Development of a novel nutrient recovery urinal for on-site fertilizer production

Article *in* Journal of Environmental Chemical Engineering · September 2018

DOI: 10.1016/j.jece.2018.09.060

2 authors, including:

Dyllon Randall
University of Cape Town
25 PUBLICATIONS **339** CITATIONS

Journal Pre-proof

Development of a novel nutrient recovery urinal for on-site fertilizer production

C.P. Flanagan and D.G. Randall

doi.org/10.1016/j.jece.2018.09.060

To appear in: Journal of Environmental Chemical Engineering

Received Date: 4 July 2018
Revised Date: 22 September 2018
Accepted Date: 28 September 2018

Please cite this article as: Flanagan CP, Randall DG, Development of a novel nutrient recovery urinal for on-site fertilizer production, Journal of Environmental Chemical Engineering, 6 (2018) 6344-6350. doi.org/10.1016/j.jece.2018.09.060

Development of a novel nutrient recovery urinal for on-site fertilizer production

C.P. Flanagan and D.G. Randall

Civil Engineering Department, University of Cape Town, 7700 Cape Town, South Africa, dyllon.randall@uct.ac.za

Abstract: Waterless urinals can save significant amounts of water but they can also be used to separate concentrated urine at source. Urine collection in established buildings is often costly because the plumbing system must be retrofitted for separate urine pipes. In addition, waterless urinals often have issues with blockages because of solids building up in the piping system.

To solve these challenges, we have developed a nutrient recovery urinal that uses no water and does not have to be connected to a conventional sewage line to operate. We designed and constructed the urinal using a plastic funnel and collection tank. The urinal recovered 11.23 ± 1.3 g of solid fertilizer per kg of urine and we found that 1000 nutrient recovery urinals could produce an income of $85/day. This novel approach offers a new and easy method for collecting urine within office blocks or other commercial buildings. In addition, the recycling of nutrients at source offers a more sustainable and environmentally method for fertilizer production since minimal energy is required and "waste" streams are converted into useful products.

Keywords: ammonia; calcium hydroxide; calcium phosphate; stabilization; urea hydrolysis; urine

Introduction

Much like other parts of the world, the City of Cape Town in South Africa is currently experiencing a severe drought with the average volume of water in dams being at 24.4% in February 2018 (City of Cape Town, 2018). The water shortage has been a driver for the city to consider waterless sanitation systems, both by the City of Cape Town and citizens. Sanitation systems such as waterless urinals would therefore help cities prepare for a water sensitive future.

In addition, waterless urinals offer an excellent method for separating urine and are well suited for office blocks because they (1) use no water for flushing, (2) can reduce operating costs for buildings, (3) water utilities can offer building owners fee discounts and (Gary Bristow et al., 2006) (4) provide novel nutrient recovery opportunities such as using ion exchange to remove nutrients (Boyer et al., 2014). Urine is rich in three key ingredients required for fertilizer production: nitrogen, phosphorus and potassium, contributing about 80% of the nitrogen, 56% of the phosphorus and 63% of the potassium typically found in domestic wastewater streams (Höglund, 2001). In addition to being rich in nutrients, the urine stream only makes up 1% of the volume of domestic wastewater streams (Larsen and Gujer, 1996). There is no doubt that urine is valuable. In fact, a recent review paper refers to urine as "liquid gold" because of its value. The paper also describes how we should re-examine our current sanitation systems to gain maximum benefit from urine (Randall and Naidoo, 2018).

However, waterless urinals are not widely used because of maintenance issues as a result of pipe clogging (Hashemi et al., 2015), odour concerns (Gary Bristow et al., 2006) and the need to retrofit the plumbing system of buildings (Udert, K.M. et al., 2003). The removal of key minerals responsible for pipe clogging could potentially solve some of these challenges. For example, Boyer showed that ion exchange could be used to remove calcium and magnesium from urine thus minimising mineral precipitation (Boyer et al., 2014). Odour concerns can be remediated by installing sealant liquid traps, membrane traps or biological blocks (Chariar and Sakthivel, 2009).

Since the clogging of pipes is a major concern with waterless urinals, it is important to understand how this happens by understanding the chemistry of urine (Boyer et al., 2014). Fresh urine hydrolyzes in the presence of microbial urease (Mobley and Hausinger, 1989) and produces ammonium carbonate and an increase in pH (Boyer et al., 2014). This leads to the precipitation of struvite and other minerals. This is the reason for the clogging of waterless urinals which can be avoided by preventing urea hydrolysis or forcing mineral precipitation to occur (Boyer et al., 2014; Larsen et al., 2009). Thus, if the precipitation process can occur in a removable container attached to a waterless urinal, these issues could be avoided.

The use of calcium hydroxide has been shown to be an effective method for stabilizing urine (preventing enzymatic urea hydrolysis) (Randall et al., 2016). This is because an increased pH results in the precipitation of calcium phosphate and magnesium hydroxide while also inhibiting the activity of urease, the enzyme responsible for enzymatic urea hydrolysis (Randall et al., 2016). In addition, the use of calcium hydroxide can be used as a passive dosing system in the urinals, dissolving as needed provided enough calcium hydroxide is added to the container. Randall and co-workers (2016) suggested a dosage of 10 g $Ca(OH)_2$ per L of urine, thus if the collection tank is 25 L, only 250 g of $Ca(OH)_2$ would be needed per urinal. This method also means the urine could be collected and stored indefinitely, provided the container is sealed and the pH remains above 12. The fundamental study by Randall and co-workers in 2016 laid the groundwork for the applied research work presented here where we report on the development and testing of a standalone and waterless fertilizer-producing urinal that does not need to be connected to a conventional sewage line.

Material and Methods

Urinal design

The makeshift nutrient recovery urinal used for the experimental process consisted of plastic components (see Figure 1). The design was found to be sturdy and successfully completed the task of collecting urine in a public bathroom such that calcium phosphate formed in the removable collection container.

The urinal itself consisted firstly of a urine collection funnel, which guided urine gradually downwards into the tank below. Secondly, the urinal had a 25 L collection tank below the funnel. This was used to capture the donated urine and house it in such a way as to mix with the pre-dosed calcium hydroxide powder. Lastly, the urinal featured a backsplash board to prevent urine from spraying back out of the funnel. The funnel was connected to the collection tank via a threaded PVC pipe which deposited urine below the actual thread. The current urinal was open to the atmosphere but future designs will include a one-way valve. In addition, the contents of the urinal were mixed manually for 30 sec each day. We found that daily mixing was adequate to keep the solution pH above 12.

