Passive evaporation of source-separated urine from dry toilets: a lab study

David N. Bethune, Angus Chu and M. Cathryn Ryan

ABSTRACT

A methodology for evaporating human urine from dry toilets using gravity-drainage through vertically stacked plastic 'cafeteria-type' trays was tested. A thin layer (500 g) of medium-grained sand on the bottom of each tray enhanced evaporation, ammonia stabilization and solid product removal. A prototype laboratory unit initially evaporated up to 8.5 L m^{-2} d^{-1} but decreased to 1.5 L m^{-2} d^{-1} over time as salinity increased. The evaporation process produces a dark, highly saline, brine solution before drying to a solid product. The solid product has almost no odor and is mostly comprised of Na, Cl, N, P and K. Nitrogen loss, primarily by ammonia volatilization, significantly decreased the amount of N relative to P and K in the brine and solid product. About 90% of the NH_4/NH_3 initially present in the input urine was lost in the evaporator system.

Key words | diversion, evaporation, sanitation, source-separation, urine

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INTRODUCTION

Rural sanitation systems based on the separation of urine and feces from the toilet onward (a.k.a. urine diversion [UD] or urine source separation; Larsen & Gujer 1996; Hanæus *et al.* 1997; Hellstrom & Johansson 1999) offer some very distinct advantages over traditional urine-feces mixed (a.k.a. blackwater) systems. Urine and feces have several important differences that make their separation advantageous to each. Urine has a much higher water content than feces (96% vs 70%) which, when combined with the annual rates of per capita production (500 L of urine vs. 50 L of feces), makes the onsite disposal or transport of urine challenging (Del Porto & Steinfeld 1999). Nutrient recovery from urine is also safer than from feces (which contain relatively high numbers of pathogens; Schonning & Stenstrom 2001), although some pathogen cross-contamination to urine can occur at the UD toilet (Schonning *et al.* 2001; Höglund *et al.* 2002). Finally, source-separated feces are drier, less odorous, and are more easily stabilized or composted than feces mixed with urine (Hill *et al.* 2013).

Urine is a saline (3.5%), normally sterile solution containing soluble salts, nutrients and organic compounds dominated by the nitrogen-rich urea. Immediately after urine exits the human body it enters a non-sterile environment and undergoes a spontaneous, irreversible process called urea hydrolysis (Warner 1942; Andrews *et al.* 1984). This conversion of organic urea nitrogen to inorganic ammonia leads to a dramatic pH increase from about 6 to 9 (Ciba-Geigy 1977; Kirchmann & Pettersson 1995; Jonsson *et al.* 1997; Udert *et al.* 2006) leading to high levels of ammonia gas producing a strong odor, and a substantial increase in alkalinity. The high ammonia levels naturally hygenize or sterilize urine over time (Höglund *et al.* 1998; Höglund *et al.* 2002) eliminating any potential pathogens within 4–6 months (Höglund 2001; Schonning & Stenstrom 2001).

Urine contains most of the nutrients excreted by humans (85–90% nitrogen, 50–80% phosphorus, and 80–90% potassium; Larsen & Gujer 1996). On average, each person produces about 15 g d^{-1} of combined nutrients (N, P, and K) in urine, and only about 3 g d^{-1} in feces (Del Porto &

doi: 10.2166/washdev.2014.058

Steinfeld 1999). Mihelcic *et al.* (2011) estimate that, if collected, phosphorus in urine and feces generated worldwide could supply about 22% of total global phosphorus demand. Urine also contains 60–70% of the pharmaceuticals in human waste providing an opportunity to treat source-separated urine for pharmaceuticals (Lienert *et al.* 2007a, 2007b).

Urine evaporation has been suggested as a novel solution leading to volume reduction, chemical stabilization, hygenization and a salty, yet nutrient-rich, fertilizer product (Maurer *et al.* 2003, 2006; Ek *et al.* 2006). Udert & Wachter (2012) studied urine evaporation in a laboratory with a combination of nitrification (in a biofilm reactor to reduce volatile ammonia losses) and distillation (using high temperatures to remove the water); however, this method is highly energy-intensive and not suitable for off-grid areas. Urine evaporation was identified by Pronk & Kone (2008) as promising in areas without reliable electricity and close to agriculture and a sand-bed filter (to lower pH and stabilize ammonia) followed by solar/heat evaporation (for hygenization and removal of micropollutants, including pharmaceuticals, hormones, pesticides, trace metals) was suggested. Intermittent infiltration of wastewater through unsaturated sand beds is a well-known treatment process aimed at eliminating organic pollution, oxidizing ammonia and removing pathogens (Bancole *et al.* 2003).

The only study we are aware of that field-tested a passive (non-powered) urine evaporation system used a solar still to passively heat and evaporate the water from urine (Antonini *et al.* 2012) where 360 g of solid fertilizer material was recovered from 50 L undiluted urine after 26 days of sun exposure (an evaporation rate of about 2 L per day).

