrolysis can offer a number of advantageous processes for the decentralised treatment of urine, but the process must carefully match the specific purpose. The most promising applications work in combination with other technologies, such as the biological degradation of organic substances or nitrification. However, there is still substantial room for improvement in electrolysis for urine treatment. For example, the transport of the reactants to the electrode surface could be accelerated by optimising the hydraulic conditions in electrolysis cells. Furthermore, current developments in material science hold the promise of new electrodes, which will be able to enhance specific chemical processes more effectively. Both these developments–improved transport of reactants and specialised electrodes–would reduce energy consumption during urine treatment and the production of unwanted by-products.

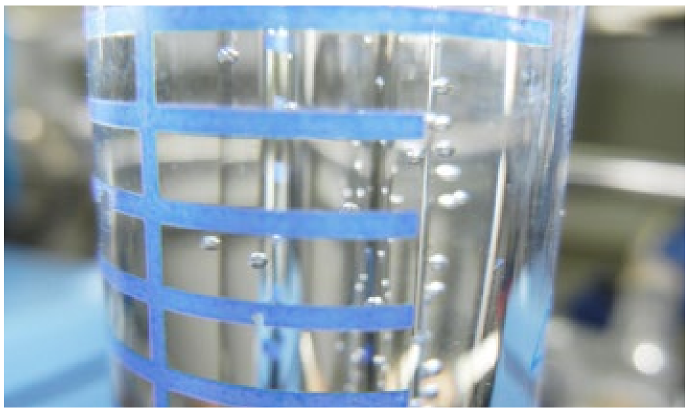


Figure 4: Off-gas from the electrolysis cell bubbles through the wash column, where chlorination by-products dissolve in an organic solvent.

Key figures

		Iridium dioxide	Boron-doped diamond	Graphite
Maximum daily organic substance removal (expressed as COD)	g/m^2	670	1 300	None
Maximum daily nitrogen removal	g/m^2	460	170	3
Energy consumption (per gram degraded nitrogen)	Wh/g	82	160	42
Current efficiency of nitrogen removal	%	21	14	33

A manually operated struvite precipitation plant at the Newlands-Mashu Field Test Site.

Struvite Precipitation

A Solid Phosphorus Fertiliser from Urine

- **Struvite can be recovered from stored urine and used as a solid phosphorus fertiliser.**
- **The process can be operated manually, e.g. in areas without an electricity supply.**
- **The process can be automated to allow efficient magnesium dosage.**
- **Magnesium dosage was controlled using turbidity or electrical conductivity signals.**
- **Efficient retention of solids determines the overall struvite recovery rate.**

Producing a phosphorus fertiliser from urine

Precipitation of struvite ($Mg\,NH_4PO_4 \cdot 6\,H_2O$) is a well-known process for recovering phosphorus from urine. The precipitation process produces solid struvite from the urine solution during a chemical reaction. The reaction is initiated by adding a soluble magnesium source (e.g. magnesium salts such as magnesium chloride or magnesium oxide, or a waste product like bittern), and nearly all the phosphorus can be precipitated from stored urine. Although struvite also contains ammonia, its precipitation is predominantly a phosphorus recovery process because less than 4 % of the ammonia in urine is recovered. After the addition of magnesium, struvite crystals form quickly, and only slight over-dosages are required for complete precipitation of all the phosphorus. The final struvite recovery rate is dependent on how efficiently filtration separates the solids from the liquid. Slow filtration and clogged filters are frequent problems in practical applications, as is the application of the correct dosage of magnesium if the phosphorus concentration in the urine is unknown.

Two different setups

Eawag initially designed and developed a manually operated struvite precipitation plant for Nepal (www.eawag.ch/stun). In eThekwini, a 40 litre plant was installed at the Newlands-Mashu field site and tested for its ease-of-use and ability to process large volumes of urine. The magnesium dose required was determined using an estimation of the typical phosphorus concentration in local urine. Filter bags were used to separate the struvite crystals, which were then dried in ambient air for one to two weeks. A novel, automated,

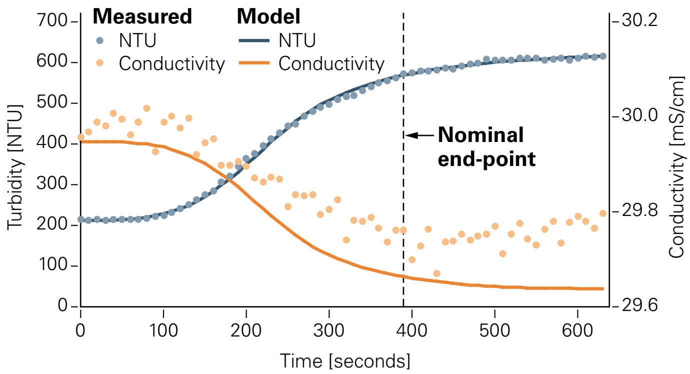


Figure 1: Measured and modelled turbidity and electrical conductivity readings indicate when struvite precipitation ceases and allow precise magnesium dosage.

50 litre plant was developed and tested in the Pollution Research Group's laboratories at the University of KwaZulu-Natal. This plant was operated using a process logic controller with software algorithms, and magnesium was dosed according to the changes in real-time sensor signals of either electrical conductivity or turbidity. Once precipitation was complete, the struvite crystals were recovered in a filtration module containing a cotton fibre disc. The operation of the automated plant was compared with results of a computer model. The manual and automated plants were both fed with urine collected in urine-diverting toilets in peri-urban eThekwini.

A process that performs in the field

Municipal staff adopted the manual process with ease due to its user-friendliness and the high volumes of urine that could be treated: trained operators could process up to 30 batches (40 litres each) per day. However, simply using typical phosphorus concentrations as a dosing strategy resulted in 30 % more magnesium being used. Experiments using the automated process showed that turbidity measurements were more sensitive than those using electrical conductivity: the turbidity signal doubled between the start and the end of magnesium dosage, while the electrical conductivity signal only changed by 1 to 2 %. However, electrical conductivity did allow a more exact determination of when struvite precipitation ceased. Stepwise dosing proved to be a promising strategy for future fully-automated plants. When adding the magnesium solution intermittently, instead of continuously, the point when struvite precipitation ceases can be determined more accurately using turbidity and electrical conductivity measurements, however the control algorithms are more challenging.

Figure 3: Producing struvite at the field test site in eThekwini.

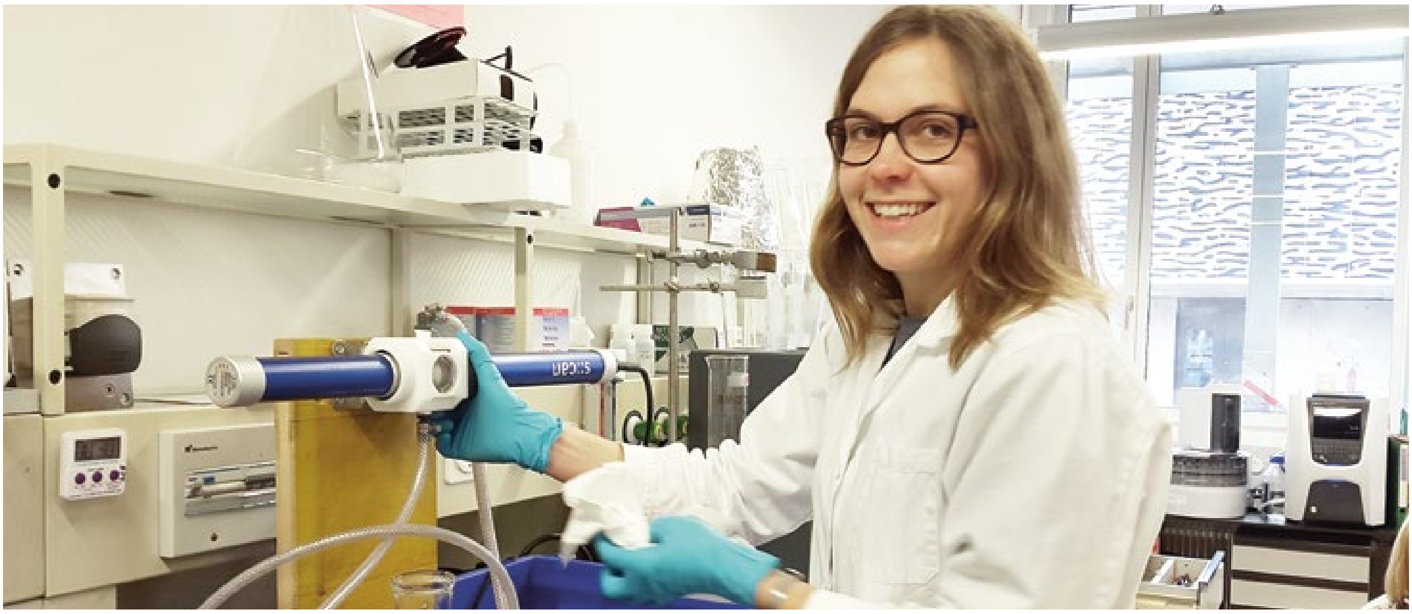
Easy-to-use technology

Overall, struvite precipitation using a manually controlled plant holds the promise for use in remote areas: the process requires no electricity, and operation can be learnt quickly by unskilled staff. The process is labour-intensive, however, and tends to be inefficient due to imprecise dosing of magnesium. Our studies showed that automation and sensor-controlled magnesium dosage can be used to build more efficient plants, but this would also require electricity and staff having a greater understanding of the process. Furthermore, the filtration of the struvite crystals remains challenging. Agricultural trials showed that struvite precipitated from stored urine performs as well as synthetic fertilisers (Fertiliser Trials, p. 22). However, struvite precipitation is a process for phosphorus recovery only. Further treatment is required to remove the other nutrients that remain in the effluent. Importantly, struvite (and the effluent) still contains infectious pathogens that are only partly eliminated while drying (Inactivating Pathogens, p. 20).

Figure 2: The automated struvite precipitation plant at the Pollution Research Group's laboratory (UKZN) doses the exact amount of magnesium and urine.