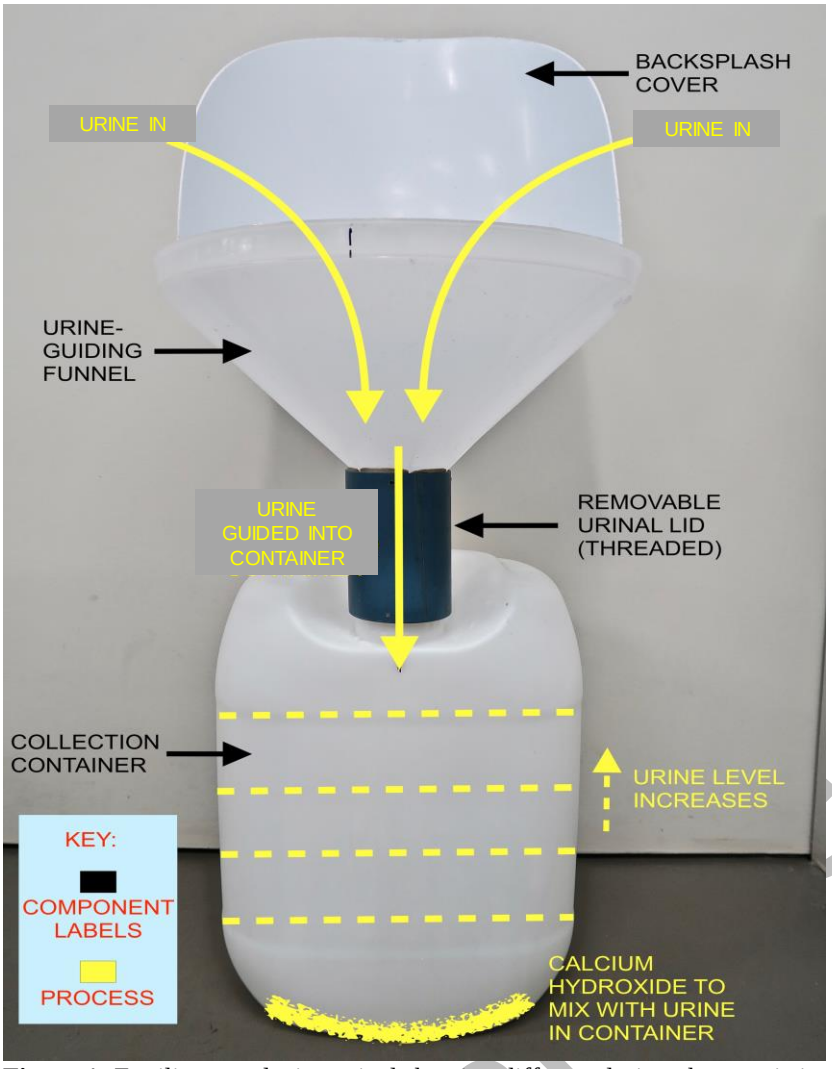

Figure 1: Fertilizer-producing urinal showing different design characteristics.

Urine collection

The urinal was installed in a male bathroom in the New Engineering building at the University of Cape Town (UCT), South Africa. Signage indicating the aims and scope of the project were placed above each urinal, as well as a consent form, the completion of which was stated as a mandatory step before donating urine. This consent form was in accordance with the UCT ethic's approval policy on the use of human subjects for research purposes.

The urinal was pre-dosed with 10 g $Ca(OH)_2$ per litre of urine thus resulting in a total mass of 250 g $Ca(OH)_2$ per 25 L urinal (Randall et al., 2016). Urine was then donated into the collection tanks by male donors and the level of urine within each collection tank was monitored daily to avoid over-filling of the tanks. Donors could donate as often as they would like. An empty urinal, except for the addition of $Ca(OH)_2$, was then installed to allow for the subsequent collection of urine. In total, there were 4 collections of urinal containers thus the experiment was repeated 4 times (see Table 1).

The urinal was used for a period of one month and the donors were anonymous. The urinals were in operation Monday to Friday from 8am to 17:00 each day. When not in use, the urinal collection tank was removed, sealed with a lid and stored in a refrigerator overnight at 4°C. The temperature of the urine is given in Table 1. The temperature was not monitored continuously but it was measured after a urinal container collection.

Urine processing

All donated urine was then carefully removed from the collection tank whenever the tank was full. This was performed within the confines of the Civil Engineering Water Quality laboratory at UCT. The contents of the tank were initially allowed to settle completely so that the solid precipitate could settle to the bottom of the tank. The liquid supernatant was then slowly and carefully removed by pumping. The liquid supernatant was send for analysis. The remaining liquid and solid precipitate in the collection tanks was then re-mixed to form a sludge. This sludge was filtered to separate the remaining liquid and solids using a vacuum filter and Buchner funnel. The diameter of the filter paper was 150 mm with a pore size of 1.2 μm (595 Schleicher & Schuell, Dassel Germany). The solids were kept in aluminium drying trays (32 x 26 x 6 cm) and dried at ambient room temperature (~22°C) until all liquid had evaporated. The amount of solid remaining was then determined by measuring the net mass of solids in the trays. The process produced a solid fertilizer as well as a liquid fertilizer.

Analysis of precipitates

The mineral composition of the solid precipitates was established by powder X-ray diffraction (XRD) using a Phillips PW 3710/40 (PANalytical, Almelo, The Netherlands) fitted with a curved graphite monochromator. X-rays were produced with a PW 1830/00 generator using a copper K-α X-Ray tube with X-ray wavelength of 1.542 A, accelerating voltage of 40 kV and current of 25 mA. Bragg 2Θ angles between 5° and 75° were used for analysis. A continuous scan step size of 0.02° was applied with a scan step time of 0.5s.

Infrared (IR) spectra of the solid precipitate were also determined with a Perkin–Elmer Spectrum 100 FTIR spectrometer (Perkin-Elmer, Waltham, U.S.A.). In addition, the solids were digested with 1 M HCl. Approximately 0.1 mg of the solid precipitate was added to a 100 mL volumetric flask, to which 50 mL deionised water and 10 mL HCl was added. The solution was then mixed and topped up to the 100 mL mark and further mixed for 1 hour at room temperature. The solution was then filtered using a 250 mL Buchner funnel with cellulose acetate membrane filter paper of pore size 0.45 μm (KimLab,

Cape Town, South Africa). A liquid sample was sent for analysis to determine concentrations of Mg^{2+}, NH_3-N, Ca^{2+} and PO_4-P.

Analytical methods

A pH probe (HI1131B, Hanna Instruments, Rhode Island, United States) was used to measure the pH and temperature of the solution. The device was calibrated daily, before any measurements were taken.

