Passive evaporation of source-separated urine from dry toilets: UES optimization and dry product accumulation over time

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ABSTRACT

A urine evaporation system (UES) was optimized and evaluated in a laboratory by adding 5 L of urine at the same time each day for 65 days. The UES consisted of a wooden box that is open at the front only with tracks for 22 vertically stacked cafeteria-type trays and a fan and chimney at the back. Urine flowed from tray to tray via gravity exiting each tray via a weir along the long side of the tray. A distinctive physical and chemical zonation in the solid urine product was observed from the upper to lower trays due to leaching of precipitated minerals in the upper trays and mineral accumulation in the lower trays. The redox conditions became increasingly oxidizing from the top to bottom trays due to contact with the atmosphere thus favouring more stable mineralized forms of nitrogen (ammonium and nitrate) and sulphur (sulphate) and disfavouring the less stable and volatile ammonia, nitrogen gas and hydrogen sulphide. The quality of the fertilizer product is higher in the upper trays with higher levels of nitrogen, phosphorus and potassium, whereas the lower trays have higher levels of sodium chloride. Nitrogen losses due to ammonia volatilization were approximately 35%.

INTRODUCTION

The ecological sanitation (a.k.a. ECOSAN) approach for rural wastewater management is based on the concept of dry toilets and the separation of faeces and urine at the toilet (a.k.a. urine diversion or urine source separation) (Larsen & Gujer 1996; Hanaeus et al. 1997; Hellstrom & Johansson 1999; Morgan 2004). Urine contains most of the nutrients excreted by humans (85–90% nitrogen, 50–80% phosphorus and 80–90% potassium) (Larsen & Gujer 1996) and their collection can provide a low-cost, local supply of fertilizer. When separate from urine, faeces have fewer odours and can more easily be dehydrated or composted (Hill et al. 2013). Urine is either collected in a barrel or jerry can or diverted to a ‘soak pit’ in the ground, where it can pose a significant threat to groundwater quality (Odong 2007).

Urine evaporation has been suggested as a possible solution to the problem of what to do with source-separated urine (i.e., collection/storage or soak pit) (Maurer et al. 2005, 2006). Pronk & Kone (2008) identified urine evaporation as a promising solution in rural agricultural areas without reliable electricity, and suggested a sand-bed filter followed by solar/heat evaporation. Antonini et al. (2012) used a solar still in Vietnam to passively heat and evaporate the water from urine at a rate of about 2 L per day and collected its dry, solid product for fertilizer. Bethune et al. (2014) developed a urine evaporation system (UES) and evaporated up to 8.5 L/m²/d of urine in a laboratory fume hood using vertically stacked cafeteria-type trays with a layer of sand on the bottom, however, observed nitrogen losses of about 90% due to volatilization.
The goals of this research are to: (a) optimize the evaporation rate by improving airflow and (b) measure the accumulation of solid urine product of the UES originally developed by Bethune et al. (2014), where urine is evaporated on vertically stacked cafeteria-type trays. In the current study, UES was optimized to enhance airflow across the surface of the trays by having only the front side open. The back wall was closed and a fan was installed, which pulled air into the front opening and across the surface of each tray. The increased airflow and resultant increased evaporation rate should reduce nitrogen losses observed in Bethune et al. (2014) as less time will be available for ammonia volatilization. In addition, the trays were significantly reconfigured: instead of having holes at one end of each tray (as in Bethune et al. 2014), a weir was cut along one of the long sides and urine passed from tray to tray via the weirs. The weirs have two advantages over the holes: (a) the weirs do not become clogged over time due to mineral precipitation and (b) the weirs provide important storage for urine and solid product. Urine storage is beneficial as the UES can handle higher loads for short periods of time. Solid product storage is beneficial as it increases the time the UES may collect solid product before the trays need to be emptied. The experiment consisted of adding 5 L of fresh urine at the same time each day to the UES until the first trays became entirely full of solid urine product (65 days). The build-up of solid product on each tray was measured and sampled over time to understand the distribution of the major minerals and fertilizer nutrients on the trays.