Key figures

Maximum phosphorus recovery efficiency (automated process)	93 %
Nitrogen recovery efficiency	< 4%
Recommended magnesium dosage	0.86 g Mg/g P (1.1 mol Mg/mol P)
Processing time for one batch (manual reactor, without drying)	50 min



Specific substances in urine absorb ultraviolet light. This can be measured with a spectrophotometric probe.

Process Control

Stabilised Control of the Nitrification Process

- **Accumulation of the intermediate chemical, nitrite, can lead to complete process failure.**
- **Nitrite measurement methods are being developed as no suitable nitrite detector is yet available.**
- **Nitrite concentrations can be estimated indirectly using dissolved oxygen concentrations and pH.**
- **Nitrite concentrations can also be estimated by measuring the absorbance of ultraviolet light.**
- **New sensors will help to further automate urine treatment processes.**

Nitrite: the key variable for a stable process

Urine nitrification (Complete Nutrient Recovery, p. 6) is rather sensitive to load disturbances. In an extreme case, this can stop the system from functioning. This can happen if too much urine is added to the process or if there is a sudden increase of the concentration of ammonia in the influent urine. In the latter case, the balance between the bacterial groups is disturbed and nitrite accumulates; this results in an inhibition of the action of some of the crucial bacterial groups. To prevent a process breakdown, the nitrite increase has to be detected within hours. This could in principle be achieved using real-time measurement techniques, but there are currently no commercial instruments available for this purpose. Two different strategies were chosen to develop technologies for real-time nitrite detection: first, an in-depth analysis of a measured ultraviolet (UV) light spectrum, and second, combining measurements of pH and dissolved oxygen using a dynamic computer model.

Ultraviolet light estimates nitrite

Commercial UV absorbance sensors are already used to detect nitrite in combined sewer wastewaters, however, the concentrations of nitrite, and interfering substances such as nitrate, are much lower than in nitrified urine. For our tests, UV light adsorption was measured through 0.5 mm samples of the treated urine using wavelength steps of 1 nm. We used a mathematical tool (Principal Component Regression) to extract and combine information about the nitrite concentrations given by each wavelength. Different urine concentrations were tested over four months of experimental work. Emphasis was placed on the influence of suspended particles and nitrate levels: particles disrupt the measurement of light, and nitrate adsorbs light at similar wavelengths to nitrite. By carefully

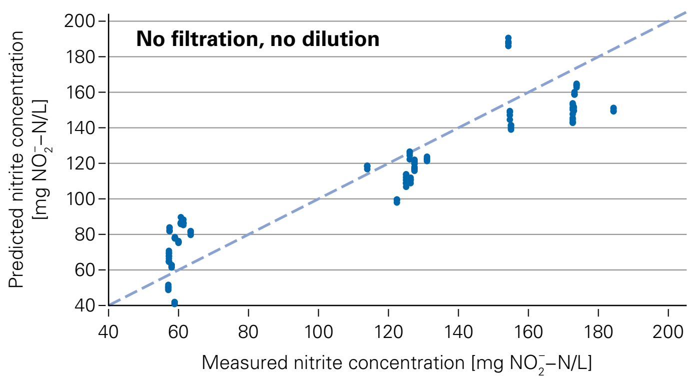


Figure 1: Demonstration of nitrite estimation based on ultraviolet light absorbance measurements. Predicted nitrite concentrations are shown as a function of measured reference nitrite concentrations.

tuning the parameters of the Principal Component Regression analysis, we developed a model providing a reliable prediction of nitrite levels, even in the presence of suspended particles and high concentrations of nitrate (Figure 1).

Using pH and oxygen data to calculate nitrite concentrations

In the second approach, we used data on dissolved oxygen levels and pH to calculate nitrite concentrations. Sensors for dissolved oxygen and pH have been successfully used in urine nitrification plants, but they are not sensitive to nitrite. However, all three parameters–dissolved oxygen, pH, and nitrite–are influenced by the chemical and microbial processes in urine, and by using a mathematical tool (in this case, an Unscented Kalman Filter, UKF), nitrite concentrations can be estimated by the measurement of the other two parameters. A UKF was tested using data from a computer model representing the processes in nitrified urine. Using a computer model allows a significant number of scenarios to be tested; doing the same with actual experiments would take months or even years. The results confirmed that nitrite concentrations can be estimated reliably using a UKF approach, and in the future this method will be further developed using a more elaborate computer model or real measurements (Figure 2).

Increasing performance with real-time sensors

Process control would benefit greatly from the continued development of both types of sensor. Current UV sensors are expensive and sensitive to clogging (e.g. by biofilms), and our software sensor still needs to be validated using real experiments. However, the results to date confirm that combining various real-time measurements allows useful information to be extracted–information which would not be exploitable if measurement series were used separately. Using current setups, nitrite can only be measured via grab samples, but this necessitates regular maintenance. Likewise, today's urine nitrification plants operate below their maximum capacity in order to have a sufficiently long reaction time to prevent the build-up of potentially process-stopping high nitrite concentrations. Future real-time nitrite sensors will help to improve performance because the process control limits will be expanded. Real-time sensors will be especially helpful to shorten process start-up times; they will also be essential elements to help run processes at remote locations with minimal maintenance.

Figure 3: To precisely measure pH and dissolved oxygen, we had to evaluate the sensors' response to changing conditions. Based on the real-time measurements, we were able to estimate the nitrite concentration in urine.

Figure 4: The nitrite concentration in urine can be estimated using an ultraviolet spectral probe. Before we tested the probe on the urine nitrification plant, we had to carefully calibrate it in the laboratory.

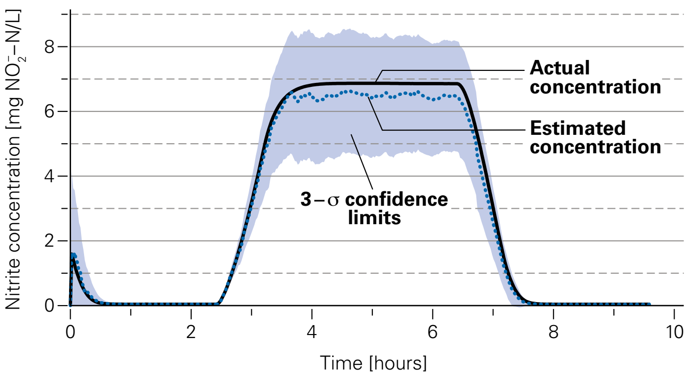


Figure 2: Demonstration of the Unscented Kalman Filter. Actual nitrite concentration (full black line), estimated nitrite concentration (dotted blue line), and 3-σ confidence limits as a function of time.

Key figures

Ultraviolet light measurements	
Range	220 to 400 nm
Resolution	1 nm
Light path length	0.5 mm

Unscented Kalman Filter	
Real-time measurements	Dissolved oxygen measurement pH measurement
Other parameters	Gas flow rate Urine loading rate Urine influent composition

We measured how a laboratory nitrification plant removes pharmaceuticals from urine.

Removing Pharmaceuticals

How Urine Treatment Affects Pharmaceuticals

- **The majority of pharmaceuticals excreted by the human body pass through urine.**
- **Ideally, urine-derived fertilisers should have negligible pharmaceutical content.**
- **Pharmaceuticals in urine are partly degraded during urine nitrification.**
- **Pharmaceuticals in urine can be removed effectively by adsorption onto activated carbon.**

Precautionary investigations

The majority of nutrients excreted by the human body–but also the majority of pharmaceuticals excreted–pass through urine. Due to the high prevalence of HIV infections in South Africa, particularly high concentrations of pharmaceuticals are to be expected in the urine collected in the eThekwini Municipality. The negative effects of pharmaceuticals on ecosystems are known from natural waters that receive high loads of wastewater. Separating and treating urine is an efficient way of preventing adverse effects on aquatic environments. Previous studies have shown that pharmaceuticals can be degraded in soil, but there are also reports of plants taking up certain pharmaceuticals. It is as yet unclear whether pharmaceuticals have negative effects on plants, or whether they might even enter the food chain, if treated urine is used as fertiliser. As a precaution, we investigated the degradation of pharmaceuticals during urine storage and biological treatment. As an additional urine treatment step, we also tested adsorption to activated carbon for the removal of pharmaceuticals.

Figure 1: Detecting pharmaceuticals in source-separated urine.

Figure 2: Measuring pharmaceuticals with solid phase extraction (SPE) coupled to liquid chromatography with tandem mass spectrometry (LC/MS/MS).

Field data guide laboratory experiments

Samples from the central urine collection tanks in eThekwini were measured for concentrations of common pharmaceuticals. Based on the results and on data in the literature about pharmaceutical usage in South Africa, Europe, and the USA, we selected a representative group of eleven pharmaceuticals (see Key figures). Since HIV infections are common in South Africa, the list contains several anti-retroviral drugs and antibiotics that are used to treat HIV/Aids and prevent infections. To determine how urine storage affects pharmaceuticals, untreated urine was spiked with the selected substances and stored in air-free conditions for up to 77 days. Additionally, we ran the urine through a laboratory nitrification plant (Nitrification, p. 8; Complete Nutrient Recovery, p. 6) and investigated, using batch experiments, how biological urine treatment removed pharmaceuticals. A final series of batch experiments was carried out using spiked nitrified urine to measure the adsorption of pharmaceuticals to powdered activated carbon.

Substances degrade differently

Air-free urine storage (anaerobic) did not remove any pharmaceuticals except for the high blood pressure drug hydrochlorothiazide, which was hydrolysed by 90 % within 50 days. Biological treatment in the aerated nitrification plant was more successful, however. After 10 to 24 hours, atazanavir, clarithromycin, darunavir, and ritonavir had been almost completely eliminated. On the other hand, atenolol, diclofenac, emtricitabine, hydrochlorothiazide, sulfamethoxazole, and trimethoprim, were relatively persistent. Since the main purpose of nitrification is to stabilise the nutrients in urine, the removal of pharmaceuticals is a beneficial side effect of this process. If required, the addition of powdered activated carbon (PAC) can adsorb pharmaceuticals. With the addition of 200 mg/L PAC, more than 90 % (by weight) of the remaining pharmaceuticals were removed. At the same time, PAC removed no beneficial nutrients. The biological and PAC treatments also reduced ecotoxicity (measured using the bacterial bioluminescence inhibition test) and estrogenic activity (YES Test).

Nice to have or need to have?