The liquid supernatant was analyzed to determine the concentration of: Ca^{2+}, NH_4^+, PO_4^{3-} and urea. The calcium concentrations were measured using a colorimetric method. A Thermo Scientific Gallery (ThermoFisher Scientific, Massachusetts, United States) automated this process. Samples were diluted with deionized water when necessary and analyzed within 30 min of sampling. Ammonium samples were acidified with 0.1M HCl to a pH of 3.5 ± 0.5. The acidification of the sample prevented volatilization of ammonia and inhibited the hydrolysis of urea such that the sample composition remained stable (Hellström et al., 1999). The nitrogen was expected to be in the Free and Saline Ammonia (FSA) form and hence an FSA test was carried out. The samples were first diluted by a factor of 50 with deionised water using a 50 mL volumetric flask. The standard total Kjeldahl nitrogen method was used to determine the nitrogen concentrations. The concentration of phosphorus was measured after treatment with calcium hydroxide using inductively coupled plasma optical emission spectrometry (735 Series, Agilent, Santa Clara, United States).

For the urea concentrations, the stabilized urine was diluted by a factor of 50. A 0.5 mL sample of the diluted sample was then transferred to 15 mL graduated vials in triplicate to which 40µL of urease (U1875-25mL, Sigma Aldrich, St Louis, United Sates) was added. Deionised water was then added to the vials until the 8 mL mark was reached. The pH of the solution was measured using a pH probe, and was adjusted to between 7 and 8 as this is the optimal pH range for urease. The solution was further diluted until the 10 mL mark on the graduated vial was reached. This resulted in a total dilution factor of 1000. The solution was stirred using a shaker and was allowed to rest for 1 hour at room temperature. The triplicate 10 mL solutions were then transferred to Kjeldahl's flasks and free and saline ammonia test was carried out. The difference between the final and initial nitrogen concentrations were then used to determine the concentration of urea.

Results and Discussion

Fertilizer production

The total solids collected from approximately 100 L of urine over a three-week period was 1.1 kg. On average, a full collection container resulted in 11.23 ± 1.3 g of solid per kg of urine collected. In order to extrapolate this figure over an entire university such as the UCT, a total number of potential urinals needs to be considered. The UCT has 260 standard urinals on its Upper Campus and for this calculation it was assumed that each of these urinals were retrofitted with a container for urine collection and fertilizer production. This study found that it took 3.75 ± 0.9 days to fill one 25 L collection tank with urine. Assuming a higher compliance of one day, the amount of urine that could be collected per day from the UCT is estimated to be 6500 L/day or 73 kg fertilizer per day. The mass balance of this is given in Figure 2A.

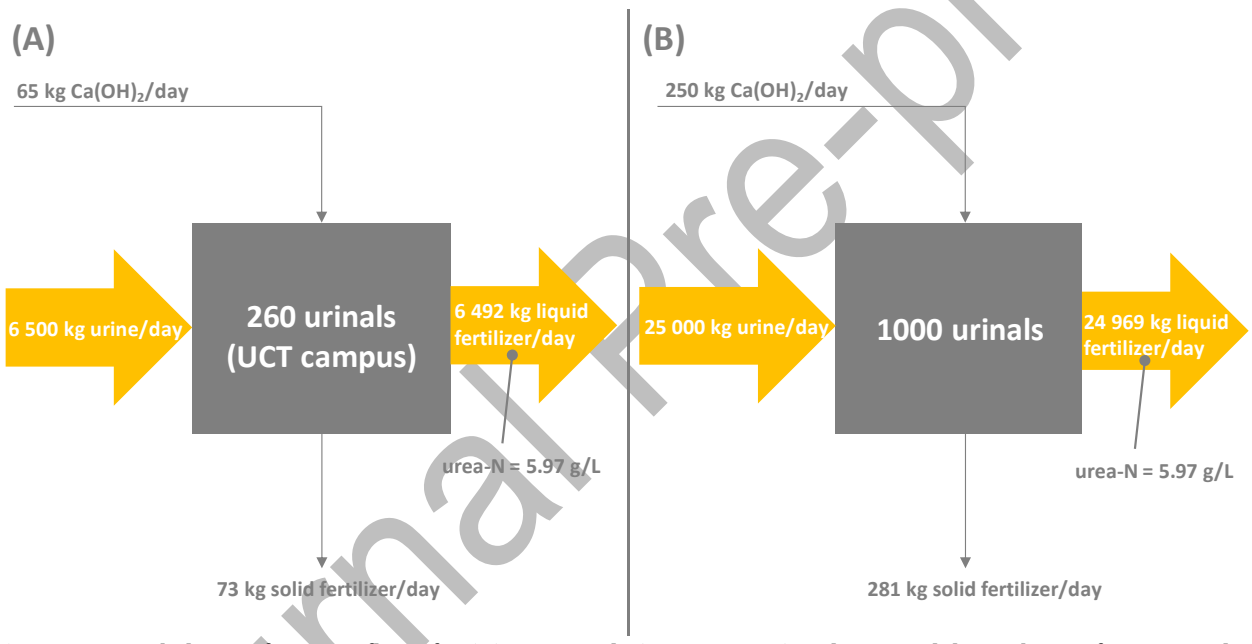

Figure 2: Mass balance of nutrient flows for (A) 260 urinals (UCT campus) and a general design basis of 1000 urinals (B). Only the solid fertilizer (calcium phosphate) and the liquid fertilizer (urea) are shown.

Chemical analysis

The average concentration of phosphorus in the liquid fraction of the stabilized urine was found to be 6.17 ± 0.124 mg/L (see Table 1). Since the initial concentration of phosphorus is not known, as the fresh urine is immediately stabilized with calcium hydroxide in the collection tank, thus resulting in the precipitation of calcium phosphate, it is impossible to determine the exact percentage recovery of phosphorus for these experiments. However, assuming the concentration of phosphorus in fresh urine is between 260 mg/L (Randall et al., 2016) and 388 mg/L (Etter et al., 2011), the recovery of phosphorus would be greater than 95%. This is consistent with recovery rates obtained by (Randall et al., 2016) using the same urine stabilization method. Importantly, the initial phosphorus concentration

in the urine could not be measured for each urine donor because the urine was immediately stabilized with calcium hydroxide upon addition of the urine to the collection tank. This resulted in the precipitation of calcium phosphate and thus a decrease in the aqueous concentration of phosphate ions.

The average measured Ca^{2+} concentration within the collected urine, after stabilization with $Ca(OH)_2$, was found to be 995 ± 72.3 mg/L (Table 1) which is close to the expected solubility of calcium hydroxide in stabilized urine (1075 mg/L) (Randall et al., 2016).