**METHODS**

An evaporation box was designed and constructed to enhance airflow across the surface of the trays by having only one side open and installing an electric fan in the back wall, which pulled air across the surface of each tray (Figure 1). A weir (20 cm long × 0.5 cm deep) was cut along one of the long sides for urine outflow to

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**Figure 1** Details of urine evaporation system (UES), including (a) a schematic showing urine and air flow, and location of electric fan; (b) a 'Tray Close-up' photo illustrating the 'weir' cut out along each tray. The tray is inserted such that weirs are located on opposite sides of the frame, so that urine flows 'back and forth' across consecutive trays; (c) a 'Tray track cross-sectional view' shows the cross-sectional detail of the horizontal tracks cut into plywood that support the trays; (d) Photos showing the 22 trays inserted into wooden frame from open-ended UES front (left-hand side) and fan inserted into cut-out in back wall of UES (right-hand side).
the tray below. Twenty-two tracks, designed to hold 22 small-size cafeteria trays (dimensions 32 cm × 25 cm × 1.5 cm) in place, and facilitate easy removal and replacement were spaced 2.5 cm apart on each side of the box. When full to the bottom of the weir, each tray held about 600 mL of liquid, thus the stack of 20 trays, when full, held about 13 L of stored volume (urine and/or solid product).

Five litres per day of urine was input to the UES at the same time each day for 65 days, which was when the first trays were entirely filled with solid product. Twenty of the 22 trays were wetted with urine each day, thus the total tray area was 1.9 m² leading to an evaporation rate of 2.7 L/m²/d. Temperature, relative humidity and air flow velocity were measured with a TSI VelociCalc© Air Velocity Meter at the fan pipe outflow and above each tray.

Urine was collected in 1 L sterilized Nalgene bottles and stored for periods of 1–20 days prior to input into the UES. The UES was placed in a laboratory at the University of Calgary (approximately 20°C and 22% relative humidity) with the fan vented to a fume hood. The mass of solid product on each tray was measured over time with an electronic top-loading electronic scale (Dakota Defender Series D30). The pH of the evaporating urine brine was measured with a VWR handheld probe (model SP70P), which was calibrated for use. Electrical conductivity was also measured on the evaporating brine with a VWR probe (Amber Scientific; model 2052), which was calibrated for use.

Soil extractions were conducted to evaluate the composition of the solid product accumulated on each tray (Carter & Gregorich 2007). The soil extractions were conducted by dissolving dry solid product (1–15 g) in deionized water (50–500 mL), followed by shaking on an orbital shaker for 30 minutes. The supernatant was subsequently filtered to 0.45 micron prior to dilution for ion chromatographic analysis (Dionex ICS-1000, Standard Methods 4110 B; Standard Methods for the Examination of Water and Wastewater (American Public Health Association 2005)), and the resulting concentrations expressed as a ratio with the total mass of dry product extracted. Reduced mineral N (as analysed in the ion chromatography) is reported as NH₄⁺, but includes both forms of the polyprotic ion (i.e. NH₃ and NH₄⁺) since negligible NH₃ is present in the acidic ion chromatograph carrier eluent during analysis (pH < 4). The major ion analyses had a standard error of ±3.0% (n = 36) when compared to standard reference materials, and ±1.9% error (n = 54) in duplicate sample analysis. Organic matter was measured by a loss on ignition test where a sample of solid product is dried then combusted at 500°C for 2 hours according to the methodology of the Environmental Protection Agency (2001). Chemical oxygen demand (COD) was measured with a HACH TNT 821 (1–150 mg/L). Total Kjeldahl nitrogen was measured with a HACH TNT 880 (1–16 mg/L N).