The results from the urine nitrification process are in line with those from research reports on biological wastewater treatment: a reasonable share of the pharmaceuticals is eliminated, but effluent concentrations remain considerable and some compounds are hardly affected. An additional treatment step can ensure that sufficiently low pharmaceutical concentrations are achieved. One of the advantages of adsorption to PAC is the lack of by-products, which would have to be considered when using other processes, such as ozonation or electrolysis. While near-complete removal of pharmaceuticals from urine-derived fertilisers would be desirable, it is unclear whether the higher costs and process complexity can be justified. Neither European nor South African legislation currently provides limits for pharmaceuticals in fertilisers. Further research is needed to determine the possible effects of pharmaceuticals from urine-derived fertilisers on the environment and human health.

Key figures

Pharmaceuticals analysed	Type of pharmaceuticals	Estimated half-life during urine nitrification	Elimination using 200 mg/L PAC
Atazanavir	Antiretroviral	40 min	> 99 %
Atenolol	Beta blocker: treats high blood pressure	14 h	98 %
Clarithromycin	Antibiotic	80 min	> 99 %
Darunavir	Antiretroviral	7 h	> 99 %
Diclofenac	Analgesic: painkiller and anti-inflammatory	> 48 h	> 99 %
Emtricitabine	Antiretroviral	> 48 h	90 %
Hydrochlorothiazide	Diuretic: promotes production of urine and treats high blood pressure	> 48 h	97 %
Ritonavir	Antiretroviral	45 min	> 99 %
Sulfamethoxazole	Antibiotic	> 48 h	96 %
Trimethoprim	Antibiotic	> 48 h	> 99 %

Pathogens originating from urine samples grow on culture media and can be counted under the microscope.

Inactivating Pathogens

Inactivation during Urine Storage and Treatment

- **Source-separated urine is cross-contaminated with pathogens from faeces.**
- **Ammonia acts as a natural sanitiser during urine storage and helps to inactivate many micro-organisms.**
- **Low moisture content is the main factor inactivating pathogens in struvite fertilisers.**
- **Nitrification only inactivates certain pathogens; further processing is required to fully sanitise the product.**

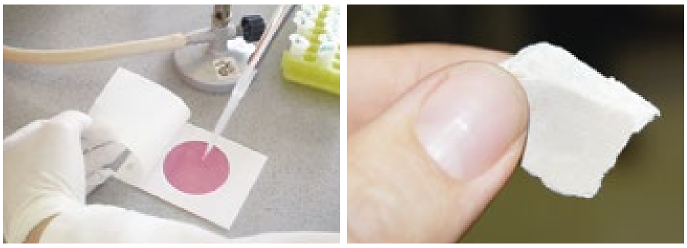


Figure 1: Evaluating the inactivation of bacteria using culture-based methods such as a dry-plate petrifilm (left) during the production of struvite (right).

Source-separated urine is not sterile

Humans excrete most of the pathogens in their bodies via faeces rather than urine. However, urine collected from urine-diverting toilets is frequently contaminated with faeces and can, therefore, contain pathogens (bacteria, viruses, helminths, and protozoa). Some pathogens (e.g. *Salmonella Typhi*, *Schistosoma Haematobium*) are also excreted in the urine of infected persons. Disease-causing pathogens in stored urine and fertiliser products could compromise the safety of urine collection systems and the quality of their end products. In order to analyse one component of human health risks during urine separation and collection, we identified pathogens in urine samples taken from various urine storage tanks in the collection areas in eThekwini. Because of the widespread detection of human viruses in the urine, and their potential persistence in stored urine, we evaluated the influences of urine storage time and conditions on the inactivation of viruses. We also investigated the extent of inactivation or removal of pathogen surrogate organisms in urine treatment processes, including struvite precipitation and nitrification.

Identifying pathogens by their genes

In addition to culture methods used to analyse heterotrophic and faecal indicator bacteria, a method based on polymerase chain reaction was used to identify specific pathogenic bacteria and viruses in field samples. This detected pathogens such as human adenovirus, rotavirus, and norovirus, which are difficult, and in some cases impossible, to measure otherwise. We selected 19 target organisms to evaluate the presence of a range of diarrhoea-causing pathogens that could pose a health risk to urine collectors or end-users. Of the bacteria tested, the most frequently detected were *Aeromonas spp.*, *Clostridium perfringens*, and *Shigella spp.* The helminth *Ascaris lumbricoides* has previously been shown to be prevalent in eThekwini. Laboratory studies investigated the fate of total heterotrophic bacteria, the virus ΦX174, and the helminth *Ascaris suum* during struvite filtration and drying (Struvite Precipitation, p. 14). We also determined the effectiveness of the nitrification process (Nitrification, p. 8) in removing pathogen surrogates from urine by measuring the bacteria *Salmonella typhimurium* and *Enterococcus spp.*, and three types of

Figure 2: Analysing samples in Durban for the presence of human pathogens.

viruses. Based on the behaviour of these pathogen surrogate organisms throughout the urine treatment process, we drew conclusions on the most efficient means of inactivating pathogens.

Ammonia, drying, and heat inactivate pathogens most effectively

Treating urine for pathogens begins during urine storage. Shortly after collection, the pH of urine rises due to urea hydrolysis, and the concentration of ammonia–a known biocide against pathogenic microorganisms–naturally rises. Under typical urine storage conditions, ammonia effectively inactivates viruses by attacking the viral genome. However, urine storage is usually too short to ensure that pathogens are completely inactivated. Protective measures are thus necessary to reduce the risk of infection during urine collection. The urine treatment processes investigated in this project only partially inactivate pathogens. Experiments on the struvite produced revealed that the main cause of pathogen die-off is the decreasing moisture content that occurs during struvite drying. The virus ΦX174 was strongly affected by decreasing moisture contents, but inactivation of the helminth *Ascaris suum* was considerably lower. In nitrification, the two bacteria evaluated, and one of the three viruses, were inactivated, but only to a lower extent given the relatively short duration of the nitrification step. The other two viruses assessed were hardly affected, suggesting that some human viruses are likely to survive the nitrification treatment step. One highly effective treatment for pathogens, however, is distillation. Nitrified urine in the distiller is heated at 80 °C for at least half an hour (Distillation, p. 10), a temperature used to pasteurise commercial food products for safe consumption.

Producing safe urine fertilisers

The major goals of this urine treatment system are to recover nutrients for productive use as fertiliser and prevent environmental pollution by uncontrolled nutrient discharges. The main criterion for choosing a technology is, therefore, its performance in nutrient conversion. However, it is also important to ensure that procedures are hygienic, and fertilisers are safe to use. Our findings on pathogen inactivation thus have an influence on the choice of an optimal process set-up. Any process that involves handling human waste products requires good hygiene practices and the use of personal protective equipment. The distillation stage of VUNA's production process for concentrated nutrient solution will inactivate pathogens in urine, but precipitated struvite may need additional treatment to ensure complete dryness prior to use. Based on this project's work so far, the potential health risks of urine collection and manual struvite production are now being investigated quantitatively. Besides the risks of pathogens to human health, an important environmental risk to consider when choosing an appropriate nutrient recovery process comes from the presence of micro-pollutants, such as pharmaceutical residues, in the urine itself (Removing Pharmaceuticals, p. 18).

Figure 3: Studying how the nitrification reactor inactivates bacteria and viruses.

Key figures

Summary of inactivation during processes

√ complete
(√) partial/possible under certain conditions
– no inactivation

Pathogen Class Indicator organism or pathogen surrogate	Storage[1]	Struvite drying[2]	Nitrification	Distillation[3]
Viruses MS2, ΦX174, Qbeta	(√)	(√)	–	√
Bacteria *Enterococcus spp., Salmonella typhimurium*	(√)	(√)	(√)	√
Helminth Ascaris suum	(√)	(√)	Not evaluated	√

[1] WHO recommends urine storage for ≥ 6 months at ≥ 20 °C prior to application. [2] Enhanced inactivation requires drying at ≥ 35 °C and low relative humidity.
[3] Distillation fulfils pasteurisation requirements (≥ 70 °C for ≥ 30 min); inactivation not measured.

Peter Klaunzer

The greenhouse guarantees well-controlled conditions for fertiliser trials.

Fertiliser Trials

Greenhouse Trials with Struvite and Concentrated Nitrified Urine

- **Struvite and concentrated nitrified urine were compared to chemical fertilisers in pot experiments.**
- **Struvite is mainly a phosphorus fertiliser.**
- **Concentrated nitrified urine contains a wide range of nutrients, but mainly nitrogen.**
- **Struvite and concentrated nitrified urine are as effective as commercial fertilisers.**
- **Future studies will have to test the fertilisers on a range of different soil types and crops.**

Human urine is a source of nutrients

Phosphorus (P) and nitrogen (N) are the most essential nutrients for growing crops. The low availability of nitrogen or phosphorus in soil often leads to low crop yields. As the world's easily extractable phosphorus reserves are both limited and concentrated in only a few countries, it is considered a potentially critical resource. Nitrogen fertilisers can be synthesised from nitrogen in the air; a process accounting for approximately 1 % of the world's energy consumption. Fertiliser prices are therefore likely to continue to increase in the future, which would amplify pressures on farmers. It is essential that scientists continue exploring alternative nutrient sources such as human urine, which is rich in nutrients essential to plants: In addition to nitrogen and phosphorus, it also contains potassium (K), sulphur (S), and numerous micronutrients. The VUNA Project tested two different technologies for extracting nutrients from urine: struvite precipitation (Struvite Precipitation, p. 14) and nitrification combined with distillation (Complete Nutrient Recovery, p. 6).