Table 1: Properties of stabilized urine obtained from each 25 L urinal. There were four collections in total. A dosage of 250 g $Ca(OH)_2$ was added to each urinal. The mass collected included the urine, undissolved calcium hydroxide and solid precipitate (fertilizer) while the dried mass was obtained after filtering the solids from the liquid fraction. *This concentration was not included as it was an outlier because of an analysis error.

Parameters	**Container Number**				**Mean**	**Std. Dev.**
	1	**2**	**3**	**4**		
pH	12.34	12.17	12.4	12.35	12.32	0.10
Temperature (°C)	20.1	19.3	19.3	19.2	19.5	0.42
Urea (mg/L)	13 900	12 100	12 300	*	12 800	987
NH_4-N (mg/L)	350	310	380	385	356	34.5
PO_4-P (mg/L)	6.25	5.98	6.21	6.22	6.17	0.124
Total Ca (mg/L)	923	943	1045	1068	995	72.3
Total Mg (mg/L)	14	14	14	19	15.3	2.50
Total K (mg/L)	588	550	755	589	621	91.5
$Ca(OH)_2$ added (g)	250.0	250.4	250.0	250.0	250.1	0.180
Mass collected (kg)	25.7	24.0	24.4	24.1	24.5	0.783
Dried mass (g)	263	249	272	318	276	29.9

Randall and co-workers showed that enzymatic urea hydrolysis can be prevented by stabilizing urine with calcium hydroxide since a higher pH prevents the reaction from occurring (Randall et al., 2016). The temperature of the solution was also critical for preventing chemical hydrolysis and it was suggested that the temperature should not exceed 40°C. This was achieved by storing the stabilized urine at an average temperature of 19.5°C. The prevention of urea hydrolysis is important for ensuring that the liquid component of the urine sample retains its nitrogen content during storage. The average urea concentration was found to be 12 800 ± 987 mg/L (Table 1) thus indicating that limited urea hydrolysis had taken place. In fact, the concentration was still high after several days of storage in the sealed container.

The initial ammonia content of the liquid component was expected to remain consistent with that of regular human urine, assuming that enzymatic urea hydrolysis was prevented. Typical concentrations of ammonia in fresh urine is 416 ± 72 mg N/L (436 mgN/L (Randall et al., 2016); 480 mg N/L (Udert, K. M. et al., 2003) and 333 (Beler Baykal et al., 2009)) . The average measured ammonia content of

the urine samples, across all four containers, was 356 ± 34.5 mg N/L. This shows that the ammonia concentration of the samples was a lower-than-average concentration when compared to the average of the three values taken from literature. Despite this, the initial average ammonia concentration was comparable to standard concentrations found in fresh human urine and thus indicated that no urea hydrolysis had likely occurred.

The XRD analysis of the solid product detected no phosphorus compounds which indicates either phosphorus was not present in the solid sample, the compound was non-crystalline or the compound was not present in the XRD database (Figure 3). However, phosphorus was detected during the digestion of the solid (see Table 2) and FTIR confirmed phosphate peaks typical of amorphous calcium phosphate (ACP) (Combes and Rey, 2010) (see Figure 4). In addition, the slight inflection around the 1163 spectra could possibly be attributed to non-stoichiometric ACP (Gadaleta et al., 1996). Meyer and Weatherall (Meyer and Weatherall, 1982) showed that ACP occurs at higher pH values and transforms to the crystalline form, hydroxyapatite but the presence of magnesium could inhibit this transformation (Boskey and Posner, 1974; Root, 1990). Considering that urine has magnesium, and many other elements present, it is likely that this transformation was indeed inhibited during the precipitation process and hence no crystalline structure was detected by XRD. The exact chemical formula of the ACP could not be determined because the Ca/P in ACP has a wide range from 1.2 – 2.2 and it was not possible to determine the amount of calcium in the sample attributed to excess calcium hydroxide. The digestion of the solid also detected magnesium (Table 2), which was expected because of the high pH values (Randall et al., 2016). The nitrogen present in the sample was likely due to the fact that the samples were not washed and thus residual liquid evaporated during the drying process leaving behind small quantities of urea. The XRD results from this study are consistent with the results from (Randall et al., 2016) and confirm that ACP forms over an extended period of operation.

Table 2: Concentrations of elements present in solid precipitate after digestion

	Sample number			
	1	**2**	**3**	**Average**
Mg (g Mg/kg solid)	11.87	12.30	12.52	12.2 ± 0.33
NH_3-N (g NH_3/kg solid)	0.20	0.040	0.15	0.130 ± 0.082
Ca (g Ca/kg solid)	343.8	342.8	343.42	343 ± 0.53
PO_4-P (g PO_4/kg solid)	20.18	20.10	20.10	20.1 ± 0.046

The FTIR analysis also showed the presence of calcium carbonate which was consistent with the work conducted by Kalinkin and co-workers (Kalinkin et al., 2005) (Figure 4). In addition, XRD also detected calcium carbonate present in the solid sample as well as calcium hydroxide (Figure 3). The presence of calcium carbonate is as a result of dissolved CO_2, either from urea hydrolysis or from the

ambient air which precipitates as $CaCO_3$ because of the high concentrations of Ca^{2+} in the stabilized urine (Pradhan et al., 2017). The drying process would speed up the dissolution of CO_2 in air and cannot be avoided in this setup. The air could be pre-treated with moist lime or wood/fly ash to reduce the concentration of CO_2 in the drying air thus avoiding this issue. Regardless, the product can still be used as an inorganic fertilizer with low pH soils. For example, Meyer and co-workers recently showed that the fertilizer produced using this stabilization and drying method produced fertilizer that was almost as effective as water-soluble P fertilizers (Meyer et al., 2017). However, the results are inconclusive as to the exact chemical formula of the ACP and further investigations should be conducted to better understand the solid product produced during this novel urine treatment process.