In this study, laboratory prototype testing evaluated the rate of passive urine evaporation, and the natural processes affecting major ions as the urine evaporated first to a saline brine, and then to a solid. The prototype evaporation system used standard, off-the-shelf, plastic cafeteria trays stacked vertically and with urine flow via gravity drainage from one tray to the next. A sand layer in each tray was used to enhance evaporation by 'wicking' liquid urine for even distribution on each tray. The sand was also intended to facilitate the stabilization of ammonia by creating oxidizing conditions necessary for oxidation of ammonia to nitrite and nitrate (nitrification) and facilitate the removal of solid urine product from the trays by making the urine product less sticky on the bottom of the tray.

METHODS

The evaporation unit consisted of standard size (25.4 cm × 38.1 cm) cafeteria trays stacked vertically in a vertical frame (Figure 1). Varying numbers of trays were used to

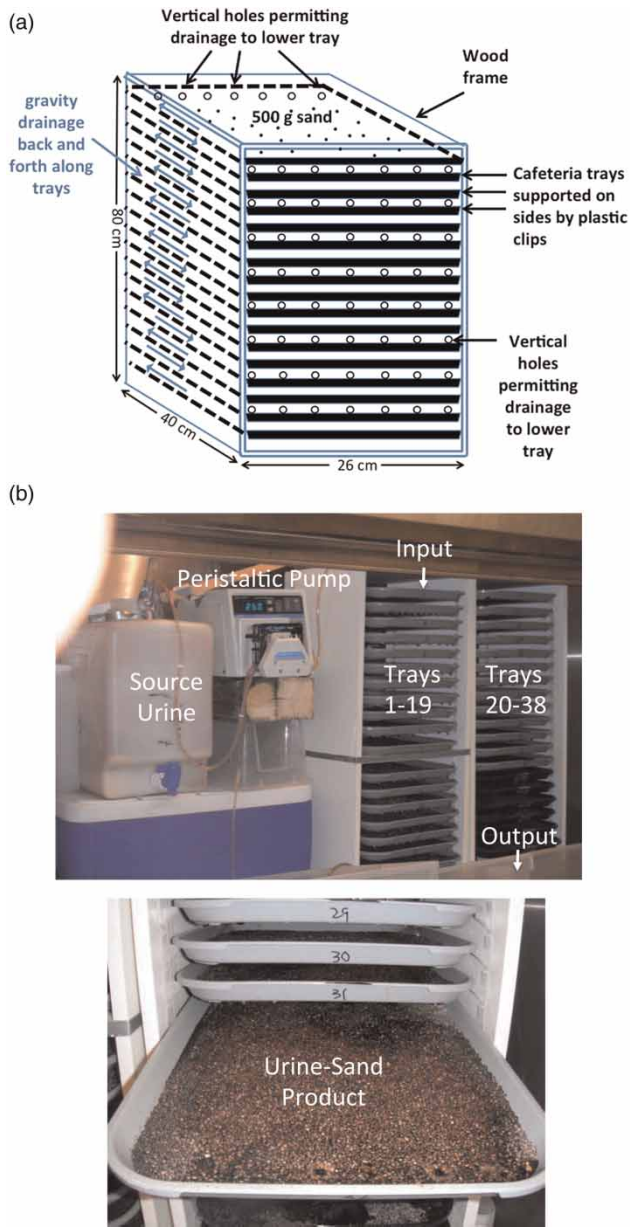

Figure 1 | (a) 'Stacked tray evaporation unit' schematic and (b) photos consisting of 17 plastic trays. Seven 4 mm diameter outlet holes are at one end of each tray alternating from front to back with the tray below, with alternating flow directions (as indicated by blue arrows). Trays are supported by parallel tracks screwed into the frame's sides. Each tray has 500 mg of silica sand spread out evenly over the tray.

evaluate the relative rate of evaporation. The unit had 6 trays for the first 18 days, 17 trays for the next 18 days and 38 trays for the next 45 days (Table 1). Each tray was set about one centimeter apart vertically. Seven holes (4 mm diameter, 2 cm apart) were drilled at alternating ends of consecutive trays such that urine would flow across each tray before dripping down to the tray below via gravity drainage. Each tray was filled with 500 g (approx. 2 cm depth) of 0.85 to 2 mm diameter silica sand. The last tray at the bottom of the unit fed into a collection container.

The trays were located in a fume hood, where stored urine was pumped (Cole Parmer, Masterflex Digital Console Drive, Model 7523-30) at average rates of 6.3 L d^{-1} with 6 trays, 8.9 L d^{-1} with 17 trays and 12.2 L d^{-1} with 38 trays. The application rate was optimized so that all trays were wetted, with minimal urine brine volume discharged into the outlet container at the bottom of the stack of trays. Airflow velocity was measured 1 cm above the urine-saturated sand on each tray with a hot wire anemometer (Omega Engineering, Stamford, Connecticut, USA, Model HHF42, Range 0.2–20 m s^{-1}).