Evaluation of fertiliser performance

The two technologies tested in VUNA produced two fertilisers: a solid phosphorus fertiliser (struvite) and concentrated nitrified urine containing all the nutrients found in urine. The main nutrient in the latter is nitrogen. We needed to evaluate how plants took up nitrogen and phosphorus from these two fertilisers. In order to precisely compare the proportions of phosphorus and nitrogen that plants assimilate from either the fertilisers applied or from the soil, we prepared the fertilisers using synthetic urine solutions containing isotopic tracers. These isotopic labels do not affect plant growth, but researchers can detect them in the plants. The results were

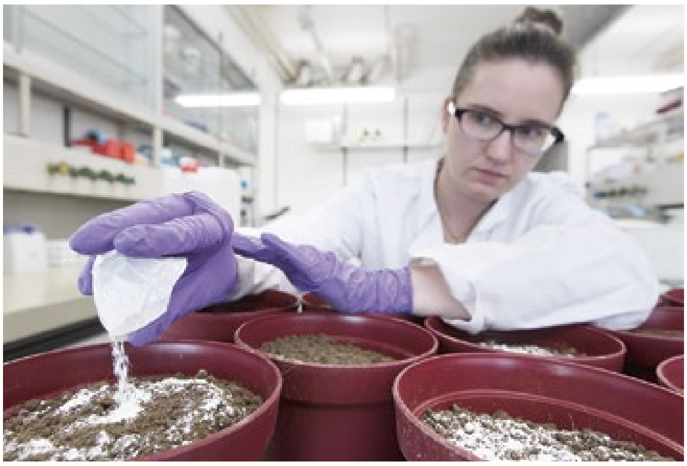


Figure 1: Carefully adding urine-derived fertilisers to the soil in the greenhouse pot trials.

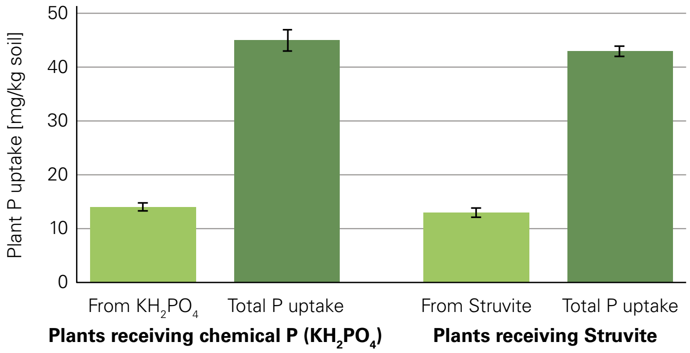


Figure 2: Plants took up struvite and a commercial chemical phosphorus fertiliser (KH_2PO_4) in equal amounts.

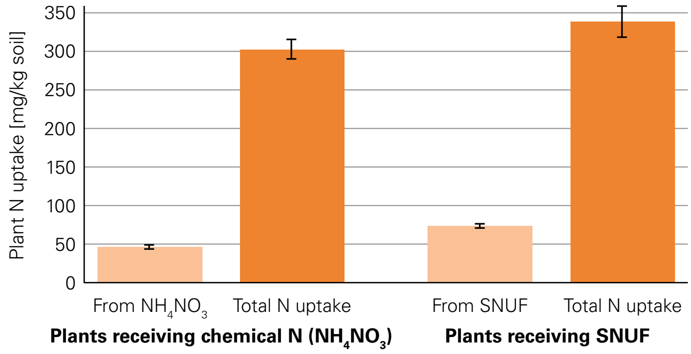


Figure 3: Plants recovered equivalent amounts of nitrogen from the concentrated nitrified urine and from the reference, water-soluble, NH_4NO_3 fertiliser.

compared with commercially available chemical fertilisers. To ensure that the ratio of nitrogen to phosphorus was the same in each fertiliser, struvite was complemented with synthetic ammonium nitrate and the concentrated nitrified urine was complemented with potassium phosphate.

Plant nutrient uptake

We grew ryegrass plants in separate pots in a climate-controlled greenhouse. Before and after sowing the ryegrass, the pots were fertilised with either struvite, concentrated nitrified urine, or water-soluble commercial chemical fertiliser. Plants grown using the struvite fertiliser took up similar amounts of phosphorus (Figure 2) to plants grown using a commercial chemical phosphorus fertiliser (26 % and 28 % of applied phosphorus, respectively). Plants grown using the concentrated nitrified urine fertiliser took up 72 % of the nitrogen applied, which was very similar to the 77 % taken up from the commercial chemical fertiliser (Figure 3). About 26 % of the phosphorus included in the concentrated nitrified urine was also available to the plants, which was a similar ratio to the struvite and chemical phosphorus fertilisers.

Effective urine fertilisers

This plant growth study demonstrated that under specific growing conditions, urine-based fertilisers performed just as well as reference commercial chemical fertilisers. The promising results obtained by both the VUNA fertilisers suggest that struvite and concentrated nitrified urine could become valuable alternatives to commercial plant fertilisers. The results obtained using struvite were also confirmed by the Crop Science Department at the University of KwaZulu-Natal, which has likewise investigated plant growth using struvite produced from real human urine. The experiments at ETHZ were conducted using ryegrass and one type of soil (acidic soil with pH 5.4 in water). In order to get a broader perspective of how effective our two urine-based fertilisers are, future studies will involve testing them on a wide range of soil types and a variety of crops. Due to the variety of nutrients it contains, concentrated nitrified urine may also be a good fertiliser for ornamental plants indoors or in gardens.

Figure 5: The VUNA fertilisers – struvite and concentrated nitrified urine – were both tested in greenhouse pot trials in Switzerland and South Africa.

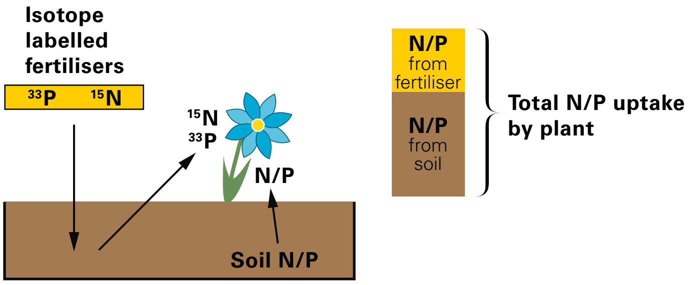


Figure 4: Isotopic tracers retrace the origin of nutrients in a plant: ^{15}N and ^{33}P originate from the labelled fertiliser, whereas unlabelled N and P originate from the soil.

Key figures

Composition of struvite	6 % N, 13 % P, 10 % Mg
Composition of the nitrified urine solid used in this study	21 % N, 1.7 % P, 7.0 % K
Phosphorus applied as struvite and recovered in plants	26 %
Nitrogen applied as concentrated nitrified urine and recovered in plants	72 %

Urine collectors transfer urine from a jerry can into the collection tank on their truck.

Optimising Urine Collection

Minimising Cost and Maximising Yield

- **A urine collection network was established in peri-urban eThekwini.**
- **In a pilot study, urine was collected from 700 urine-diverting toilets.**
- **Facilitators ensured good communication between the local community, the Municipality, and researchers.**
- **Hiring staff in the community created jobs, and their local knowledge improved collection rates.**
- **Good communication and awareness raising are as important as optimised logistics.**

Providing urine for the VUNA Project

Before the start of the VUNA Project, the urine from urine-diverting toilets in eThekwini was not collected but was left to infiltrate into the ground. To provide urine for our research on urine treatment (Complete Nutrient Recovery, p. 6; Struvite Precipitation, p. 14), a urine collection system had to first be established. This new system formed part of the research on how incentives affect the use of urine-diverting toilets (Incentives for Urine Production, p. 32). Two types of collection areas were established: firstly, control areas, in which the Municipality organised urine collection from the toilets and transportation to the laboratories at the University of KwaZulu-Natal and the Newlands-Mashu Field Test Site; secondly, treatment areas, in which toilet users received incentives to carry their urine to local collection tanks, from where the Municipality collected it. In order to set up a urine collection system, the requirements and constraints of several stakeholder groups had to be considered: research teams and local facilitator, local communities and their leaders, and municipal staff.

Figure 1: Municipal workers connect a 20-litre urine tank to the urine-separation pipe at a household toilet in eThekwini.

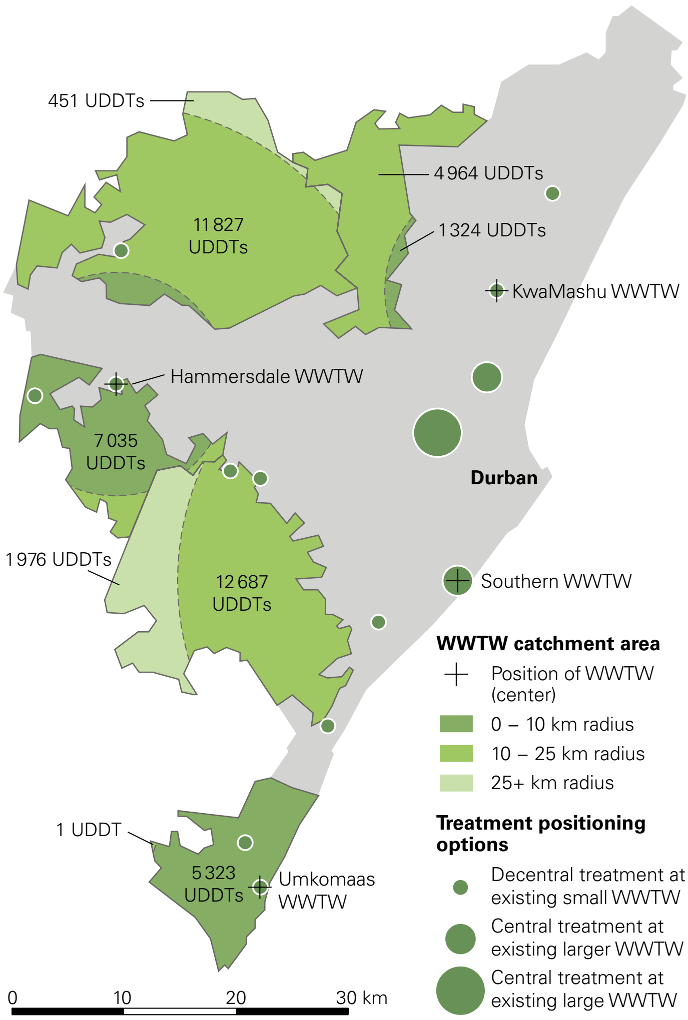


Figure 2: The urine collection areas and treatment sites in eThekwini.