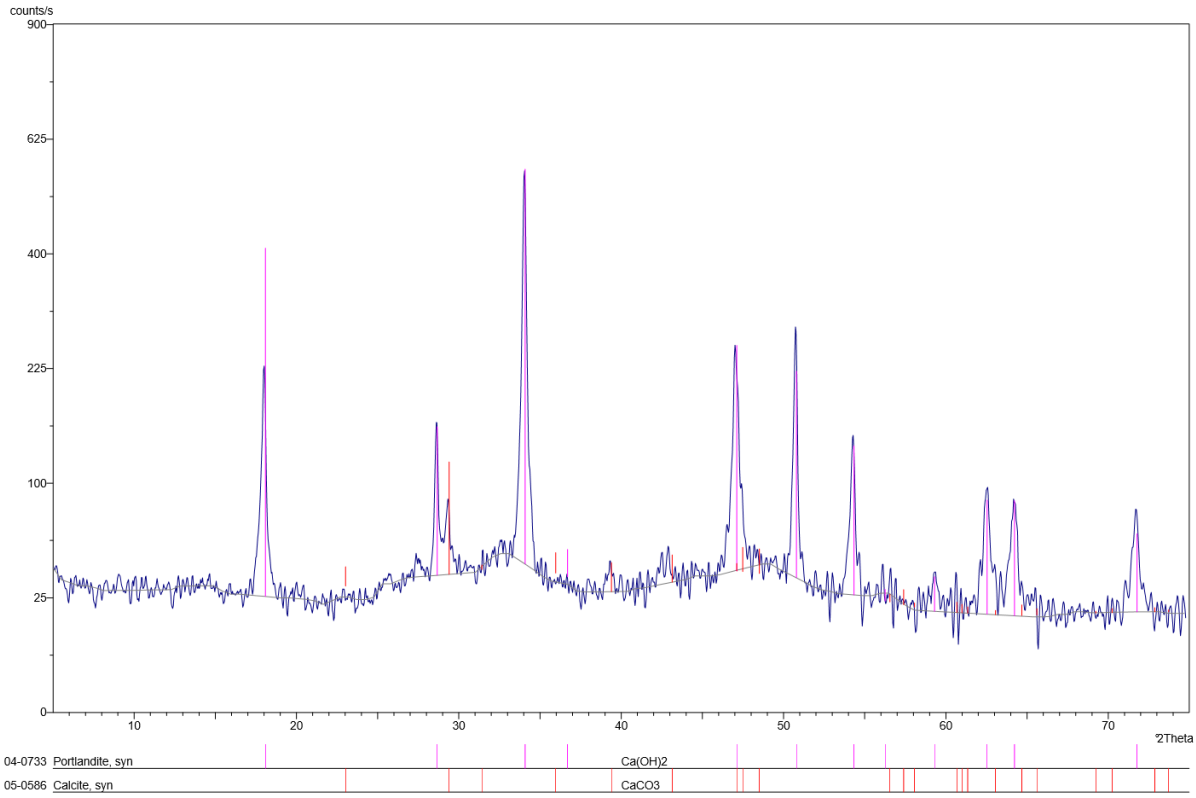

Figure 3: XRD analysis of the solid precipitate formed in the urinal. The analysis detected $Ca(OH)_2$ and $CaCO_3$ but no magnesium compounds or phosphate compounds.

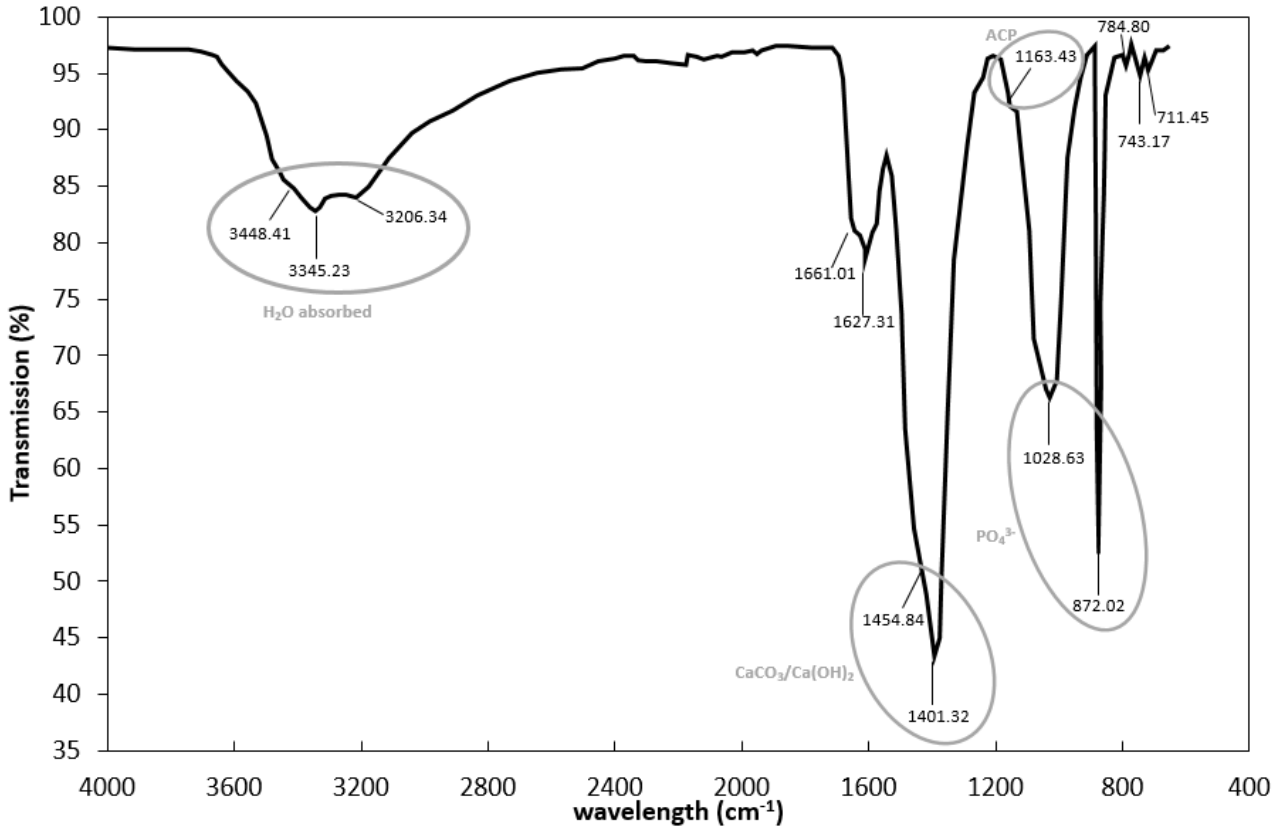

Figure 4: FTIR analysis of the solid precipitate formed in the urinal.