Fresh urine was collected in one-liter autoclaved Nalgene bottles from anonymous participants and collated and stored for varying periods of time (averaging about one month) in large carboy containers.

Chemical analyses were conducted on 'snapshot' samples after 21 days (after input of 135 L) and 81 days (after input of 782 L) on: (a) the input urine, (b) the residual urine brine collected from individual trays, and (c) the final urine brine output from the system. The snapshot samples were suctioned from each tray bottom with a pipette, diluted 1,000 times, and analyzed for major ions by ion chromatography (Dionex ICS-1000, Standard Methods 4110 B; American Public Health Association [APHA] 2005). Reduced mineral N is reported as NH_4^+, but includes both forms of the polyprotic ion (i.e. NH_3 and NH_4^+) since negligible NH_3 is present in the acidic ion chromatograph carrier eluent during analysis (pH < 4). The major ion analyses had an average error of ±3.0% ($n = 36$) when compared to standard reference materials, and ±1.9% error ($n = 54$) in duplicate sample analysis. Electrical conductivity and pH were measured with a VWR handheld probe (Model SP70P), which was calibrated for use. Alkalinity was measured with a HACH Alkalinity test kit (10–4000 mg L^{-1}, Model AL-DT).

The effect of evaporation on ion concentrations was separated out from processes by means of 'evaporation-corrected' relative concentrations using Cl as a tracer. Chloride is an appropriate, conservative tracer, except at high concentrations when halide precipitation occurs (Appelo & Postma 1999). When saturation indices (estimated using AquaChem®; Schlumberger Inc) indicated halide minerals (e.g. halite, sylvite) were under-saturated, the evaporation-corrected concentrations of non-Cl parameters were estimated as

$$[X]_{\text{evap corr}} = [X]_{\text{meas}} \times \frac{[Cl]_{\text{source}}}{[Cl]_{\text{meas}}} \quad (1)$$

where $[X]_{\text{evap corr}}$ is the 'evaporation-corrected' concentration of parameter 'X', $[X]_{\text{meas}}$ is the measured concentration of parameter 'X', $[Cl]_{\text{source}}$ is the chloride concentration of the un-evaporated source urine, and $[Cl]_{\text{meas}}$ is the chloride concentration of the residual urine sampled at the same time and place as $[X]_{\text{meas}}$. The relative concentration (C/C_o) of parameter 'X' was estimated as:

$$\frac{C}{C_o} = \frac{[X]_{\text{evap corr}}}{[X]_{\text{source}}} \quad (2)$$

Table 1 | Average urine loading and evaporation over time. Urine was input almost continuously over 81 days. Urine input average rates are presented as actual rates were highly variable due to clogging of pump tubing. Tray area = 0.12 m^2/tray. Evaporation rates were calculated as difference between input (peristaltic pump) and output (collected in vessel after last tray)

					Evaporation Rate per Unit Area (L m^{-2} d^{-1})			
# Trays in Evaporator	Total Tray Area (m^2)	Average Input Rate (L d^{-1})	Days Input	Cumulative Input (L)	Average	Std Dev (*n*)	95% CI	Range
6	0.76	6.3	18	110	6.3	4.2 (19)	1.7	2.8–8.5
17	2.16	8.9	18	269	3.9	0.53 (13)	0.29	3.0–4.3
38	4.82	12.2	45	782	2.5	2.1 (23)	0.84	1.5–3.3

where $[X]_{source}$ was the initial concentration in the source urine.

Chemical analyses were also conducted to evaluate the composition of the solid product (including dried brine and sand). Solid product was collected from Tray 39 after 782 L of urine was applied over 81 days, and extracted using deionized water (for K and Cl analyses) and KCl solution (for all other ions). In each case 5 g of solid product were shaken with 50 mL of 2.0 M KCl solution or deionized water for 30 minutes, and analyzed by ion chromatography as described above.

Spot chemical compositional analyses of the solid urine product were evaluated with a JEOL JXA-8200 electron microprobe (Geoscience, University of Calgary). A solid material such as a mineral can be analyzed on the microprobe at a scale of a few microns or less which allows the detection of small compositional variations within an individual crystal, which could not be observed by standard chemical analysis.

The potential for microbiological activity on the air-dried solid product was evaluated by total heterotrophic plate counts (APHA 2005) conducted on six solid product subsamples collected from trays 21, 24, 28, 32, 36 and 39. Total heterotrophic plate counts were conducted using one mL of solution from deionized water extractions of the solid product (as described above).