Setting up urine collection areas

Several areas were chosen for urine collection, each with approximately 100 contributing urine-diverting toilets. Technical and social criteria were used to decide whether an area was suitable for urine collection: the number and density of toilets had to be sufficiently high, cell phone reception had to be good, and the risk of violence and riots had to be low. Before installing the collection tanks, both the local political representatives (councillors) and the households owning the toilets had to agree to the establishment of a collection system. Facilitators were hired to ensure good communication between the local community and the Municipality. Each urine collection team consisted of two workers. They picked up the urine from the urine-diverting toilets and carried it to a municipal truck that transported the urine to the large collection tanks at either the Newlands-Mashu Field Test Site or the University of KwaZulu-Natal. Urine was collected once every two weeks.

Experiences in local communities

Urine was eventually collected from 700 toilets. Several toilets had to be refurbished before urine tanks could be installed. Twenty-litre jerry cans proved to be the optimal tanks to use at the urine-diverting toilets because overflow was low and the tanks could be carried easily. Labelling the tanks with "urine" in isiZulu helped to reduce losses through misuse or theft. Direct contact with the head of the household, but also with the other household members, was essential to ensure the household's involvement and support in the urine collection scheme. In order to ensure good communication and to raise awareness, both the facilitators and the urine collection teams had to be knowledgeable about the project's background and goals. Hiring urine collectors locally not only provided jobs in local communities but also made collection more efficient: local collectors knew the fastest ways to the toilets and remembered them, as well as which tanks filled up fastest and which ones had been emptied recently.

Lessons for scaling-up

Based on these experiences in the field and the results of other VUNA studies (Performance Modelling, p. 26; Incentives for Urine Production, p. 32), the urine collection system is currently being further optimised. In one project, the logistics of urine collection are studied and optimised with the help of modern technical tools: smart phones (instead of spreadsheets) are used for reliable data collection, and GPS signals are recorded to learn more about collection routes. However, improving technical aspects is not sufficient to set up an efficient urine collection system. Care must be taken to establish a direct, personal contact between the Municipality, local stakeholders, and households. This can only be achieved if the local facilitators and urine collectors are chosen carefully. Last, but not least, urine collection is also strongly influenced by external factors. Civil unrest and bad weather can obstruct access to the urine collection areas for many days at a time.

Figure 3: Rural settlement: Houses in rural eThekwini are scattered, making access for urine collectors difficult.

Key figures

Average number of households per pilot study area	100
Typical household tank size for urine-diverting toilets	20 litres
Typical tank size on the collection truck	500 to 1 000 litres
Urine collection team size	1 driver from the Municipality, 2 collectors, 1 local facilitator
Maximum volume collected per week during the pilot study	1 500 litres
Average daily travel distance of one collection truck	200 to 300 km

Density of toilets strongly influences the collection team's driving distance, and thus the collection costs.

Performance Modelling

Computer Simulations Help to Optimise Urine Collection

- **Cost-effective urine collection from scattered tanks requires a well-organised procedure.**
- **The model developed, DeSaM, allows the comparison of alternative urine collection setups.**
- **DeSaM uses a modular structure and statistical assumptions to quantify performance.**
- **Large urine tanks at urine-diverting toilets and "on demand" collection lower costs effectively.**
- **Different collection schemes are optimal for maximising revenue and minimising pollution by overflows.**

Challenging collection

A waterless sanitation system, such as the urine-diverting toilets in eThekwini, does not require an expensive sewer network; it can be implemented on demand whenever funds are available. However, if in-situ urine use is not possible, other methods of collection need to be investigated. Our experience has shown (Optimising Urine Collection, p. 24) that, in order to minimise costs, urine collection must be well managed. Developing an optimal strategy for urine collection is a demanding task: there are thousands of toilets, each with different properties such as number of users, usage patterns, distance from the street, or the state of repair. Numerous different resources also have to be managed wisely, such as the number of municipal workers involved, working hours, and whether to use roving urine collection trucks or urine tanks at collection points. Finally, the collection strategy has to be chosen based on the overall performance goal, which could be maximising revenue per litre of

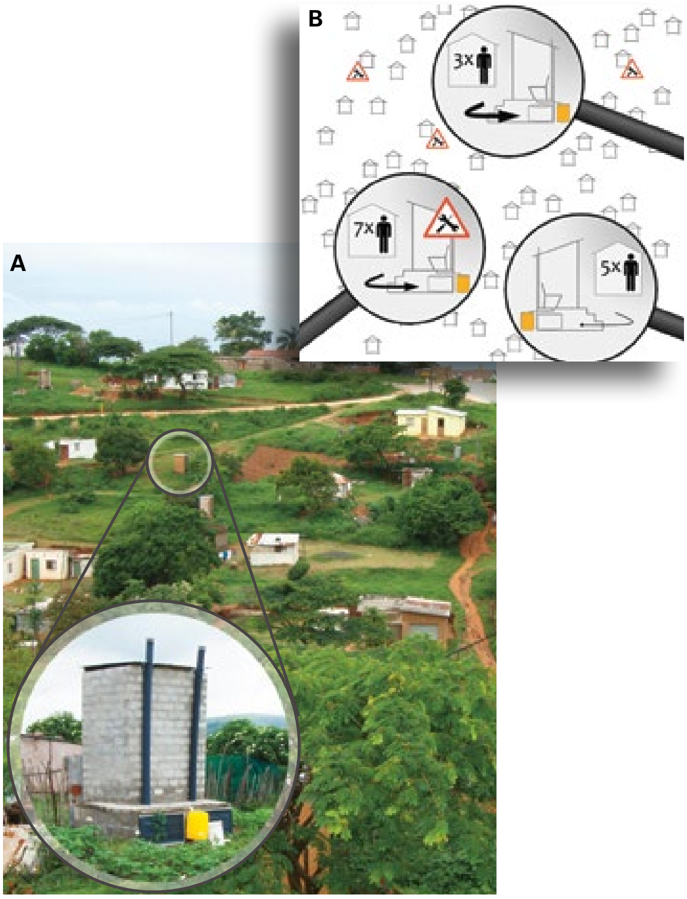


Figure 1: The Decentralised Sanitation Product Management Model (DeSaM) is used to describe the real situation in eThekwini in a simplified way (A). It allows us to consider every urine collection tank as an individual module that may be affected by random events (B).

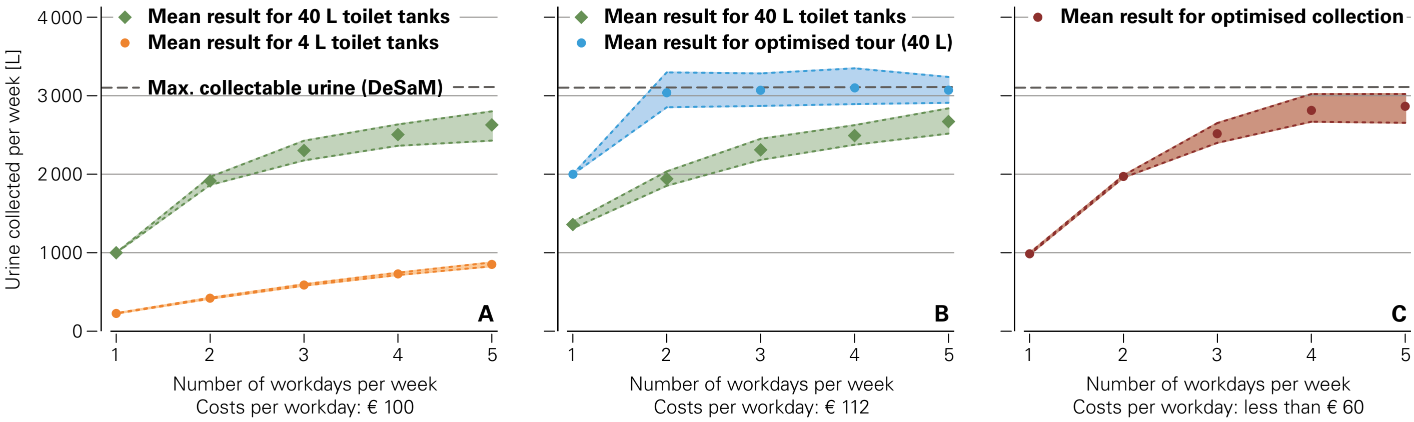


Figure 2: A) The initial design for toilet tanks (4 L capacity) is not sufficient (orange); the performance is improved by increasing the toilet tank capacity to 40 L (green). B) A bigger vehicle tank (green) and an optimised collection route (servicing the fullest tanks first; blue) bring further improvement. C) Decentralising the collection by employing local collectors can help to reduce costs (red). The dotted lines with the shaded areas mark the 10 % and 90 % confidence intervals.

urine, minimising environmental pollution by urine overflows, or providing an optimal service for the toilet users.

From centralised to decentralised

The Decentralised Sanitation Product Management Model (DeSaM) was developed to compare different management approaches. The model's high flexibility is based on the following principles. Firstly, its basic building blocks are tanks with varying properties, such as urine inflows and outflows; and whether they are stationary (e.g. at a toilet) or mobile (e.g. on a collection vehicle). Secondly, statistical distributions are used to simulate known variables (e.g. the number of users per toilet) or to express uncertainties such as toilet usage by a single person. Thirdly, the model is dynamic, because it considers time dependent events such as urine pick-up. This structure allows the model to simulate a wide range of urine collection setups (or even other waste streams). We focused mainly on the following two setups: firstly, a fully centralised setup (municipal collection) with municipal staff collecting urine and bringing it to a central treatment facility; and secondly, a semi-decentralised setup (local collection) with local workers bringing urine to large intermediate storage tanks, which are then emptied by municipal staff. The data on costs (e.g. salaries, transport times) were based on our own research in eThekwini.

More volume

A key element in reducing costs and environmental impact is the local tank at the urine-diverting toilet. Increasing the tank size reduces the cost per litre of urine collected considerably. The optimal size was found to be 40 litres, e.g. made up in the in form of two 20-litres jerry cans. Using larger transport tanks on the trucks, however, has little effect on the overall volume of collected urine but adds to the costs per litre of urine. Increasing the number of visits by the collection staff has a similar effect. Another effective way to reduce costs substantially is to optimise the order of collections. Collecting the fullest tanks first (collection on demand) is optimal and brings large efficiency gains. This strategy requires sensors, notification by the toilet users, or local workers who acquire experience on filling rates. The simulations also revealed that if mean values were assumed instead of statistical distributions, and constant conditions were assumed instead of time dependency, then urine overflows were substantially underestimated.

