Passive evaporation of source-separated urine from dry toilets: prototype design and field testing using municipal water

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

ABSTRACT

A prototype urine evaporation unit (UEU) that removes water from human urine produced from a urine-diverting dry toilet using passive solar evaporation was designed and field-tested at a meteorological station. Municipal water was evaporated on vertically stacked plastic cafeteria-style trays that create a large evaporation surface with a small land-area footprint. The trays were located inside a Plexiglas® enclosure exposed to UV light while passively heating the UEU like a solar oven. A metal black chimney also heated up in the sun, causing air to enter the UEU at the front of the UEU through a louvered vent, flow across each tray, and then exit at the back up through the chimney. The UEU was field-tested in a semi-arid temperate climate (Calgary, Canada) from 22 August to 5 November 2013. The average UEU evaporation rate was 3.2 L/day (0.66 mm), varying from 0.4 L/day (0.08 mm/day) on a cloudy day to 8.8 L/day (1.82 mm) on a sunny day. A multiple-regression analysis indicates that 63% of the UEU evaporation rate can be explained by changes in air temperature, wind speed and incoming solar radiation, thus allowing for predictions of the UEU's relative evaporation potential in other climates.

Key words | dry toilet, passive, solar evaporation, urine-diversion

David N. Bethune (corresponding author)
Angus Chu
Civil Engineering,
University of Calgary, 2500 University Drive NW,
Calgary,
AB T2N 1N4,
Canada
E-mail: *bethuned@ucalgary.ca*

M. Cathryn Ryan
Geoscience,
University of Calgary, 2500 University Drive NW,
Calgary,
AB T2N 1N4,
Canada

INTRODUCTION

An estimated 2.5 billion people do not have access to improved sanitation, and a little over one billion people practise open defecation (WHO & UNICEF 2014). Furthermore, the so-called 'improved' sanitation systems, including pit latrines and septic systems, can produce strong odours, pollute water resources (especially where groundwater is shallow; Krishnan 2011), and are inefficient as they fail to recycle nutrients for agricultural use. The 'ecological sanitation' (a.k.a. ECOSAN) approach is commonly associated with the concept of separation of feces and urine at the toilet (a.k.a. urine-diversion or urine source separation; Larsen & Gujer 1996; Hanæus *et al.* 1997; Hellstrom & Johansson 1999). The ECOSAN approach seeks safe sanitation (including the containment and stabilization of wastes) and recycling of nutrients with a minimal use of water, and source separation toilets are manufactured in several countries (or can be constructed easily).

When separated from urine, feces are significantly drier, less odorous, more easily dehydrated or composted (Hill *et al.* 2013), and thus less favourable to pathogen survival (Schonning & Stenstrom 2001). Separation of urine eliminates one of the major challenges with composting toilets: high saturation (which limits aeration and leads to anaerobic conditions), ammonia odour, an unfavourable carbon to nitrogen ratio, and slowed microbial growth (Jonsson *et al.* 2004).

Urine without feces is a saline, liquid composed of about 97% water and 3% dissolved solids, which are mostly salts (Na, Cl) and nutrients (N, P, K). Urine has a relatively low pathogen load (Larsen & Gujer 1996). Source separation of urine from feces also facilitates urine storage, transportation, on-site treatment or disposal, evaporation of the water component, and/or its re-use as a fertilizer. The health risk to handling urine has been found to be negligible

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(Hoglund *et al.* 2002) as stored urine undergoes urea hydrolysis spontaneously, with sufficiently high pH values (>9) to sterilize the stored urine.

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 (requiring electricity) to remove the water. Pronk & Kone (2008) identified urine evaporation as a promising solution in areas without reliable electricity and close to agriculture and suggested a sand-bed filter (to lower pH and stabilize ammonia) followed by solar/heat evaporation (for hygenization and removal of micropollants, including pharmacueticals, hormones, pesticides, trace metals). Bethune *et al.* (2014) evaporated 1.5–8.5 L m^{-2} d^{-1} of hydrolyzed urine in a laboratory using vertically stacked cafeteria-type trays connected by passive gravity-drainage. The final solid product was low odour, easy to extract from the trays, and mostly comprised of potassium, sodium and chloride and phosphorous, but only 10% of the original ammonia nitrogen. In Vietnam, Antonini *et al.* (2012) used a solar still to passively heat and evaporate the water from urine. After 26 days of sun exposure, 360 g of solid fertilizer material was recovered from 50 L undiluted urine (an evaporation rate of about 2 L per day).