RESULTS AND DISCUSSION

A total of 782 L of stored urine ('Input') were pumped onto the cafeteria trays over a period of 81 days (average rate 9.75 L d^{-1}; Table 1). Since mineral precipitation on the walls of the Teflon tubing resulted in variable pump rates, average input rates are presented for each of the three tray configurations (Table 1). Evaporation rates also varied (as a function of the input rate), with consequent average evaporation rates of 6.3 L m^{-2} d^{-1} with 6 trays, 3.9 L m^{-2} d^{-1} with 18 trays and 2.5 L m^{-2} d^{-1} with 38 trays (Table 1). The average rate of evaporation per unit tray area decreased over the data collection period as a function of increasing salinity of the urine brine in the first trays from previously evaporated urine.

While temperature of the air across the trays was constant at 20 °C, relative humidity increased from ~20% at the inlet side of the trays to ~22% at the outlet side (data not shown). The velocity of air above the trays, caused by fume hood suction from above, varied from 0.8 m s^{-1} above the lower trays to 0.3 m s^{-1} above the upper trays, which is consistent with the airflow patterns expected in the fume hood (i.e. more air drawn in at the bottom). Given that the total amount of open area above all the trays is about 0.16 m^2, and assuming an average airflow velocity of 0.5 m s^{-1}, the total volumetric airflow rate through the unit is estimated to be 80 L s^{-1}, which accounts for the relatively high urine evaporation rates that were observed.

The concentrations of major ions in stored urine in the literature (Udert 2003) was consistently about double the values for the stored input urine in the study, presumably due to normal variations particularly in water intake, diet and metabolism. The observed pH of 9.2 and alkalinity of 420 mM in the stored input urine suggests advanced urea hydrolysis.

Relative molar fractions in different stages of the urine evaporation process permit a comparison of the relative proportions of the major constituents as their concentrations increase during evaporation and then dry to a solid (Figure 2). A dramatic decrease in the molar fraction of NH_4 (from input, to urine brine, and solid product; Figures 2(c)–2(e)) compared to the other constituents is discussed in below. The fraction of PO_4 decreases significantly from fresh urine to stored urine and the urine brine but increases in the solid urine product, suggesting mineral precipitation occurs after urea hydrolysis, forming P-bearing minerals.

The modified Piper plot of snapshot samples taken after 21 days of urine input (Figure 3) identifies a decrease in relative SO_4 contribution. High saturation indices for aragonite (2.21 to 2.85) suggest the decrease in SO_4 concentration may be due to aragonite precipitation. The contribution of Ca and Mg are consistently small, likely due to aragonite and carbonate precipitation (see below). The more significant trend in water type during evaporation is a linear trend on the modified Piper plot from NH_4-HCO_3 type in the input urine to K-Na-HCO_3-Cl in the output urine brine, along with a steady increase in total dissolved solids (TDS) (Figure 3). The increase in TDS is mirrored in steady concentration increases for most major ions, but

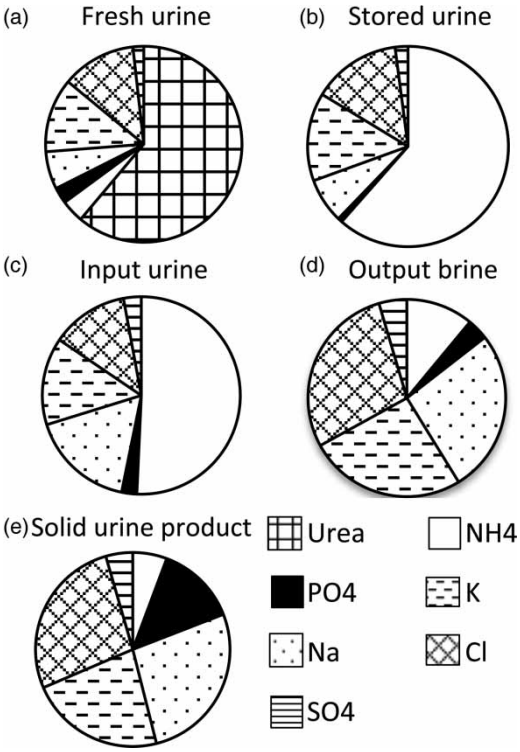

Figure 2 | Molar fractions of major ions including (a) fresh (Putnam 1971) and (b) stored urine (Udert 2003) from the literature and (c) input urine, (d) residual urine brine, and (e) solid urine product from this study. PO_4 analyses were not available for stored urine. The solid urine product was sampled from Tray 39 after application of 782 L of urine.