Model assesses scenarios based on goals

This study confirmed that optimising urine collection is a challenging task: not all the influences on the system can be described in detail, and the interdependency of the different elements can have a strong effect on the overall performance. Additionally, the final decision on the optimal collection scheme depends on the overall performance goal. A computer model like DeSaM allows us to identify the most critical elements and assess the effects caused by changes to parts of the system. This type of model is especially valuable as a decision support tool for the design of an appropriate collection scheme, as different options can be tested easily and inexpensively. Since urine collection is one of the main cost factors in transforming urine into fertiliser (Business Model, p. 34), a computer model such as DeSaM can be a decisive tool for setting up a sanitation system relying on a collection scheme. DeSaM can also be used as a cheap alternative to preliminary field studies for testing novel collection setups.

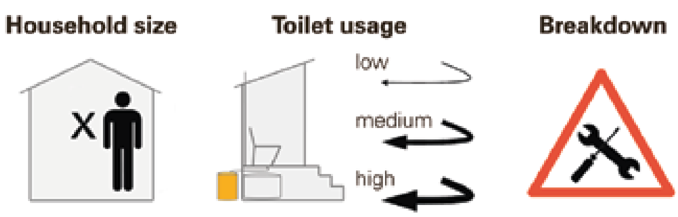


Figure 3: The computer model analyses how different parameters, e.g. household size, toilet usage frequency, or breakdowns, affect the urine volume collected.

Key figures

Model use

Software costs	0 ZAR (freeware)
Simulation time for one scenario	2 seconds

For the urine collection situation in eThekwini we assessed

Minimum required capacity of a toilet tank	approximately 40 litres
Minimum cost of collecting 1 litre of urine	< 0.8 ZAR (< 0.06 EUR)

Community members describe how they perceive the urine-diverting toilets.

Social Acceptance

The Evolving Results on Toilet Acceptance

- **Satisfaction with urine-diverting toilets increased between 2011 and 2014.**
- **Odour remained a dominant concern in 2014.**
- **In 2014, urine-diverting toilet users continued to aspire to have flush toilets.**
- **Respondents largely support an official (municipal) vault clearing service.**

Figure 1: Some users converted their urine-diverting toilet to a flush toilet.

Why study social acceptance?

In 2002, the eThekwini Municipality initiated a programme to implement dry sanitation on a large scale. This occurred after the municipal boundaries had been expanded to include an additional 75 000 households, 80 % of which were without appropriate sanitation services. The Municipality embarked on a project to provide urine-diverting toilets and yard tanks to all households in unserviced areas. To date, approximately 82 000 urine-diverting toilets have been installed. In 2011, the Municipality commissioned a study to explore the social acceptance of urine-diverting toilets. The main focuses of the study were user satisfaction, possible problems with the toilet after its construction, the measures needed to ensure the sustainability of urine-diverting sanitation, and the need for municipal services such as emptying faeces vaults. In 2014, we repeated that assessment (with a smaller sample size) in order to identify any changes over time.

How social acceptance was assessed

In 2011, we developed a structured questionnaire and, using mobile phone technology, we interviewed 17 500 householders in 65 areas of eThekwini. Considering the large sample size, mobile phones offered a more efficient approach than pen and paper, allowed better control of data quality, and immediate digital data capture. In the second survey, in 2014, we interviewed 1 500 householders in five areas of eThekwini (two more rural areas and three more urban areas). Both surveys comprised direct questions to the householder as well as an observational checklist completed by trained fieldworkers. Additional questions in the second survey assessed perceptions of a municipal vault-clearing service, usage of the urinal and the children's toilet seat, and investigated perceptions of previous educational campaigns. The smaller sample size allowed for a pen and paper survey, which we captured digitally on completion of the fieldwork.

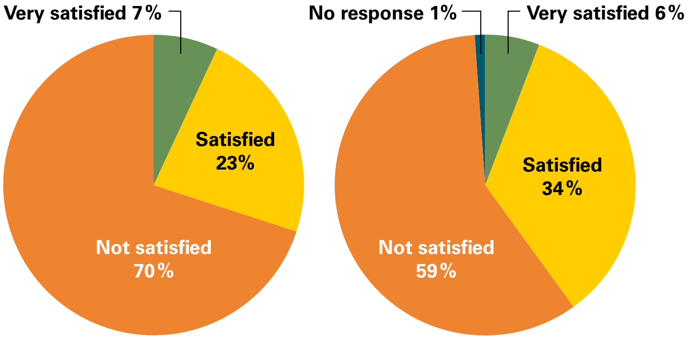


Figure 2: Respondents' satisfaction with urine-diverting toilets increased from 2011 (left) to 2014 (right). (2011: n = 17 449; 2014: n = 1 567)

Acceptance and key issues

We found that the percentage of respondents who were satisfied or very satisfied with their urine-diverting toilets increased from 30 % in 2011 to 40 % in 2014. This was a key result. In 2011, users complained most about odour (27 %), the toilet door not closing (22 %), and poor construction (12 %). In 2014, their complaints were odour (26 %), the condition of the door (15 %), and the faecal vault not being cleared (14 %). The 2014 survey asked toilet users what they thought about an organised vault emptying service, and 80 % of respondents supported this idea. Of the people surveyed 59 % would be satisfied by having the vault contents taken offsite, while 26 % would be satisfied having it buried onsite. All five areas indicated greater levels of acceptance for an official municipal emptying service rather than community vault-emptying teams. Since the first survey, there had been a clear decrease in households receiving information on urine-diverting toilets (from 90 % to 66 %, respectively). Only 50 % of the 2014 respondents stated that they had personally received information, and 36 % of respondents found this useful.

Figure 3: Over the years, the eThekwini Municipality has constantly improved the toilet design to make it more robust, durable, and easy to install.

Targeting better acceptance

Survey results have guided–and continue to guide–the management of urine-diverting toilets in eThekwini. The fact that toilet users would welcome a vault clearing service, and would prefer that the contents be removed offsite, is considered positive in light of eThekwini Municipality's present plans for nutrient collection and reuse. The support for vault emptying is especially strong in more urban areas. Addressing user satisfaction is vital for the next stage in the development of sanitation systems aimed at recovering nutrients. Results from the 2014 survey suggest that there has been a decrease in the proportion of respondents who have been educated about toilet usage and maintenance. With well targeted and designed educational activities, we may yet be able to overcome the remaining negative perceptions and barriers in relation to collecting and reusing excreta (Campaigning for Health and Hygiene, p. 30).

Figure 4: Some users were not satisfied with their urine-diverting toilet, because the doors were stolen or damaged, or the vent pipes were dysfunctional.

Key figures

	2011	2014
Respondents satisfied or very satisfied with their urine-diverting toilet	30 %	40 %
Respondents who maintain a pit latrine in addition to their urine-diverting toilet	14 %	17 %
Respondents who had received education on toilet usage	90 %	66 %
Complaints of smell	27 %	26 %
Respondents in support of a vault clearing service		80 %
• in the more rural areas		77 %
• in the more urban areas		82 %

School children learn about the health and hygiene aspects of urine-diverting toilets.

Campaigning for Health and Hygiene

Improving Health and Hygiene Education in eThekwini

- **Many households still do not completely approve of urine-diverting toilets.**
- **Health and hygiene education enhances proper toilet use and maintenance.**
- **The community appreciated the educational material developed by the Municipality.**
- **The feedback from the community shapes the education campaign.**

Figure 1: EWS facilitators and household members discuss whether the urine-diverting toilet is a permanent asset to the household.

Health and hygiene education meets sanitation

One of South Africa's development priorities is the provision of safe water and proper sanitation to its entire population. In the past, sanitation was seen mainly as a technical issue that included building toilets. However, toilets are not the only factor in the provision of good sanitation. Indeed, in order to break the cycle of sanitation-related disease, all the factors affecting sanitation must be addressed. It has become increasingly clear that social considerations are a vital part of the battle. Throughout the health and hygiene education campaign carried out in eThekwini, we explored how awareness promotes the acceptance, usage, and maintenance of urine-diverting toilets. Health and hygiene education is mostly about changing people's behaviour through raising awareness. We assume that everybody would like to be healthy and clean and that people who know about good hygiene also practice good hygiene. Awareness can be raised using different means of communication, for example, entertainment, education, or printed materials.

Developing a campaign using toilet users' own words

We aimed to study and understand how toilet users perceive toilets and hygiene. Our survey collected qualitative data through a process of data triangulation, using desktop analysis, in-depth interviews, and focus group discussions in three rural areas: Zwelibomvu, Lower Maphephetheni, and Hlanzeni. We probed participants' answers to elaborate and clarify the matters being discussed. All the interviews and focus group discussions were recorded and transcribed word for word in isiZulu, and were then translated into English. Our work was guided by a symbolic interactionism approach, a process by which meanings for individuals are formed through the interactions between individuals in a society. Categories were developed from these findings and were later coded to themes. People's perceptions and reported behaviours concerning toilets and hygiene formed the ba-

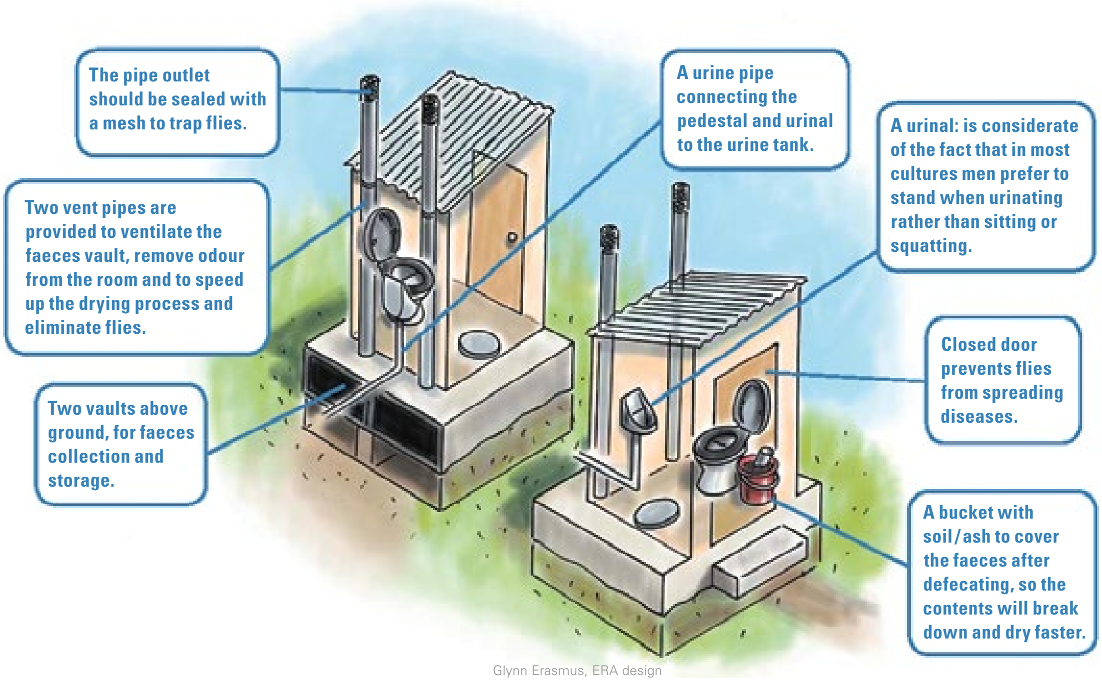


Figure 2: Educational material shows the urine-diverting toilet's physical structure and the importance of each item.