Although these studies indicate urine evaporation is promising, they did not identify the design criteria that most strongly affect the evaporation rate to predict the relative evaporation rate and optimize the UEU design. The objectives of this research were to: (a) field test and evaluate the design of a urine evaporation unit (UEU) to passively evaporate water from urine at a household scale, and (b) collect detailed meteorological data (i.e. temperature, humidity, wind speed, solar radiation, air pressure) to correlate relative evaporation rate with meteorological conditions such that: (i) relative evaporation rates can be reasonably predicted in differing meteorological conditions around the world, and (ii) the parameters that most strongly affect the evaporation rate are identified so UEU designs can be optimized.

The UEU design would ideally evaporate water anywhere in the world using sunlight and wind, be simple to construct and maintain, safe for humans, inexpensive and use commonly found materials. This research builds upon the work of Bethune *et al.* (2014) by designing, constructing and testing an outdoor passive UEU based on the conceptual design described by this research specifically: vertically stacked cafeteria trays connected by gravity-drainage held in place on horizontal tracks in a vertical-walled structure that allows airflow across the tray surfaces.

METHODS

The field UEU evaporated urine on vertically stacked cafeteria-type trays, with urine travelling across one tray to the next tray (i.e. back and forth across consecutive trays), by gravity drainage (Figure 1). The trays were located within a clear Plexiglas-enclosed solar oven that was vented by a solar chimney comprised of sheet metal painted black to heat the air within it when exposed to sunlight, creating upward airflow within the entire unit. Air was drawn into the UEU through a louvered front vent, and then pulled across the surface of each tray before exiting through the chimney. The UEU was designed to optimize evaporation rate by heating up in sunlight and increasing temperature of the evaporating liquid while continuously drawing lower-humidity air from outside across the tray evaporation surfaces.

The trays were standard small-size (25.4 × 38.1 cm) plastic cafeteria trays placed in two vertical stacks, with 17 trays in each stack. A weir (20 cm long × 0.5 cm deep) was cut through the upper edge of one of the longer sides of each tray to allow drainage (during high flow rates) to the tray directly below. Even with the weir, each tray provided 0.6–0.7 L of storage prior to overflowing to the lower tray, for a combined storage of 23–27 L within the 38 trays in the UEU.

Field-testing of the prototype UEU was conducted from 22 August to 5 November 2013 at the University of Calgary meteorological station (AB, Canada). The UEU was oriented to provide maximum daily sun exposure on the main Plexiglas compartment. The UEU was placed on a top-loading electronic scale (Dakota Defender Series D30), which was placed on a level plywood base. The scale was connected to a computer (in a weather-proof box) that was set to log