Water Saving

One of the key implications of collecting fresh urine in a waterless urinal is that no water is required to dilute the urine or to flush it away. In fact, water is avoided as this will only serve to increase the cost and volume of urine requiring treatment. Regular urinals can use up to 4 liters of water per flush (von Munch et al., 2009) while more efficient models can reduce this to 2 liters per flush. The number of flushes can be reduced by installing automatic flushes, sensor activated flushing systems, low flushing systems or no flushing systems (waterless urinals). Figure 5 shows the annual water consumption we calculated for different types of urinal flushes that are typically used on UCTs Upper Campus. The sensor activated systems used the most amount of water since they are dependent on the number of users per day. The low flushing system uses 5.12 m^3 (assuming 4 L/flush) of water per annum but when this is compounded with several urinals in an office block or an entire city, this amount of water could be substantial. Considering that potable water is often used to flush urinals, and an ever-increasing risk of water shortages, waterless urinals should be the norm for all commercial buildings. For example, UCT used about 8 Olympic sized swimming pools of water just to flush their urinals in 2017 (unpublished results). The water saved also results in direct operating cost savings for buildings. The price of water varies from country to country with Denmark currently having the highest cost ($6.7 per kL) (Kjolberg, 2016) so these cost savings could be significant.

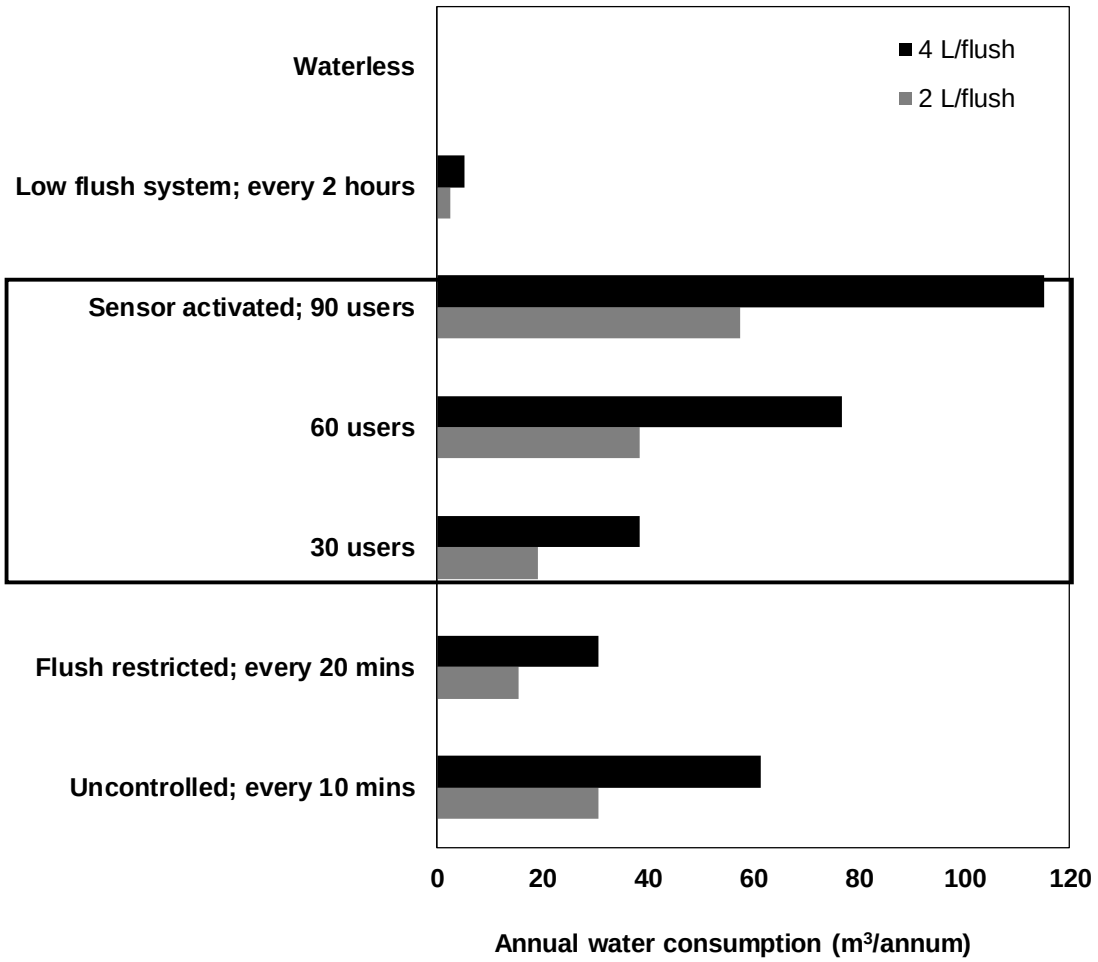

Figure 5: Annual water consumption for different types of urinal flushing assuming 2 L and 4 L of water is used for flushing. The calculations are based on a standard working day of 8 hours and 320 days per year of work.

Financial Implications

The urinals used in this study were constructed in South Africa using a 25 L Jerry can ($20.12), funnel and piping system ($2.34) and splash-back ($1.98), a total of $24.44 per urinal. It is expected that this price would decrease as more urinals are constructed. For example, considering economies of scale, the cost to make 1000 urinals is expected to decrease to $5.83 from a base-case of $24.44, assuming the six-tenth rule (Berthouex, 1972).

The nutrient recovery urinals used in this study recovers calcium phosphate on-site which could be sold for $4.45 m^{-3} of urine. In addition, ammonium sulfate could be produced from the remaining liquid fraction for a profit of $9.68 m^{-3} of urine (Pradhan et al., 2017) while there is potential to also produce potassium-based fertilizer from the urine (Ledezma et al., 2015). A summary of the cost calculations is given in Table 3 and shows that $85/day could be made from 1000, 25 L urinals. The solid fertilizer and urea rich solution nutrient flows are given in Figure 2B. A detailed economic analysis would need to be conducted to obtain more accurate values that includes capital, labour and

maintenance costs while also taking into account indirect benefits such as reduced nutrient loads to WWTPs, reduced water bills, reduced building maintenance costs (because of reductions in pipe blockages) and improved environmental conditions.

Table 3: Theoretical economic assessment for urine collected in novel nutrient recovery urinals

Item	Amount kg/day	Cost $/day	Reference
Expenses			
$Ca(OH)_2$	250	30.6	(Corathers, 2016)
Energy for Ca-P drying	-	0	
Ammonium sulfate process		249	(Pradhan et al., 2017)
Total expense		279	
Income			
Ca-P + $CaCO_3$	281	111	(Pradhan et al., 2017)
Ammonium sulfate	836	242	(Pradhan et al., 2017)
Potassium fertilizer	30.1	10.8	(Jasinski, 2017)
Total income		364	
Total profit		**85**	

Note: calculations based on 1000 urinals and a total urine production of 2500 kg/day. Calculations were based on recent work by (Pradhan et al., 2017) but updated based on our concentrations. The calculations do not include capital costs, labour or maintenance costs. It was assumed that the drying of the Ca-P + $CaCO_3$ mixture would occur at room temperature and thus there is no energy demand for this. Indirect benefits such as reduced nutrient loads to WWTPs and environmental damage were not included in the calculations. A recovery rate of 93% for ammonium sulfate was assumed (Pradhan et al., 2017). All values are in US dollars.