Saturation indices (SIs) were calculated for all common minerals in a solution with the input urine composition with increasing evaporation using the geochemical modelling software PHREEQC (United States Geologic Survey 2014) to evaluate whether mineral precipitation was expected. The SIs were reported as log values:

\[ SI = \log(IAP/K_{sp}) \]  \hspace{1cm} (1)

where IAP is the ion activity product and K_{sp} is the solubility product constant. If SI > 0 the mineral form is likely to form, if SI < 0 the mineral is below saturation (and likely to dissolve if present), and SI = 0 represents equilibrium. The SI for the mineral struvite (MgNH₄PO₄·6H₂O) was calculated manually based on ion activities provided by PHREEQC since this mineral is not included in the PHREEQC mineral database. Struvite solubility decreases with increasing pH to a minimum solubility at pH = 9. Thus, a pH-dependent solubility product was applied; this varied from 1.3 × 10⁻⁷ at pH 7 to 4.0 × 10⁻¹⁰ at pH 9.4 (Doyle & Parsons 2002).

The sodium adsorption ratio (SAR) describes the ratio of sodium to the sum of calcium and magnesium in soil solution, and represents the potential for sodium to replace calcium and magnesium in a soil. The usual formula to calculate SAR is given below, with concentrations expressed in milliequivalents per litre (meq/L) as analysed from a saturated paste soil extract. In this study, the SAR is calculated in meq/g on the extractions obtained from the dry product:

\[ SAR = \frac{Na^{+}}{\sqrt{1/2[Ca^{2+} + Mg^{2+}]} \]  \hspace{1cm} (2)

The salt index of a material is expressed as the ratio of the increase in osmotic pressure of the salt solution
produced by 20 lbs of the material to the osmotic pressure of the same weight of a chosen standard, NaNO₃, which has a set value of 100 \( (\text{Mortvedt 2003}) \). The salt index of the dry product on each tray was calculated based on the concentrations of N, P and K (converted from mg/g to lb/20 lb bag or kg/9.1 kg bag) and an estimated SI per nutrient unit of 1.618, which is a typical value for urea fertilizer \( (\text{Mortvedt 2003}) \).

**RESULTS AND DISCUSSION**

The mass of solid urine product accumulated after 65 days on each tray \( (\text{Figure 2}) \) increased from the top to bottom tray, with: (i) relatively little solid product accumulation on trays 1–7, and (ii) increasing rates of solid product accumulation on trays 8–11, with the highest masses of solid product (>1 kg) collected on trays 12–19. This pattern defines two distinct zones in the upper trays with respect to solid accumulation: ‘leaching’, where relatively little solid product is accumulated (trays 1–7) and ‘accumulation’ (trays 12–19) \( (\text{Figure 2}) \).

Accumulation of solid material on the trays occurs when mineral SIs are reached, and mineral precipitation occurs. A small amount of solid product was visually observed on the upper trays before the daily loading of urine, but did not accumulate. The once-per-day input of 5 L of urine led to a daily ‘recharge event’ of unevaporated urine into the top trays. The relatively low salinity of the ‘fresh’ urine re-dissolved some of the solid material that had been deposited over the previous day, and leached the material to the lower trays. Mineral SIs in the upper trays would be lowest immediately after recharge, and would increase as evaporation proceeded over the remaining part of the day, until the next day’s recharge.

Most of the minerals formed at the end of the daily evaporation period are apparently ‘leached’ from the upper trays to the lower trays on a daily basis, leading to minimum rates of solid product accumulation in trays 1–7. As solid product was deposited on the middle and lower trays, the urine storage capacity of each tray progressively declined, and thus the daily urine application flowed progressively deeper into the UES, with significant masses of solid product being stored on progressively lower trays in the vertical stack.

Another factor that could have affected the distribution of solid product in the vertical tray stack was the fan location, which was set closest to the vertical centre of the trays \( (\text{Figure 1}) \). This led to higher air velocity \( (\text{Figure 2}) \), which would produce relatively higher evaporation rates for the middle trays. It is noted that the trays with the maximum solid product accumulation are slightly below the trays with the highest air velocity, which may reflect the dual influences of air velocity/evaporation rate and the daily leaching effect.