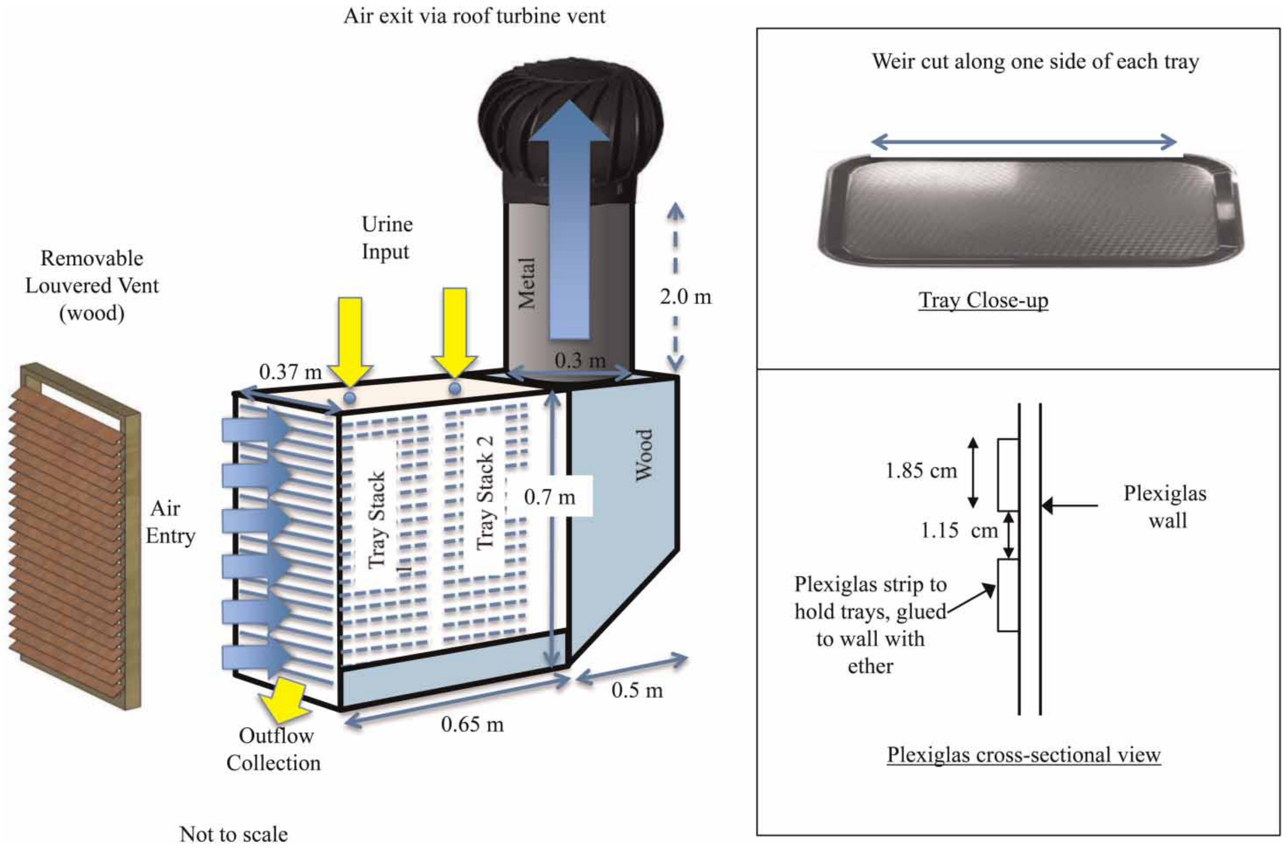

Figure 1 | Schematic of UEU. Trays are held in place with Plexiglas strips glued to side of Plexiglas wall (cross-sectional detail shown in box). Location of weir alternates 'side-to-side' from adjacent trays above and below.

every 10 minutes. Omega OM-62® temperature and relative humidity data loggers collected measurements every 10 minutes from outside (underneath in shade) and inside (i.e. between the stacks) the UEU. Temperature, relative humidity and airflow were logged every 10 minutes inside the chimney (half way up) with a TSI VelociCalc© Air Velocity Meter. Wind speed and incoming solar wattage (ISW) data were provided by the University of Calgary Meteorological station.

The UEU was 'loaded' with City of Calgary municipal water sourced from the Bow River (pH ~8.2, total dissolved solids *ca*. 260 mg/L; Iwanyshyn *et al.* 2008). The decision to use municipal water instead of urine was based on the necessity of measuring the correlation between UEU evaporation rate and meteorological parameters while holding all other variables constant. If urine had been used, the UEU evaporation rate would have gradually decreased as salinity gradually increased (a.k.a. the salinity effect; Janson 1959) and it would not have been possible to separate out the decrease in evaporation rate due to meteorological factors, as the days became shorter and colder during the late summer and fall, from the decrease in evaporation due to the salinity effect. The salinity of the urine increased significantly with time in the previous experiment (Bethune *et al.* 2014), and at variable rates on individual trays depending on their location in the vertical tray stack. Three litres of municipal water was added to the UEU at about 8:00 a.m. for 5 days each week, with 1.5 L of municipal water added to the top tray of each of the two stacks. This amount ensured the UEU was filled close to capacity but not overfilled.

The short-term evaporation rate at any given time was calculated based on change in mass measured over a 10-minute period. Since the scale weights fluctuated significantly due to external factors (e.g. wind gusts, precipitation falling on the unit), a 6-hour running average was plotted with time (where each evaporation rate calculated for each time was the mean rate estimated for the 3 hours before and the 3 hours after that time). Multiple-regression analyses were conducted with an Excel Multiple-Regression Analysis and Forecasting Template (Business Spreadsheets©).

RESULTS AND DISCUSSION

The UEU evaporation rate over the 76-day study period (Figure 2) was highly variable depending on the time of day and day-to-day weather conditions. Overall, there was a clearly decreasing rate over time as the number of daylight hours and average temperature both naturally decreased during the transition from summer to fall over the monitoring period. The mean daily UEU evaporation rate varied from as high as 8.8 L/day (1.8 mm/day) on a sunny warm day (September 23) to as low as 0.4 L/day (0.08 mm/day) on a cloudy cool day (October 30). Over the entire study period (22 August–5 November), the mean daily evaporation rate was 3.2 L/day (0.66 mm/day). When viewed in more detail over a 10-day period (23 September–3 October; Figure 3), the overall daily UEU evaporation rate pattern was similar, with variations that reflect the particular meteorological conditions of the day.