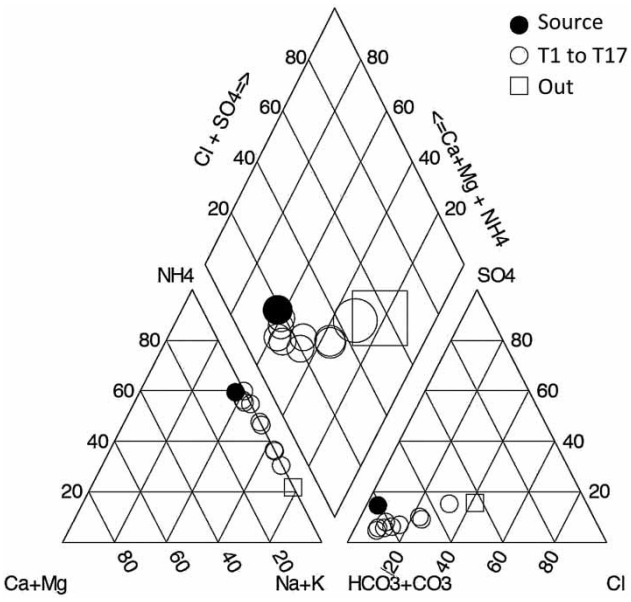

Figure 3 | Modified Piper diagram for input urine, trays 1 to 17 and the outlet. Modification consists of inclusion of NH_4 in apex of the cation ternary diagram, and collating Mg and Ca on another apex. Symbol size in the central diamond is proportional to the calculated TDS concentration.

particularly in Na, K, and Cl (Figure 4(a)). TDS increased by a factor of seven from ca. 60 g L^{-1} in the stored urine to ca. 400 g L^{-1} in the residual urine brine.

Relative changes in ion concentrations in snapshot samplings (Figure 4(a)) are masked by concentration increases due to evaporation. Calculated saturation indices for halite were under-saturated throughout (ranging from −1.12 to −1.76 for sylvite and −1.10 to −4.64 for halite). Chloride concentrations were thus used to calculate an evaporation-corrected relative concentration (Figures 4(c) and 4(d)), which facilitated the identification of processes other than evaporation (e.g. chemical reaction, mineral precipitation, or volatilization) affecting ion concentrations.

Evaporation-corrected Na and K concentrations, while slightly lower than Cl, did not vary significantly, suggesting they are mainly affected by evaporation. Particularly low Ca, SO_4, and alkalinity concentrations and over-saturated saturation indices for $CaCO_3$ and $CaSO_4$ (Supplementary Information found online at http://www.iwaponline.com/washdev/004/058.pdf) suggest mineral precipitation began in the urine input storage container and continued within the trays. A white precipitate, consistent with carbonate and aragonite minerals, was visually observed at the bottom of the stored urine container. A gradual decrease in evaporation-corrected NH_4 and NO_2 concentrations was observed (Figures 4(c) and 4(d)), whereas PO_4 and NO_3 concentrations fluctuated up and down, with no clear tendency.

The decrease in NH_4 could be due to ammonia volatilization and/or partial nitrification. The increase in evaporation-corrected relative NO_3 concentrations (Figure 4(b)) suggests partial nitrification may have occurred, although the overall low NO_3 concentrations (Figure 4(a)) suggest it was not significant relative to the loss of ammonium. Ammonia volatilization was likely significant, particularly from the early trays (where pH values were high) and was evident by odor. At the pH of the input urine (9.2; Figure 4(a)) and a TDS value of 60 mg L^{-1}, an estimated 60% of the nitrogen species would be in the NH_3 form and 40% in the NH_4 form (Clegg & Whitfield 1995). In the final tray sampled on Day 21 (Figure 4(a)), the lower pH of 7.5 suggests less than 5% of the NH_4/NH_3 would be present as NH_3 (Clegg & Whitfield 1995). Decreased ammonia losses during evaporation likely result in a less odorous urine brine with increasing evaporation or flow through