Other considerations

Future design considerations

The urine-$Ca(OH)_2$ mixture should be mixed at least once a daily to ensure the pH of the solution remains above 12 such that enzymatic urea hydrolysis is avoided (Randall et al., 2016). The contents of the urinals were manually mixed for 30 seconds in this study. We found that this duration of mixing was sufficient to maintain a high pH. The high solubility of calcium hydroxide and the addition of urine to the container helped facilitate dissolution of calcium hydroxide in the urine. The manual mixing is not ideal though and an automated mixing system would have to be implemented going forward. This could be achieved by installing a mixer from the side of the collection tank, connected to a small solar panel and timer. The energy requirements are expected to be minimal since only 30 seconds of mixing is required per day to maintain a high solution pH. The exact energy consumption would need to be measured in any future urinal designs though.

Social acceptance

A recent survey at a university in the Southeastern region of the United States showed that 84% of respondents would vote in favour of urine separation in residence halls (Ishii and Boyer, 2016). Water conservation was one of the most important benefits and respondents were also overwhelmingly happy to use urine-based fertilizers (Ishii and Boyer, 2016). Similar results were found from 7 European countries with an 80% acceptance of urine separation (Lienert and Larsen, 2010). In a separate survey conducted in Hawaii, female respondents (48%) were less likely than male respondents (65%) to install urine diversion toilets at home for free (Lamichhane and Babcock, 2013). It is important to educate users as to the benefits of such devices in which would increase their usage while also spreading the importance of using such devices (limited natural phosphate rock reserves, water scarcity etc.).

Heavy metals, pathogens and pharmaceuticals

Urine is inherently sterile (Bennett et al., 2017) but it can be cross-contaminated with faeces (Schönning et al., 2002). However, this cross-contamination is expected to be less with urine that is collected directly in urinals. A study found that 64% of 212 pharmaceuticals were found in excreted urine (Lienert et al., 2007). While pharmaceuticals are found in the liquid phase of urine, much lower concentrations are found in solid precipitates formed form urine. For example, (Ronteltap et al., 2007) showed that 98% of hormones and pharmaceuticals remained in the liquid phase of urine during struvite precipitation while struvite precipitated from normal urine had heavy metals below the detection limit. In addition, the implementation of proper washing and drying steps can inactivate and remove pharmaceuticals from end-products (Bischel et al., 2015). The high pH values obtained during urine stabilization with $Ca(OH)_2$ is also expected to kill viruses and pathogens. Nonetheless, technologies focusing on pharmaceutical removal from the liquid phase of urine should be considered, especially if liquid fertilizers are to be produced from the urine.

Transport considerations

Urine is predominately water and it is more expensive to transport large volumes of liquid, instead of concentrated urine or solid products. To reduce transportation costs, urine should be ideally treated on-site at locations where large volumes are generated (Etter et al., 2011). This would be ideal in office blocks where the fertilizer could be produced on-site. If this is not an option, the stabilized urine and fertilizer could be transported from several commercial buildings to a decentralised resource recovery. This cost of this would have to be factored into the business model of the process though. Kavvada and co-workers recently showed that decentralized urine treatment using ion-exchange has lower costs and greenhouse gas emission when compared to centralized nitrification-denitrification process for

fertilizer production (Kavvada et al., 2017). A comprehensive life cycle assessment should be conducted to see which resource recovery and transportation method is best, both in terms of economic viability and environmental impact.

Conclusions

We envision a sustainable future where buildings become mini-resource recovery plants, providing much needed fertilizer within the confines of major cities and agricultural areas surrounding cities. The use of novel fertilizer-producing urinals offers one method for recovering valuable nutrients directly from human urine. We utilize the scaling potential of the urine to form calcium phosphate in the collection tank of the urinal, rather than allowing it to form in the plumbing system. The high pH of the stabilized urine prevents ammonia formation as well as other smells typically associated with stored urine. In addition, we have confirmed that stabilizing urine with calcium hydroxide prevents the enzymatic urea hydrolysis thus allowing the urine to be stored for extended periods of time with limited nitrogen loss. We recovered 11.23 ± 1.3 g of solid fertilizer per kg of urine and found that 1000 urinals could produce a profit of $85/day. Future designs of nutrient recovery urinals should be incorporated into existing urinals such that the original urinal is kept in place while the outlet of the urinal is connected to a collection tank housing the mixer and calcium hydroxide. This tank would have to be removable so that the stabilized urine and fertilizer can be easily transported when full.

Acknowledgements

The authors would like to gratefully acknowledge the University of Cape Town for their financial support. We also wish to thank Njabulo Thela and Hector Mafungwa from the Water Quality Lab for all their technical support with the experiments as well as Nadia Baartzes for the FTIR analysis and Nicholas Laidler for the XRD analysis. We also acknowledge the receipt of the 2017 Greenovate Engineering Award for the design of this innovative nutrient recovery urinal.

References

Beler Baykal, B., Kocaturk, N.P., Allar, A.D., Sari, B., 2009. The effect of initial loading on the removal of ammonium and potassium from source-separated human urine via clinoptilolite. Water Science and Technology 60(10), 2515-2520.

Bennett, J.E., Dolin, R., Blaser, M.J., 2017. Mandell, Douglas, and Bennett's infectious disease essentials. Elsevier, Philadelphia, PA.

Berthouex, P.M., 1972. Evaluating Economy of Scale. Journal (Water Pollution Control Federation) 44(11), 2111-2119.

Bischel, H.N., Özel Duygan, B.D., Strande, L., McArdell, C.S., Udert, K.M., Kohn, T., 2015. Pathogens and pharmaceuticals in source-separated urine in eThekwini, South Africa. Water Research 85(Supplement C), 57-65.

Boskey, A.L., Posner, A.S., 1974. Magnesium stabilization of amorphous calcium phosphate: A kinetic study. Materials Research Bulletin 9(7), 907-916.

Boyer, T.H., Taylor, K., Reed, A., Smith, D., 2014. Ion-exchange softening of human urine to control precipitation. Environmental Progress & Sustainable Energy 33(2), 564-571.

Chariar, M., Sakthivel, R., 2009. Waterless urinals: a resource book. Delhi, India.

City of Cape Town, 2018. Dam Levels. http://www.capetown.gov.za/Family%20and%20home/residential-utility-services/residential-water-and-sanitation-services/this-weeks-dam-levels. (Accessed 19 February 2018).