A typical day began with low evaporation rates that experienced a gradual increase in the hours soon after sunrise, followed by a rapid increase in evaporation over the morning hours. The maximum evaporation rate typically occurred just after midday and was followed by a rapid decrease in evaporation rate in the afternoon and evening, eventually decreasing in the evening. In the pre-dawn hours, evaporation rates were close to zero, or slightly below zero due to natural condensation or 'dew' collecting on the UEU. As expected, most of the evaporation occurred during the daylight hours, with evaporation rates peaking at over 10 mL/min (equivalent to 0.6 L/hour if continuous) on the 12 warmest days.

A 24-hour plot of UEU evaporation and various meteorological parameters (30 September; Figure 4(a)) shows the UEU evaporation rate was slightly below zero after midnight (as a result of dew forming on the UEU) and increased gradually during the early morning (pre-dawn) hours due to gradually increased wind speed and outside air temperature. The UEU evaporation rate then increased more dramatically at dawn when solar radiation (ISW) began to increase (at about 06:00) followed by increased wind speed and outside air temperature. The increase in outside air temperature was accompanied by a corresponding

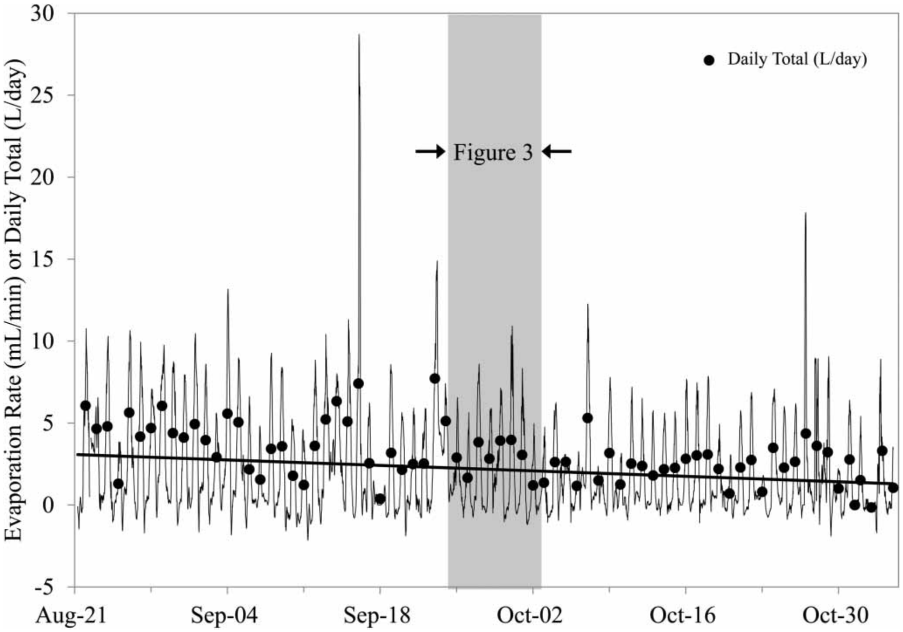

Figure 2 | Evaporation rate (mL/min) plotted as 6-hour average, trend line and daily evaporation total (L) are plotted, where the daily total is cumulative evaporation rate over 24 hours.

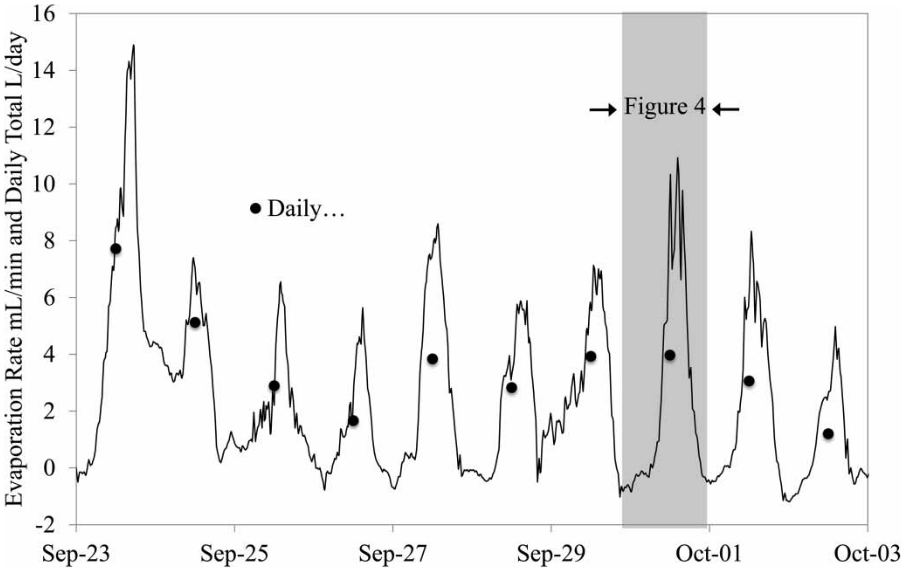

Figure 3 | Evaporation rate versus time for 10-day period (23 September to 3–13 October 2013).

increased temperature inside the UEU and decreased relative humidity both inside and outside of the unit (Figure 4(b)), both of which are related to the observed increased evaporation.