The once-per-day input or urine produced an uneven accumulation of solid product, which does not utilize the storage potential of all the trays, especially the upper trays. A more dispersed input over the 24-hour period during the day would lead to a smaller number of trays being leached by ‘fresh’ urine, mineral accumulation on trays that are higher in the vertical stack, and thus a more even accumulation of dry product from top to bottom with a resultant increase in overall tray longevity (i.e., time for tray to completely fill with dry product).

When urine leaves the human body and enters the environment, it spontaneously undergoes irreversible urea hydrolysis \( (\text{Warner 1942; Andrews et al. 1984}) \), leading to a
pH increase from about 6 to 9 (Ciba-Geigy 1977; Kirchmann & Pettersson 1995; Jonsson et al. 1997; Udert et al. 2006). The pH increase triggers the precipitation of low solubility minerals and ammonia volatilization.

The pH and redox conditions of the urine brine during evaporation indicate a clear trend: (i) from reduced to oxidized conditions from top tray to bottom tray, and (ii) a tendency for pH and Eh (oxidation-reduction potential) to stabilize with time (with less change observed between 59 and 65 days than observed between 39 and 59 days). Relatively constant values of pH (6–7) and Eh (30–50 mV) were observed after 65 days (Figure 2). The pH values are linearly correlated with pE, with a slope that is parallel to the upper and lower stability lines of H₂O (Figure 3). The urine brine is initially (i.e., after 39 days) more reduced in the upper trays and oxidized in the lower trays, relative to the final trend after 65 days. Similarly, the pH values are initially highest in the upper trays and lowest in the lower trays (Figure 3). In both cases, the values stabilize with time.

The chemical composition of any particular tray is based on where it is located in the vertical sequence of trays (Figure 4). Chloride is the only ion that continuously increases in concentration from top to bottom, eventually precipitating as either sylvite (KCl) or halite (NaCl) in the very final stages of evaporation. Since these are the only chloride-bearing minerals, and they are relatively soluble, the chloride is leached gradually downward through the
trays in urine brine without mitigation by mineral precipitation. All other ions decrease in concentration when the various minerals they form reach saturation.

Results of the PHREEQC simulations (Table 1) indicate that, as expected, the SI values reflect the order in which the SIs suggest minerals should form (i.e., those with lowest solubility first and higher solubility later). Hydroxyapatite, struvite and dolomite were super-saturated prior to evaporation and thus begin precipitation soon after input to the UES. Calcite reached supersaturation after about 40% of the liquid was evaporated from the urine, and halite and sylvite reached supersaturation after close to 99% of the urine liquid was evaporated.

Organic matter is a large fraction of the total ‘solid product’ varying between 39% and 80% of the total mass (mean 55%; Figure 5). A slight increase in OM can be seen in the upper trays (leaching and transition zones), which likely results from leaching. A slight decrease is observed on the accumulation zone, which likely reflects the loss of urea during ongoing urea hydrolysis.

Evidence of partial nitrification is provided by the increase in nitrate from top to bottom and favourable (i.e., oxidizing) redox conditions. Nitrate would eventually precipitate with calcium, sodium, potassium or ammonia depending on the SIs of each. Struvite, with relatively low solubility, particularly in high pH, is precipitated in the upper trays (1–14), until no detectable Mg is found, and hence further struvite precipitation is not possible. Sulphur is also lost partially due to volatilization as H₂S at lower pE in the upper trays. Once oxidized to SO₄ as indicated by a notable increase in concentration at tray 11, sulphur is precipitated as potassium sulphate in the lower trays (Figure 6). Na and K begin to precipitate in the lower trays with Cl as halite and sylvite, respectively.

The solid urine product is thus higher in nitrogen and phosphorus in the upper trays and higher in potassium, sodium and chloride in the lower trays, thus the quality of the fertilizer product is higher in the upper trays and lower in the lower trays. The SAR gradually increases from below 10 on the top trays to as high as 40 on the bottom trays. A SAR value above 3 represents a healthy soil and a soil with a SAR of >13 is sodic (Richards 1954). The trays in the lower half are thus classified as sodic. The salt index compares the concentrations of N, P and K to a standard fertilizer value of 100 (for NaNO₃) used to compare fertilizers. The calculated values vary from 9 to 23, which are considerably lower than the fertilizer standard.