Combes, C., Rey, C., 2010. Amorphous calcium phosphates: Synthesis, properties and uses in biomaterials. Acta Biomaterialia 6(9), 3362-3378.

Corathers, L.A., 2016. Lime, 2014 Minerals Yearbook. U.S. Geological Survey, USA.

Drangert, J.O., 1998. Fighting the urine blindness to provide more sanitation options. Water SA 24(2), 157-164.

Etter, B., Tilley, E., Khadka, R., Udert, K.M., 2011. Low-cost struvite production using source-separated urine in Nepal. Water Research 45(2), 852-862.

Gadaleta, S.J., Paschalis, E.P., Betts, F., Mendelsohn, R., Boskey, A.L., 1996. Fourier transform infrared spectroscopy of the solution-mediated conversion of amorphous calcium phosphate to hydroxyapatite: New correlations between X-ray diffraction and infrared data. Calcified Tissue International 58(1), 9-16.

Ganrot, Z., Dave, G., Nilsson, E., 2007. Recovery of N and P from human urine by freezing, struvite precipitation and adsorption to zeolite and active carbon. Bioresource Technology 98(16), 3112-3121.

Gary Bristow, James D. McClure, David Fisher, 2006. Waterless Urinals: Features, Benefits, and Applications. Journal of Green Building 1(1), 55-62.

Hashemi, S., Han, M., Kim, T., 2015. Identification of urine scale problems in urinals and the solution using rainwater. J Water Sanit Hyg De 5(2), 322-329.

Hellström, D., Johansson, E., Grennberg, K., 1999. Storage of human urine: acidification as a method to inhibit decomposition of urea. Ecological Engineering 12(3), 253-269.

Höglund, C., 2001. Evaluation of microbial health risks associated with the reuse of source-separated human urine. Royal Institute of Technology, Stockholm, Sweden.

Ishii, S.K.L., Boyer, T.H., 2016. Student support and perceptions of urine source separation in a university community. Water Research 100(Supplement C), 146-156.

Jasinski, S.M., 2017. Potash, 2017 Mineral Commodity Summaries. U.S. Geological Survey, USA.

Kalinkin, A.M., Kalinkina, E.V., Zalkind, O.A., Makarova, T.I., 2005. Chemical Interaction of Calcium Oxide and Calcium Hydroxide with CO2 during Mechanical Activation. Inorganic Materials 41(10), 1073-1079.

Kavvada, O., Tarpeh, W.A., Horvath, A., Nelson, K.L., 2017. Life-Cycle Cost and Environmental Assessment of Decentralized Nitrogen Recovery Using Ion Exchange from Source-Separated Urine through Spatial Modeling. Environmental Science & Technology 51(21), 12061-12071.

Kjolberg, T., 2016. Highest Water Prices in the World. Daily Scandinavian.

Lamichhane, K.M., Babcock, R.W., 2013. Survey of attitudes and perceptions of urine-diverting toilets and human waste recycling in Hawaii. Science of The Total Environment 443(Supplement C), 749-756.

Larsen, T.A., Alder, A.C., Eggen, R.I.L., Maurer, M., Lienert, J., 2009. Source Separation: Will We See a Paradigm Shift in Wastewater Handling? Environmental Science & Technology 43(16), 6121-6125.

Larsen, T.A., Gujer, W., 1996. Separate management of anthropogenic nutrient solutions (human urine). Water Science and Technology 34(3-4), 87-94.

Ledezma, P., Kuntke, P., Buisman, C.J.N., Keller, J., Freguia, S., 2015. Source-separated urine opens golden opportunities for microbial electrochemical technologies. Trends in Biotechnology 33(4), 214-220.

Lienert, J., Bürki, T., Escher, B.I., 2007. Reducing micropollutants with source control: substance flow analysis of 212 pharmaceuticals in faeces and urine. Water Science and Technology 56(5), 87-96.

Lienert, J., Larsen, T.A., 2010. High Acceptance of Urine Source Separation in Seven European Countries: A Review. Environmental Science & Technology 44(2), 556-566.

Maurer, M., Pronk, W., Larsen, T.A., 2006. Treatment processes for source-separated urine. Water Research 40(17), 3151-3166.

Meyer, G., Frossard, E., Mäder, P., Nanzer, S., Randall, D.G., Udert, K.M., Oberson, A., 2017. Water soluble phosphate fertilizers for crops grown in calcareous soils – an outdated paradigm for recycled phosphorus fertilizers? Plant and Soil.

Meyer, J.L., Weatherall, C.C., 1982. Amorphous to crystalline calcium phosphate phase transformation at elevated pH. Journal of Colloid and Interface Science 89(1), 257-267.

Mobley, H.L., Hausinger, R.P., 1989. Microbial ureases: significance, regulation, and molecular characterization. Microbiological Reviews 53(1), 85-108.

Pradhan, S.K., Mikola, A., Vahala, R., 2017. Nitrogen and Phosphorus Harvesting from Human Urine Using a Stripping, Absorption, and Precipitation Process. Environmental Science & Technology 51(9), 5165-5171.

Randall, D.G., Krähenbühl, M., Köpping, I., Larsen, T.A., Udert, K.M., 2016. A novel approach for stabilizing fresh urine by calcium hydroxide addition. Water Research 95, 361-369.

Randall, D.G., Naidoo, V., 2018. Urine - the liquid gold of wastewater. Journal of Environmental Chemical Engineering (in press).

Ronteltap, M., Maurer, M., Gujer, W., 2007. The behaviour of pharmaceuticals and heavy metals during struvite precipitation in urine. Water Research 41(9), 1859-1868.

Root, M.J., 1990. Inhibition of the amorphous calcium phosphate phase transformation reaction by polyphosphates and metal ions. Calcified Tissue International 47(2), 112-116.

Schönning, C., Leeming, R., Stenström, T.A., 2002. Faecal contamination of source-separated human urine based on the content of faecal sterols. Water Research 36(8), 1965-1972.

Udert, K.M., Larsen, T.A., Biebow, M., Gujer, W., 2003. Urea hydrolysis and precipitation dynamics in a urine-collecting system. Water Res 37(11), 2571-2582.

Udert, K.M., Larsen, T.A., Gujer, W., 2003. Biologically induced precipitation in urine-collecting systems. Water Science and Technology: Water Supply 3(3), 71-78.

Udert, K.M., Wachter, M., 2012. Complete nutrient recovery from source-separated urine by nitrification and distillation. Water Research 46(2), 453-464.

Wilsenach, J., van Loosdrecht, M., 2003. Impact of separate urine collection on wastewater treatment systems. Water Science and Technology 48(1), 103-110.