The meteorological conditions during the study period (Table 1) are typical of a continental semi-arid climate with large variations in temperature. When each of these meteorological parameters is simultaneously correlated to the observed UEU evaporation rate over the 76-day study period (day and night), the resultant multiple-regression equation was:

$$\text{Evap} = 0.03\,\text{T}_{\text{OUT}} + 0.37\,\text{WS} + 0.01\,\text{ISW} - 0.33 \pm (1.91) \tag{1}$$

where Evap = UEU evaporation rate (mL/min); T_{OUT} = outside air temperature (°C); WS = wind speed (m/s); and ISW = incoming solar wattage (watts/m^2).

As expected, temperature had a 96% multicollinearity with relative humidity, however, multicollinearity was not observed between the other parameters. This is expected, as relative humidity is defined as the amount of water vapour in the air, expressed as a percentage of the maximum amount that the air could hold at a given temperature. Thus, relative humidity was not included in the regression equation. The results of the multiple-regression analysis (Table 2) indicate that outside air temperature, wind speed, and solar radiation were roughly equivalent in relative importance, with their combination accounting for 63% of the variation in UEU evaporation rate over the 76-day study period. Solar radiation was slightly more important (26%) than wind speed (20%) and temperature (22%). Correlations during the daylight hours were as high as 98% (7 October; Table 1), in this case with wind speed (91%) and solar radiation (88%) having much more influence than temperature (48%).

The multiple-regression analysis allows one to make predictions of relative fresh-water evaporation rates when temperature, wind speed, and solar radiation are known, and within the ranges observed in this study (Table 1). Use of the equation beyond the meteorological range of this study will reduce the accuracy of the result but may be used as an approximation. Based on the historical average monthly temperature, wind speed and ISW for Calgary, the regression equation predicted (Table 3) that the UEU would evaporate an average of approximately 986 L (204 mm) during the period between 1 March and 31 October, when daytime temperatures are above freezing in Calgary. Note the multiple-regression equation has an error of ±1.91 leading, to a range of 408–2,783 L evaporated between 1 March and 31 October.

The amount the UEU will evaporate in other climates around the world will be highly variable and will only be