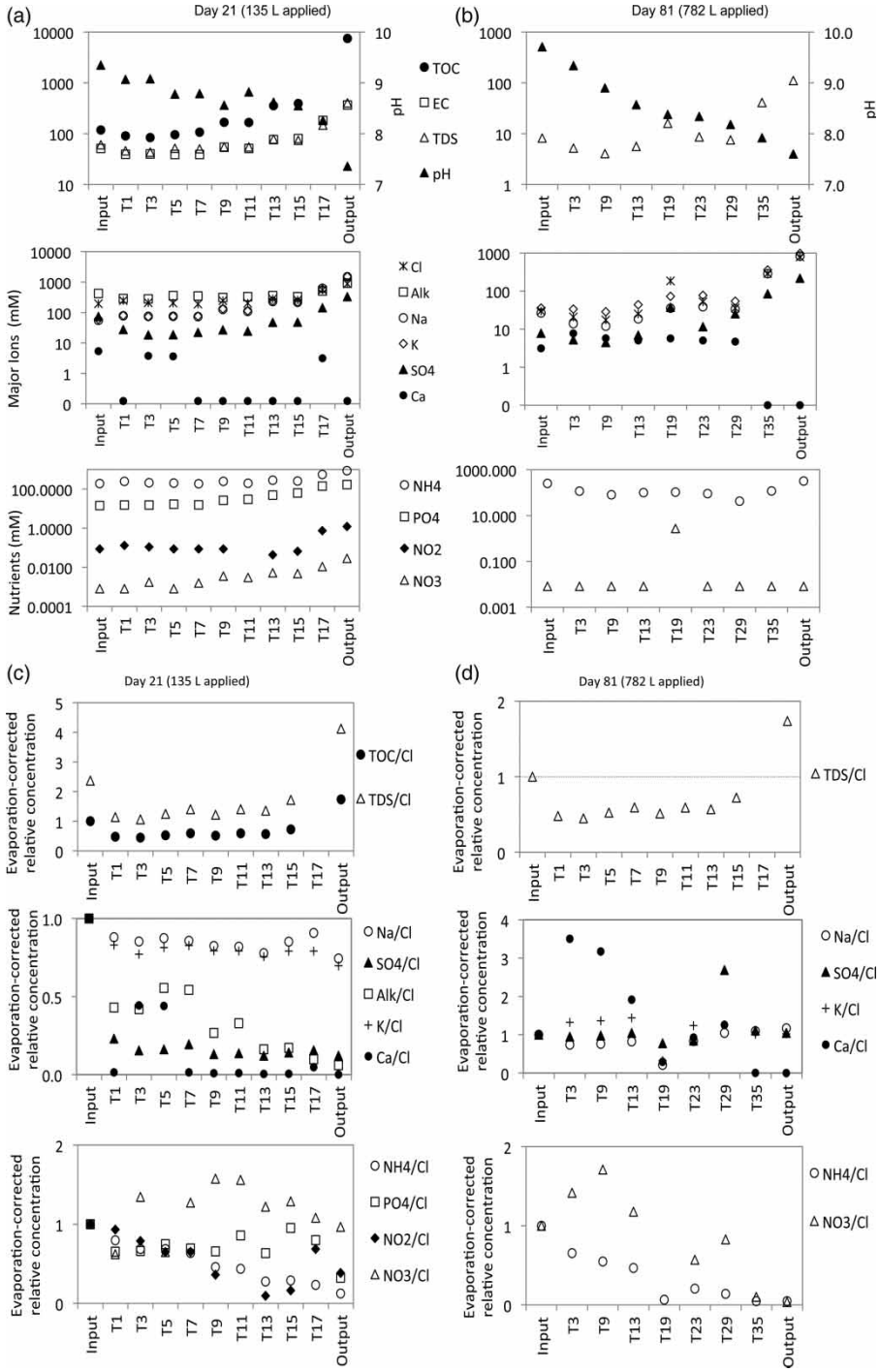

Figure 4 | Geochemical 'snapshots' of input urine, urine brine in the unit and output brine in (a) mmol L^{-1} and (b) evaporation-corrected concentrations. Parameters (including total organic carbon [TOC] and TDS (g L^{-1}), Electrical Conductivity (EC; mS), and pH), major ions (Cl, alkalinity (mM as $CaCO_3$), Na, K, SO_4, and Ca), and nutrients (NO_3, $NH_4 + NH_3$, PO_4). Sampling occurred on (a) and (c) Day 21 (after input of 135 L) and (b) and (d) Day 81 (after input of 782 L). T1 is the first tray, T17 (Figures 4(a) and 4(c)) or T38 (Figures 4(b) and 4(d)) is the last tray, and the outlet is the final capture vessel. Non-detectable calcium concentrations are plotted as half of the detection limit (0.1 mmol L^{-1}). Data for EC, TOC, alkalinity, NO_2, and PO_4 were not analyzed for the Day 81 sampling event. Magnesium is not included since it was not detected. In Figure 4(b), values greater than one indicate the evaporation-corrected concentration has increased relative to the input concentration of that parameter, whereas values less than one suggest the it has decreased relative to the input concentration (by biochemical reaction, mineral precipitation, or volatilization).

Table 2 | Concentration of Fresh, Stored and Evaporated Urine from Literature and Present Study. Input Stored Urine is stored for several weeks prior to input. Urine Brine and Solid Urine Product were obtained from last tray of evaporation unit

	Literature			STUDY RESULTS										
	Fresh Urine[a]	Stored Urine[b]		Input Stored Urine (average)				Urine Brine During Evaporation (average)				Solid Urine Product		
	mM	mM	Fraction %	mM	*n*	*SD*	Fraction%	mM	*n*	*SD*	Fraction%	mg g^{-1}	mmol kg^{-1}	Fraction %
Urea $(NH_2)_2CO$	550	0	0	n/m	n/a	n/a	n/a	n/m	n/a	n/a	n/a	n/m	n/m	n/a
$NH_4^+ + NH_3$	34	475	61	211	3	35	51	542	7	175	11	29.7	16	3.6
$NO_3^- + NO_2^-$	0	0	0	0	1	n/a		1	1	n/a	< 1	0.02	0.3	< 1
PO_4	24	6	1	15	1	n/a	2	171	1	n/a	3	5.6	60	14
K	56	56	7	49	3	12	17	1523	7	1319	27	4.9	124	28
Na	110	110	14	42	3	15	14	1508	7	1270	26	0.6	98	22
Ca	5	0	0	5	3	1.4	< 1	2	7	2	< 1	0.03	0.7	< 1
Mg	4	0	0	0.1	3	0.2	< 1	0.3	7	0.1	0	< 0.1	< 0.1	< 1
Cl	110	110	14	27	3	25	13	1403	7	366	28	4.1	117	27
SO_4	16	16	2	3	3	5	3	330	7	75	5	2.3	24	2.7
pH	6	9.1	n/a	9.2	1	n/a	n/a	7.5	1	n/a	n/a	n/a	n/a	n/a
Alkalinity (mg L^{-1} $CaCO_{3)}$	22	490	n/a	420	1	n/a	n/a	929	1	n/a	n/a	n/a	n/a	n/a
COD (mg L^{-1})	10,000	10,000	n/a	4,570	1	n/a	n/a	29,3000	1	n/a	n/a	n/a	n/a	n/a