A mass-balance for ammonia provides an approximation of the amount of ammonia that is lost due to volatilization. The mean concentration of ammonia in the input urine was 298 mmol/L and the total amount of urine input was 325 L, thus the total amount of ammonia input was approximately 96,850 mmol. Given that a total of 62,526 mmol of ammonia was measured in the solid product, the ammonia loss is approximately 35%, which is significantly less than the 90% ammonia losses observed by Bethune et al. (2014). This results from the higher evaporation rate achieved with the optimized UES.

<table>
<thead>
<tr>
<th>% Evaporated</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>99</th>
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<tr>
<td>Volume (L)</td>
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<td>0.80366</td>
<td>0.6031</td>
<td>0.40255</td>
<td>0.20203</td>
<td>0.01685</td>
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<tr>
<td>Minerals precipitated</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Hydroxyapatite</td>
<td>Ca₅PO₄OH</td>
<td>10.28</td>
<td>9.7</td>
<td>10.27</td>
<td>10.33</td>
<td>10.53</td>
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<tr>
<td>Struvite</td>
<td>MgNH₃PO₄</td>
<td>9.98</td>
<td>7.72</td>
<td>7.71</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Dolomite</td>
<td>CaMgCO₃</td>
<td>0.75</td>
<td>0.87</td>
<td>1.13</td>
<td>1.28</td>
<td>1.5</td>
</tr>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
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<td>–0.13</td>
<td>0.01</td>
<td>0.2</td>
<td>0.47</td>
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<tr>
<td>Halite</td>
<td>NaCl</td>
<td>–4.57</td>
<td>–4.4</td>
<td>–4.17</td>
<td>–3.85</td>
<td>–3.3</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄2H₂O</td>
<td>–3.13</td>
<td>–2.53</td>
<td>–2.43</td>
<td>–2.43</td>
<td>–2.03</td>
</tr>
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</table>

Struvite SIs calculated from Ksp and ion activity product:
SIs > 0 indicated with bold font.

Table 1 | SIs for major minerals during various stages of urine evaporation estimated by PHREEQC.
CONCLUSIONS

The UES design improvements are evident with the evaporation rate of 2.7 L/m²/d, which is significantly higher than the 1.5 L/m²/d measured by Bethune et al. (2014). This improvement is apparently due to the improved airflow as all other conditions in the laboratory were the same as the Bethune et al. (2014) experiment. The distinctive physical and chemical zonation of the solid urine product on the trays, characterized by mineral and organic matter leaching in the upper trays and their accumulation in the lower trays, leads to the possibility of separating the soluble salt ions (Na and Cl) from the less-soluble nutrient ions (N, P, and K). The solid urine product is thus higher in nitrogen and phosphorus in the upper trays and higher in potassium, sodium and chloride in the lower trays, therefore the quality of the
fertilizer product is higher in the upper trays and lower in the lower trays. The observed transition from reducing (low $E_0$) and high pH conditions in the upper trays to more oxidizing (high $E_0$) and lower pH conditions in the lower trays indicates a chemical stabilization from top to bottom where the more mineralized forms of nitrogen and sulphur (NH$_4$, NO$_3$ and SO$_4$) are favoured and the odorous NH$_3$ and H$_2$S are disfavoured. This leads to decreased nitrogen losses due to ammonia volatilization (approximately 35%) compared to the 90% observed by Bethune et al. (2014). At a practical level, this means that by harvesting the solid product from the upper trays only, it is possible for the UES to produce a fertilizer that is not excessively salty. The challenge of this approach will be to optimize and adapt the basic UES design for different climates, availability of local construction materials, fertilizer requirements, income levels and cultural acceptance.

**REFERENCES**


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