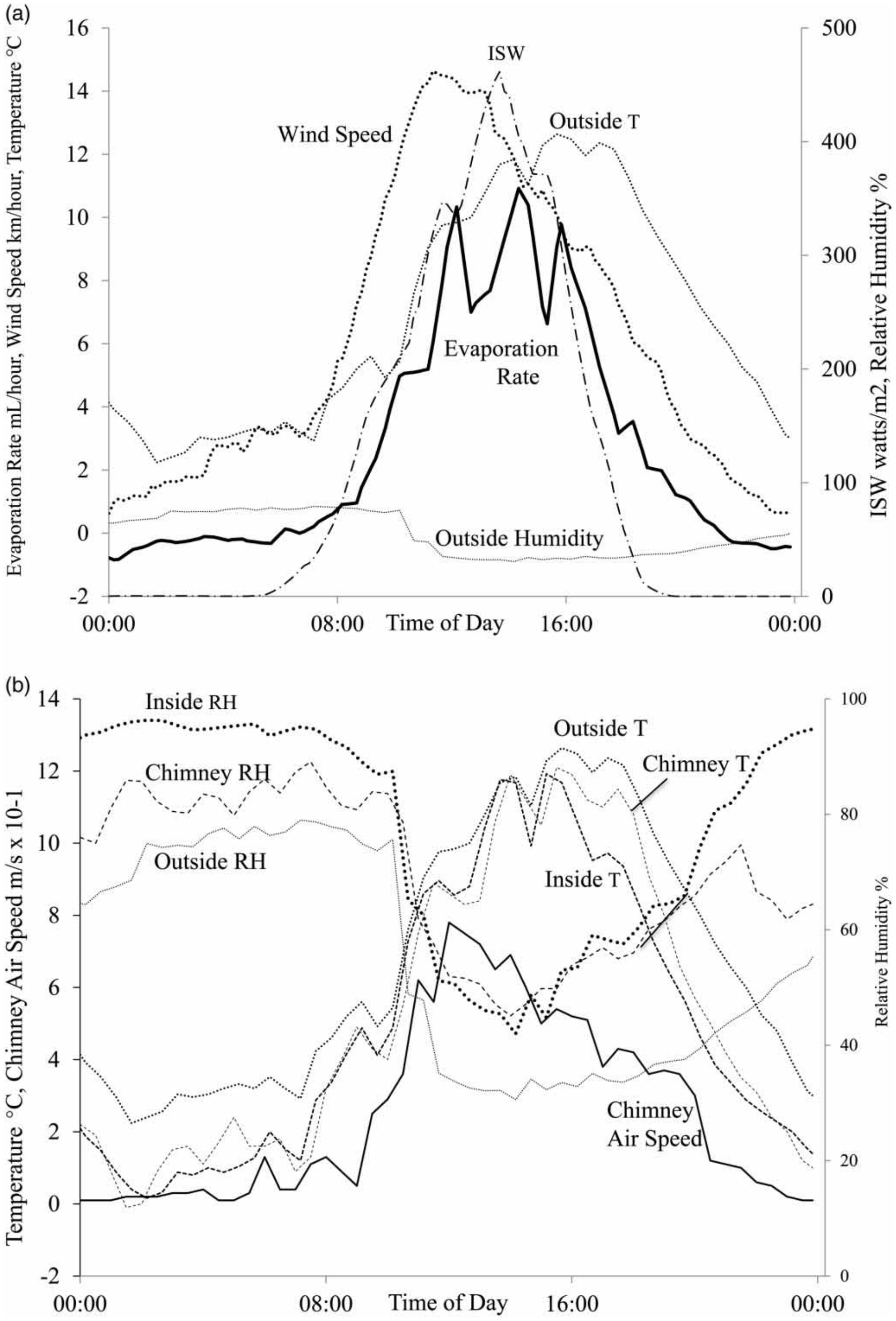

Figure 4 | (a) Evaporation rate and key meteorological parameters, and (b) Urine Evaporation Unit performance parameters for a single cloudless, fall day (30 September 2013). Evaporation rate, wind speed and incoming solar radiation (ISW) plotted as 6-hour averages.

qualitatively discussed. In comparison to the continental climate of this study, a coastal climate will have higher temperatures, higher humidity and lower solar radiation leading to less UEU evaporation. A mountainous climate would have lower temperatures, higher humidity, higher wind and less hours of sunlight, also leading to less UEU evaporation. In mountainous climate, slightly reducing air entry into the UEU should allow the UEU to heat up significantly due to higher solar radiation at altitude. The number of days with a mean temperature above zero must be

Table 1 | Meteorological conditions during study period (22 August–5 November 2013)

	Temperature (°C)	Relative humidity (%)	Wind speed (m/s)	ISW (watts/m²)
Mean	9	66	4	137
Minimum	–10	20	0	0
Maximum	31	99	25	913
StnDev	8	19	3	203
N	10,915	10,915	10,915	10,915

considered and thus the need for urine storage during winter months in northern climates unless a heated space can be provided (e.g. basement). By contrast, a tropical environment would have relatively high temperatures all year but could have either high or low humidity. The UEU would have the highest possible evaporation rates in a dry tropical climate with high amounts of wind and solar radiation. During the wet season the UEU could function intermittently as typically, in a tropical environment, there is sunshine in the morning and rainfall in the afternoon.

Understanding the functioning of the UEU and relevant design criteria are useful to evaluate future prototypes. The UEU design performance can be more closely evaluated by comparing air temperature and relative humidity inside the UEU (measured in the middle of the trays), inside the UEU chimney, and outside the UEU with air speed in the chimney (Figure 4(b)). For example, in the night time, the temperature inside the UEU is about two degrees colder than the outside air. This condition continues until about 10:00 a.m. when the UEU inside temperature becomes almost equal to outside temperature for an hour or so and the UEU inside temperature is slightly higher than the chimney temperature. At this point, the solar oven and chimney are heating up in the sun and air is beginning to rise up through the chimney, as indicated by increases in chimney air speed and evaporation rate. The three RH measurements mirror the temperature tendency, with outside RH consistently lower than inside and chimney RH. This indicated the UEU functioned as intended – the UEU heated up during the day as a function of solar heating, causing increased airflow of relatively warm air within the unit. It is the combination of high temperature and airflow, where the latter leads to warm and low relative humidity air inside the UEU, that leads to increased evaporation rates.