Category	Explanation	Percentage
Maintainers	The urine-diverting toilet is in good condition: all items intact, e.g. door, vent pipe. Broken items are repaired using appropriate materials.	17 %
Non-maintainers	The urine-diverting toilet is in bad condition: it has broken items, and they either remain unrepaired or are repaired using inappropriate materials.	80 %
Non-users	Households that have a urine-diverting toilet but choose not to use it.	3 %

Table 1: The study distinguished toilet maintainers, non-maintainers, and non-users.

sis for developing educational materials comprising leaflets, posters, a video, and workshops. These materials were presented in isiZulu language, the first language in all the study areas. The final stage was to test the educational materials in households, with community members, and at schools.

Urine-diverting toilet users aspire for more

One hundred and twenty people participated in our focus group discussions, and 25 key informants had in-depth interviews. Participating householders were grouped into categories based on the condition of their toilet (see Table 1). Overall, 97 % of households actually used their urine-diverting toilet. Of these, however, 80 % did not maintain them properly, failing to repair broken items, for example. Most people in this group reported not having received any education on toilet usage. The level of acceptance of urine-diverting toilets was very low. Strikingly, more than 90 % reported that they did not regard them as a permanent asset to their household: they aspired to have a flush toilet. Findings also revealed that children took the leading role in toilet maintenance and that younger survey participants better accepted the toilets as a permanent asset than older people. Findings further revealed that toilets are not a topic of interest and conversation in the community; people reported that they did not know how their neighbours felt about their toilets or whether they maintained them.

Engaging education material for all ages

Educational materials were developed to address the surveys' key findings about water scarcity, the benefits of urine-diverting toilets, the role and importance of each item in the toilet, the contamination cycle, and hand washing. However, different modules were developed for different groups: households, communities, primary schools, and high schools. A large proportion of the local inhabitants was receiving health and hygiene education for the first time. Focus group discussion participants were shocked to learn about water scarcity and the role that urine-diverting toilets were playing in saving water and the environment: "I'm excited about this information. All people need to know about this… you need to come again and again until we all know and understand." The fact that the campaign's six facilitators were university graduates and had been well trained on the modules contributed significantly to the successful roll out of this health and hygiene education campaign. The final evaluation will be carried out in the future as a separate project.

Key statements form toilet users

Preference	"I am waiting for the Municipality to come and change those urine-diverting to flush toilets." *Focus Group Discussion (FGD) Participant*
Role models	"If it was such a good toilet then why is our councillor not using it or even our president." *FGD Participant*
Happy with urine-diverting toilets	"We were given this toilet because there is no other suitable one for an area like this, so I have to be okay with it." *FGD Facilitator*
Unhappy with urine-diverting toilets	"Who wants to touch their own faeces really, we are human beings as well, we have feelings." *FGD Participant*
Benefits	"We were told about using the dried faecal matter as manure, but not all of us have gardens." *Ward Committee Member*

Municipal employees pick up urine from a local collection tank, where incentives are distributed for urine.

Incentives for Urine Production

Cash Transfers to Increase Toilet Use

- **Current use of urine-diverting toilets is low.**
- **Financial incentives were provided for bringing urine jerry cans to collection points.**
- **Cash payments were successful in increasing toilet use.**
- **Walking distance to collection points must be minimised to foster participation.**
- **Cash transfers could not only be a tool for improving sanitation but also for reducing poverty.**

Figure 1: Exchanging urine for tokens. Toilet users received tokens according to the volume of urine they delivered to the collection points during the pilot study. Tokens could then be exchanged for cash.

Many toilets, few users

Conditional cash transfers–cash payments linked to some kind of desired action or behaviour–have been successfully used to encourage school attendance, increase vaccination rates, and promote other similar, socially desirable behaviours. Prior to the VUNA Project, they had not been tested for sanitation. In the areas we studied, the majority of residents had access to a urine-diverting toilet, but consistent use and proper maintenance were lacking. Toilet use and hygiene are usually promoted using educational campaigns and health messages (Campaigning for Health and Hygiene, p. 30), but these are not always effective or sustainable. We wanted to test whether offering incentives for collecting and transporting urine to a collection point could encourage people to make greater use of their toilets. Furthermore, we wanted to determine whether incentivised collection would be a more cost-effective way to collect large quantities of urine for nutrient recovery than institutionalised collection (Optimising Urine Collection, p. 24).

Multi-phase data collection and field experiments

In order to determine the impact of cash transfers on the use of urine-diverting toilets, we first had to establish to what extent they were being used beforehand. Twenty-litre plastic tanks were installed on the outside of about 700 toilets in order to collect all the urine produced. The volumes generated were measured three times a week for a month in order to determine the daily average. We also administered household questionnaires to better understand family compositions, financial situations, and sanitation practices. Over approximately six months, we tested how households responded to different pricing schemes in which cash was offered in exchange for the urine to be collected and transported to a local collection point. We wanted to see how many people participated, how much urine they generated, and how these factors varied de-

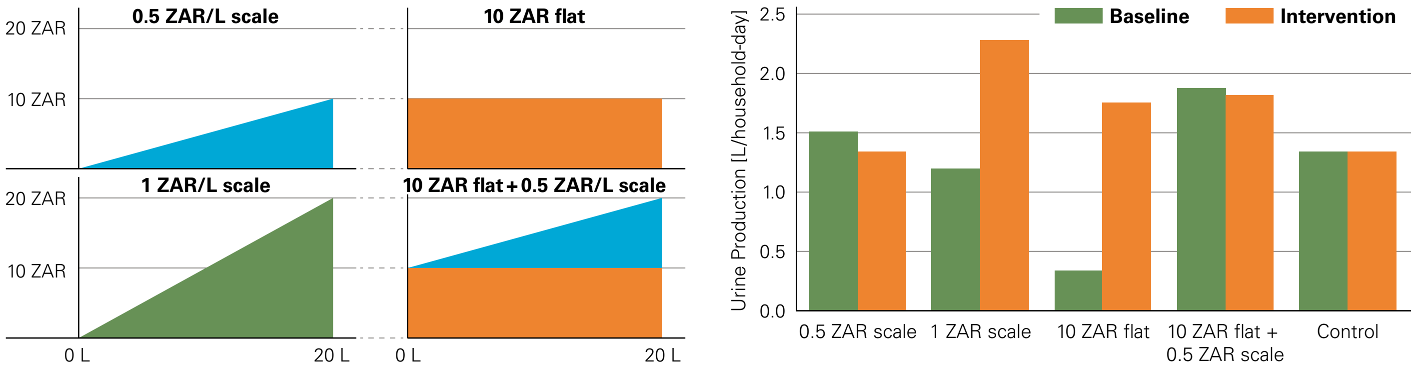


Figure 2: The cash transfer was different in each of the four study areas (left), in order to investigate what amount was necessary to encourage toilet users to collect and drop off their urine. Only the 1-ZAR scale and the 10-ZAR flat rate appeared to cause an increase in toilet use and urine production (right).

pending on the price and the distance that householders had to walk to deliver their urine. After this experiment, we carried out another household questionnaire in order to understand why people did or did not participate.

Use is low, but can be increased

Based on medical data, an average household of six people should produce at least 42 litres of urine a week. However, depending on how many people go to school or work, the volume collected at home would be somewhat less. Measurements before the incentive experiment showed that only about 10 litres per week were being collected, which is far below the possible maximum. When a small incentive of 0.5 ZAR per litre was offered, people did not produce more urine, and participation remained low. However, at the higher urine price of 1 ZAR per litre, production increased by almost 7 litres per household per week, or an increase of about 70 % over the initial level. People were effectively being compensated at twice the minimum wage for a 1 hour round trip walk, if they delivered a full tank. About 74 % of households collected at least one payment, while about 35 % of households participated weekly. Not surprisingly, however, longer walking distances correlated with lower participation and smaller volumes being delivered. We also determined that there was no typical participant, i.e. poorer families did not participate more than wealthier ones.

Figure 3: Encouraged by the incentives, a young toilet user delivers urine to a collection centre.

Willingness is a function of price

Measuring urine production at the household level was an easy, safe way to estimate toilet use that could be used by future projects. We were able to show that toilet use could be increased substantially by offering conditional cash payments. Although not every household participated, we now understand how the price per litre and programme implementation could be optimised to increase participation and toilet use. Although the incentive payments are costly, they induce a positive change in behaviour, whereas institutionalised collection likely does not have the same effect. In addition, the costs associated with the incentives help create local employment, reduce transport costs for the Municipality, and put much-needed cash into the hands of the very poor. Although this was a small study, conditional cash transfers for sanitation programmes appear to be a promising means of increasing toilet use, and over time they could encourage the formation of a sustainable habit.