[a]Ciba Geigy (1977) as reported in Udert (2003).
[b]Udert (2002).
[c]n/a: not applicable.
[d]n/m: not measured.

the evaporator system. About 90% of the NH_4/NH_3 initially present in the input urine was lost throughout the evaporator system (Figure 4(b)).

Small, but significant concentrations of NO_2 were observed in the urine brine (0.4 to 0.7 mg N L^{-1}; Figure 4(a)), with relative concentration decreases when corrected for evaporation. The sources and sinks of nitrate are not clear, but could be due to nitrification (which is implicated by increasing relative nitrate concentrations; Figure 4(b)).

The solid urine product material had low odor (i.e. one had to sniff within a few centimeters to notice the odor). The microprobe analysis of the solid urine product identified halite (NaCl) and sylvite (KCl) as the dominant minerals, indicating they would be eventually precipitated as brine concentration increased. Additional minerals identified by the microprobe include gypsum ($CaSO_4$), potassium phosphate (K_3PO_4), potassium sulfate (K_2SO_4) and struvite ($NH_4MgPO_4{\cdot}6H_2O$).

Live heterotrophic bacteria were not detected in any of the six plate counts conducted with the rehydrated solid urine product, indicating that the air-dried solid urine product did not likely contain any viable heterotrophic organisms. Since pathogens are typically heterotrophic, this suggests the dried product was sterile.

The solid urine product N:P:K ratio (1:4:8; Table 2) has substantially less N than liquid urine (ca. 11:1:2; Morgan 1999), which can be beneficial when potassium uptake is important (Hills 1981). The high levels of sodium and chloride in the solid urine product could be problematic in sodic or saline soils.

CONCLUSIONS

Source-separated urine from dry sanitation systems was passively evaporated in vertically stacked cafeteria trays, producing a low-odor, microbiologically inactive, chemically stable fertilizer product consisting primarily of mineralized halite, sylvite, gypsum, struvite, K_2PO_4 and K_2SO_4. Most major ion concentrations increased dramatically during evaporation, with some mineral formation. Sodium, K, and Cl concentrations were affected by evaporation only. About 90% of the NH_4/NH_3 was lost during evaporation, mostly due to volatilization, and phosphate mineral precipitation occurred. The N:P:K ratio of the solid urine product was approximately 1:4:8. Elevated sodium and chloride concentrations could be problematic in sodic or saline soils.

Evaporation of source-separated urine could allow people in areas with appropriate meteorological conditions to passively convert human waste into a safe-to-handle soil fertilizer. It could also reduce the need to purchase fertilizer and help reduce the loading of human waste on local water resources. This simple technology could be an important option for rural sanitation in diverse settings including back-country huts, cabins, cottages and rural populations in emerging countries. The challenge of this approach will be to optimize the basic concept and design for different climates, availability of local construction materials, fertilizer requirements, and income levels.

REFERENCES

American Public Health Association (APHA) 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st Edn., APHA, Washington, DC.

Andrews, R. K., Blakeley, R. L. & Zerner, B. 1984 Urea and urease. *Advances in Inorganic Biochemistry* **6**, 245–283.

Antonini, S., Nguyen, P. T., Arnold, U., Echiert, T. & Clemens, J. 2012 Solar thermal evaporation of human urine for nitrogen and phosphorous recovery in Vietnam. *Science of the Total Environment* **414**, 592–599.

Appelo, C. A. J. & Postma, D. 2005 *Geochemistry, Groundwater and Pollution*. Balkema, Rotterdam.

Bancole, A., Brissaud, F. & Gnagne, T. 2003 Oxidation processes and clogging in intermittent unsaturated infiltration. *Water Science and Technology* **148** (11–12), 139–146.

Ciba-Geigy 1977 *Wissenschaftliche Tabellen Geigy, Teilband Körperflüssigkeiten (Scientific tables Geigy volume body fluids)*, 8th edn., Ciba-Geigy, Basel. In German.

Clegg, S. L. & Whitfield, M. 1995 A chemical model of seawater including dissolved ammonia and the stoichiometric dissociation constant of ammonia in estuarine water and seawater from -2 to 40° Sch. Environ. Sci., Univ. East Anglia, Norwich, UK. *Geochimica et Cosmochimica Acta* **59** (12), 2403–2421.