There are two additional factors that affect the UEU evaporation rate. On sunny days, complete drying of the upper tray of each 17-tray stack (which was exposed to direct UV through the Plexiglas top) was visually observed, often before midday. This decreased the effective evaporation surface, and led to a 6% decrease in evaporation rate (data not shown). This also implies that direct exposure to

Table 2 | Multiple-regression analysis of evaporation rate versus meteorological parameters (outside air temperature, wind speed, solar radiation) for the entire study period with day and/or night periods specified and select days

		UEU Evaporation		Correlation (R^2%)			
Date	Meteorological conditions	L/day	mm/day	Overall	Temperature	Wind speed	Solar radiation
21 August–5 November 5 day and night[a]	n/a	3.20	0.66	63	22	20	27
21 August–5 November 5 day	n/a	n/a	n/a	55	7	27	48
21 August–5 November night	n/a	n/a	n/a	99.8	99.1	99.7	0
22 August day	Sunny	8.8	1.82	90	46	33	70
8 September day	Sun and cloud	3.5	0.73	94	0.2	53	92
16 September day	Sunny	7.4	1.53	50	41	40	41
18 September day	Cloudy	0.4	0.08	58	25	32	9
30 September day	Sun and cloud	4	0.83	92	64	67	81
7 October day	Sunny	5.3	1.10	98	48	91	88

Relative humidity is not presented in the multiple-regression analysis as this parameter has a >90% multicollinearity with temperature. The 'Overall' correlation considers temperature, wind speed, and solar radiation.

mm/day = L/m²/day. n/a = not applicable.

[a] Entire study period.

Table 3 | Calculated and measured UEU Evaporation from April to October, when average daytime temperatures are above freezing in Calgary

		Calgary historic averages			UEU evaporation calculated with regression				Measured EUE evaporation in 2013	
	ISW (watts/m^2)	Wind speed (m/s)	Temperature (°C)	RH (%)	L	min	max	mm	L	Mm
April	218	4.7	4.1	51	143	60	410	30	n/m	n/m
May	227	4.7	9.7	45	154	71	424	32	n/m	n/m
June	246	4.4	14	50	163	81	447	34	n/m	n/m
July	248	3.9	16.4	48	158	76	441	33	n/m	n/m
August	227	3.6	15.7	47	144	61	409	30	n/m	n/m
September	180	3.9	10.6	49	121	39	351	25	117	24
October	141	4.2	5.7	55	103	20	302	21	76	16
Total	–	–	–		986	408	2,783	204	–	–

solar radiation facilitates faster evaporation. This design criterion could be used to an advantage, although at the cost of the size of the UEU footprint.

The other factor that would reduce the UEU evaporation rate effect is increased salinity, which gradually increases during evaporation of any liquid with dissolved ions including the City of Calgary municipal water used in this experiment. The rate of evaporation decreases with increasing salinity due to a decrease in vapour pressure at the surface of the liquid. Moore & Runkles (1968) found that for a solution of NaCl dissolved in water, the ratio of brine evaporation (E) to distilled water evaporation (E_0) ranged from 0.96 (50,000 mg/L, 4.4 °C, 40% RH) to 0.44 (300,000 mg/L, 27 °C, 80% RH) showing a strong decrease in E/E_0 with increasing temperature and relative humidity. Moore & Runkles (1968) computed a multiple-regression equation that uses twenty regression coefficients and five measured parameters (air temperature, wind speed, relative humidity, NaCl concentration, and temperature) to estimate the relative evaporation rates of solutions with varying salinity.

City of Calgary municipal water, which has a TDS concentration of ca. 260 mg/L (Iwanyshyn *et al.* 2008), was used in the experiment to minimize the salinity effect. Based on the total volume of water input into the UEU during the experiment (81 L) and the total storage on all 38 trays (about 25 L), it can be calculated that the urine salinity increased during the experiment to about 1,000 mg/L which has an E/E_0 of >0.99 (Moore & Runkles 1968) and thus a negligible effect on evaporation.

If urine had been evaporated in the experiment instead of municipal water, the Moore & Runkles (1968) relation can predict how much urine would have evaporated. Urine has a TDS ranging from 36,700 to 46,700 mg/L (Putnum 1971) and, based on the total volume of water input into the UEU during the 76-day experiment (81 L) and the total storage on all 38 trays when completely full (25 L), it is estimated that the salinity of the urine would have gradually increased to a maximum of about 130,000 mg/L assuming that no precipitation has occurred. This represents a ratio of saline water to deionized water evaporation (E/E_0) of 0.74–0.94 depending on meteorological conditions (Moore & Runkles 1968). Assuming the lower value of 0.74 is the initial ratio and as salinity increases daily, the ratio would gradually decrease. Thus, the estimated 986 L of municipal water that would have evaporated from April to October would represent 730 L of evaporated urine (the amount produced in this time period by 2.8 persons). The annual amount of urine produced by a typical four-person household is about 2,000 L. To evaporate this amount, the UEU would need to be expanded in evaporation surface area (by adding more trays and/or increasing the size of the trays) by a factor of 2.2–2.7.