Key figures

Exchange rate at the time of publication: 1 EUR =	13 ZAR
Number of tanks where baseline urine production was measured	700
Number of households benefiting from incentives	384
Maximum daily urine production rate per household	2.7 litres
Participants stating that incentives had a "big" impact on their budgets	95 %

The business model examined the value chain from urine collection to the final fertiliser product.

Business Model

Investigating the Value Chain for Source-separated Urine

- **The business model covers the value chain from urine collection to the final fertiliser product.**
- **Urine treatment in a large plant is less expensive, but transportation costs are higher.**
- **A concentrated liquid fertiliser can provide more revenue than a solid bulk fertiliser.**
- **Besides fertiliser, distilled water is another potential marketable product.**
- **Social, technical, and environmental boundaries also have to be considered when choosing a system.**

Figure 1: The business model examined different urine collection scenarios at various scales: A) twelve small decentralised urine treatment plants; B) two medium centralised treatment plants; C) one large centralised treatment plant.

Value and nutrient flows

The VUNA Project aims to reduce the overall costs of sanitation by recovering nutrients from urine and creating value from waste. To estimate the potential financial benefits that could be generated from source-separated urine, it is important to identify possible end products, establish their value, and estimate the costs along the value chain, such as those for the collection and treatment of urine, or for marketing the final products. In order to better understand the value chain, we analysed the various components of the nutrient recovery system with a business perspective using the so-called Business Model Canvas. The Canvas integrates components such as resources and activities, key partners, and customer relationships; it identifies the cost and revenue streams in the system. Based on an overall picture of the market that one intends to enter, the methodology also helps to explore potential market segments and to define market expectations towards a product.

Key Partners	Key Activities	Value Proposition	Customer Relations	Customers
• Water & Sanitation Utility • Local Service Providers • Etc.	• Collection • Treatment • Sales	• Reliable and safe emptying • Quality Fertiliser • Distilled Water	• Regular collection • Fertiliser sales	• Toilet owners • Public • Farmers • Etc.
	Key Resources		**Marketing**	
	• Urine • Funds • Personnel		• Value-added service • Niche products	

Cost Structure	Revenue streams
• Investment • Operation • Incentives	• Fees • Sales of end products

Figure 2: The "Business Model Canvas" integrates the components of a value chain from a business perspective.

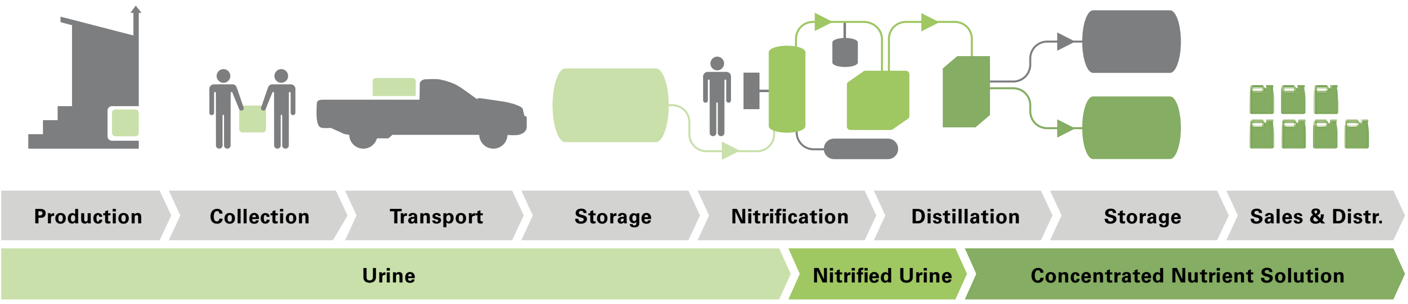


Figure 3: The VUNA value chain includes the nutrient recovery process from urine collection to the final fertiliser product. Urine collection and treatment at a larger scale will provide a more reliable estimate of the exact costs.

From urine collection to the fertiliser market

In the case of VUNA, the value chain ranges from urine collection at the household level to the sale of final fertiliser products. The research on the business model initiated a new pilot study on urine collection (Optimising Urine Collection, p. 24). This in turn incorporated findings from previous studies, but varied important parameters of this institutionalised approach–the size of household urine tanks and the frequency of collection by municipal workers. A separate study looked at a scheme in which toilet users dropped off their urine at collection centres (Incentives for Urine Production, p. 32). For the treatment of urine, the business model study focussed on the nitrification/distillation process, since this technology had proved its worth at a pilot scale and is able to recover all the nutrients in urine. Finally, the study evaluated the market potential for its final product and the prices of existing fertilisers by discussing these issues with fertiliser producers and sellers.

Plant size versus transport distance

On the cost side, urine collection has a high potential for further optimisation. During the pilot study involving 700 households, collection costs were as high as 4 000 ZAR per 1 000 litres of urine. Our calculations estimated that costs could be as low as 820 ZAR per 1 000 litres in an optimised system. The cost of urine treatment can be reduced by increasing the size of the treatment plants. Producing concentrated urine fertiliser in one of the VUNA pilot plants (Complete Nutrient Recovery, p. 6) cost about 1 900 ZAR per 1 000 litres collected urine. In a large plant treating 120 000 litres of urine per day (estimated daily volume from the 82 000 urine-diverting toilets in eThekwini), costs could be as low as 91 ZAR per 1 000 litres. On the revenue side, 1 000 litres of collected urine are worth 120 ZAR based on bulk fertiliser prices for nitrogen, phosphorus and potassium. However, specialised fertilisers such as flower fertiliser for the home market can have retail prices up to 80 times higher for the same amount of nitrogen, phosphorus, and potassium.

Integrating cost factors

The data from the business model indicated some general trends: in the case of eThekwini, treatment and collection costs could be reduced by approximately a factor of 20 compared to the costs of the pilot studies. However, more experience needs to be gained in optimising urine collection (Optimising Urine Collection, p. 24), and a better understanding of the technical and environmental risks of large urine treatment plants is required. On the revenue side, the type of end product will strongly influence the sales price: if the liquid fertiliser is sold based on bulk fertiliser prices, revenues will be low. If maximum revenue is the goal, the fertiliser will have to be marketed as a niche product, such as flower fertiliser. In addition to fertiliser, distilled water (a by-product of urine treatment) can also be sold to increase revenue. In order to make a final decision on the exact urine management scheme, more factors will have to be considered: job creation, available expertise and technology, environmental protection, and the possibility that the Municipality uses the fertiliser for its own green areas.

Elisabeth Real

Figure 4: Putting a price tag on VUNA liquid fertiliser: The business model compared fertiliser prices based on nutrient content, but also found out that retail prices vary greatly regardless of nutrient content.

Key figures

Estimated costs and prices per 1 000 litres of urine

Collection costs (depending on scale and optimisation)	820 to 2 000 ZAR
Treatment costs (depending on scale and optimisation)	91 to 1 900 ZAR
Net nutrient value (based on bulk NPK fertilisers)	120 ZAR
Retail price (depending on branding and product type)	120 to 10 000 ZAR

Key figures are under review and being developed further.

The VUNA team gathering at the Newlands-Mashu Field Test Site.

Project Team

The VUNA Family 2010 – 2015

Partner Institutions

Eawag
Swiss Federal Institute of Aquatic Science & Technology

EWS
eThekwini Water & Sanitation

UKZN
University of KwaZulu-Natal

ETHZ
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EPFL
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Swiss National Science Foundation
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Urine Collection Networks

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Further Readings

Selected VUNA Publications and Conference Contributions

Urine Treatment Processes

Etter, B., Hug, A., Udert, K.M. (2013) Total nutrient recovery from urine – operation of a pilot-scale nitrification reactor. WEF/IWA International Conference on Nutrient Removal and Recovery 2013, 28-31 July, Vancouver, Canada.

Etter, B., Udert, K.M., Gounden, T. (2014) VUNA – Nutrient harvesting from urine: lessons from field studies. WISA Biennal Conference, 25-28 May, Mbombela, South Africa.

Etter, B., Udert, K.M., Gounden, T. (2014) VUNA – Scaling up nutrient recovery from urine. Technology for Development International Conference, 4-6 June 2014, EPFL, Lausanne, Switzerland.

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Fritzsche, C. (2012) The formation of chlorinated organics during electrolytic urine treatment. Master's thesis, ETH Zurich.

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Fumasoli, A., Morgenroth, E., Udert, K.M. (2015) Modeling the low pH limit of nitrosomonas-type bacteria in high-strength nitrogen wastewaters. Submitted to Water Research.

Fumasoli, A., Weissbrodt, D., Wells, G.F., Bürgmann, H., Mohn, J., Morgenroth E., Udert K.M. (2015) Low pH selects for nitrosococcus in high and nitrosospira in low salt environments. In preparation.

Fumasoli, A., Etter, B., Sterkele, B., Morgenroth, E., Udert, K.M. (2015) Complete nutrient recovery from urine in a pilot-scale nitrification/distillation plant. IWA Conference Nutrient Removal and Recovery, 18-21 May, Gdansk, Poland. In Preparation.

Grau, M.G.P., Rhoton, S., Brouckaert, C.J., Buckley, C.A. (2015) Development of a fully automated struvite reactor to recover phosphorus from source-separated urine collected at urine diversion toilets in eThekwini. Accepted for Water SA.

Grau, M.G.P., Etter, B., Hug, A., Wächter, M., Udert, K.M., Brouckaert, C., Buckley, C. (2012) Nutrient recovery from urine: Operation & optimization of reactors in eThekwini. International Faecal Sludge Management Conference, 29-31 Oct, Durban, South Africa.

Grau, M.G.P., Etter, B., Udert, K.M., Brouckaert, C.J., Buckley, C.A. (2012) Development and operation of struvite reactors to recover phosphorus from source separated urine in eThekiwini. WISA Biennial Conference, 05-09 May, Cape Town, South Africa.

Grau, M.G.P., Rhoton, S.L., Brouckaert, C.J., Buckley, C.A. (2013) Development of a fully automated struvite reactor to recover phosphorus from source separated urine collected at urine diversion toilets in eThekwini. WEF/IWA International Conference on Nutrient Removal and Recovery 2013, 28-31 July, Vancouver, Canada.

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VUNA - By recovering nutrients from urine, we want to develop a dry sanitation system, which is affordable, produces a valuable fertiliser, promotes entrepreneurship and reduces pollution of water resources.

Elisabeth Real

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