Del Porto, D. & Steinfeld, C. 1999 *The Composting Toilet System Book*. Centre for Ecological Pollution Prevention, Concord, USA, 234.

Ek, M., Bergstrom, R., Bjurhem, J. E., Bjorlenius, B. & Hellstrom, D. 2006 Concentration of nutrients from urine and reject water from anaerobically digested sludge. *Water Science and Technology* **54** (11–12), 437–444.

Hanæus, J., Hellstrom, D. & Johansson, E. 1997 A study of a urine separation system in an ecological village in Northern Sweden. *Water Science and Technology* **35** (9), 153–160.

Hellstrom, D. & Johansson, E. 1999 Swedish experiences with urine separating systems. *Wasser & Boden* **51** (11), 26–29.

Hill, G. B., Baldwin, S. A. & Vinneras, B. 2013 Composting toilets a misnomer: Excessive ammonia from urine inhibits microbial activity yet is insufficient in sanitizing the end-product. *Journal of Environmental Management 119C* **29** (2013) PMID 23435183.

Hills, L. D. 1981 *Fertility Gardening*. Cameron & Taylor, London.

Höglund, C. 2001 Evaluation of microbial health risks associated with the reuse of source-separated human urine. Doctoral thesis, Royal Institute of Technology, Swedish Institute for Infectious Disease Control, Stockholm.

Höglund, C., Stenstrom, T. A., Jonsson, H. & Sundin, A. 1998 Evaluation of faecal contamination and microbial die-off in urine separating systems. *Water Science and Technology* **38** (6), 17–25.

Höglund, C., Ashbolt, N., Stenstrom, T. A. & Svensson, L. 2002 Viral persistence in source-separated human urine. *Advances in Environmental Research* **6** (3), 265–275.

Jonsson, H., Stenstrom, T. A., Svensson, J. & Sundin, A. 1997 Source-separated urine-nutrient and heavy metal content, water saving and faecal contamination. *Water Science and Technology* **35** (9), 145–152.

Kirchmann, H. & Pettersson, S. 1995 Human urine – Chemical composition and fertilizer use efficiency. *Fertilizer Research* **40**, 149–154.

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

Lienert, J., Burki, T. & Escher, B. I. 2007a 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., Burki, T. & Escher, B. I. 2007b The ecotoxicological risk of pharmaceuticals and metabolites in urine and feces are equal. *Environmental Science and Technology* **41**, 4471–4478.

Maurer, M., Schwegler, P. & Larsen, T. A. 2003 Nutrients in urine: energetical aspects of removal and recovery. *Water Science and Technology* **48**, 37–46.

Maurer, M., Pronk, W. & Larsen, T. A. 2006 Treatment processes for source separated urine. *Water Research* **40**, 3151–3166.

Mihelcic, J. R., Fry, L. M. & Shaw, R. 2011 Global potential of phosphorus recovery from human urine and feces. *Chemosphere* **84** (6), 832–839.

Morgan, P. 1999 *Ecological Sanitation in Zimbabwe. A compilation of manuals and experiences*. Vols. I, II, III and IV. Aquamor Pvt. Ltd., Harare.

Pronk, W. & Kone, D. 2008 Options for urine treatment in developing countries. *Desalination* **248**, 360–368.

Putnam, D. F. 1971 Composition and concentrative properties of human urine, NASA Report CR-1802, McDonnell Douglas Astronautics Company, Washington DC, USA.

Schonning, C., Leeming, R. & Stenstrom, T. A. 2001 Faecal contamination of source-separated human urine based on the content of faecal sterols. *Water Research* **36** (8), 1965–1972.

Schonning, C. & Stenstrom, T. A. 2001 Guidelines for the Safe Use of Urine and Faeces in Ecological Sanitation Systems. EcoSanRes Programme. Report 2004-1. Stockholm Environment Institute, Stockholm, Sweden.

Udert, K. M. 2002 The fate of nitrogen and phosphorus in source-separated urine. PhD thesis. Swiss Federal Institute of Technology (ETH), Zurich.

Udert, K. M. 2003 *The Fate of Nitrogen and Phosphorus in Source-Separated Urine*. Schriftenreihe des Instituts fur Hydromechanik und Wasserwirtschaft, Vol. 16. Institute for Hydromechanics and Water Resources Management, Swiss Federal Institute of Technology, Zurich.

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

Udert, K. M., Larsen, T. A. & Gujer, W. 2006 Fate of major compounds in source-separated urine. *Water Science and Technology* **54** (11–12), 413–420.

Warner, R. C. 1942 The kinetics of the hydrolysis of urea and of arginine. *Journal of Biological Chemistry* **142**, 705–723.

First received 24 March 2014; accepted in revised form 15 June 2014. Available online 18 July 2014