CONCLUSIONS

This research designed a technology to passively evaporate urine from dry toilets and tested it with municipal water to understand the influence of meteorological factors on

UEU evaporation rate without the influence of increasing salinity as urine evaporates. The resultant UEU is simple to construct from commonly found materials. Field-testing indicates the UEU heated up in sunlight, which combined with a solar chimney drew in outside air and created airflow across the surface of each tray. The average evaporation rate over the study period was 3.2 L/day (0.66 mm/day) with monthly amounts of 117 L (24.3 mm) for August and 76 L (15.8 mm) for September. A multiple-regression analysis indicates that continuously running of the UEU from 1 April to 31 October (when daytime temperatures in Calgary are consistently above freezing) would have evaporated a total of approximately 986 L (204 mm) of municipal water, which is equivalent to approximately 730 L of urine or the amount produced by 2.8 persons in this seven-month time period. The multiple-regression analysis indicated there was a good correlation (63%) between UEU evaporation rate with roughly equivalent importance of commonly measured meteorological parameters (air temperature, wind speed and solar radiation), and particularly good correlation (up to $R^2 = 98\%$) on high evaporation days. This means that the relative amount the UEU will evaporate in a different climate can be reasonably predicted based on historical records of these meteorological parameters.

This is a prototype unit, and performance may be improved by design improvements in subsequent units. Further research should conduct the same experiment with the UEU connected to a urine-diverting dry toilet in order to investigate the effect of salinity on the UEU evaporation rate. In parallel, the social acceptability of the technology should be assessed and the results integrated into future design optimization. Social acceptability of handling human waste differs around the world but, in general, UDDTs, that either collect or divert urine to the ground, have been successfully accepted around the world. The UEU will require humans to periodically remove trays of dried urine and either empty or replace them, which should have a similar social acceptance as collecting unevaporated urine in a jerry can or storage barrel. Social acceptability should increase over time as the benefits of UEU become increasingly seen and valued and the interaction between humans and the UEU interaction is improved. This technology holds promise for the future but will require adaptation to different climates, availability of local materials, fertilizer requirements, cultural acceptance and income levels.

REFERENCES

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. *Sci. Total Environ.* **414**, 592–599.

Bethune, D. N., Chu, A. & Ryan, M. C. 2014 Passive evaporation of source-separated urine from dry toilets: a lab study. *J. Water Sanit. Hyg. Dev.* **4** (4), 654–662.

Ek, M., Bergstrom, R., Bjurhem, J. E., Borlenius, B. & Hellstrom, D. 2006 Concentration of nutrients from urine and reject water from anaerobically digested sludge. *Water Sci. Technol.* **54** (11–12), 437–434.

Hanæus, J., Hellstrom, D. & Johansson, E. 1997 A study of a urine separation system in an ecological village in Northern Sweden. *Water Sci. Technol.* **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. *J. Environ. Manage.* **119**, 29–35.

Hoglund, C., Ashbolt, N., Stenstrom, T. A. & Svensson, L. 2002 Viral persistence in source-separated human urine. *Adv. Environ. Res.* **6** (3), 265–275.

Iwanyshyn, M., Ryan, M. C. & Chu, A. 2008 Separation of physical loading from photosynthesis/respiration processes in rivers by mass balance. *Sci. Total Environ.* **390**, 205–214.

Janson, L. E. 1959 *Evaporation from Salt Water in Arid Zones*. Trans. of the Royal Institute of Tech. Nr. 137. Stockholm, Sweden.

Jonsson, H., Richert, A., Vinneraas, B. & Salomon, E. 2004 *Guidelines on the Use of Urine and Faeces in Crop Production*. EcoSanRes Publications Series, Stockholm.

Krishnan, S. 2011 *On-site Sanitation and Groundwater Contamination: A Policy and Technical Review*. INREM Foundation, Anand, India.

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

Maurer, M., Schwegler, P. & Larsen, T. A. 2003 Nutrients in urine: energetical aspects of removal and recovery. *Water Sci. Technol.* **48** (1), 37–46.

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

Moore, J. & Runkles, J. R. 1968 *Evaporation from Brine Solutions Under Controlled Laboratory Conditions*. Texas Water Development Board Report 77. www.twdb.texas.gov/publications/reports/numbered_reports/doc/R77/R77.pdf.

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

Putnum, D. F. 1971 *Composition and Concentrative Properties of Human Urine*. National Aeronautics and Space Administration, Washington, DC. Report No. NASA CR-1802.

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

WHO, UNICEF 2014 *Progress on Sanitation and Drinking Water – 2014 Update*. World Health Organization, Geneva, Switzerland. www.unicef.org/publications/files/JMP_report_2014_webEng.pdf.

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