Fertilizer from dried human urine added to ash and lime – a potential product from eco-sanitation system
Shanta Dutta and Björn Vinnerås

ABSTRACT
This research explored the possibility of making fertilizer at a laboratory from source separated and untreated human urine added to ash and lime by drying at low temperatures. A mixture of ash and lime (1:1) was used as drying agents and human urine was applied as undiluted and fresh. Ash and lime were chosen as drying agents for maintaining a pH > 10 during the drying process, which should inhibit urea hydrolysis in urine, and thereby urea should be retained in the drying agent. The drying technique was developed and drying capacity of the system was quantified; three specific temperatures (20°C, 35°C, 60°C) and two airflow rates (1 L/min and 5 L/min) were used in the experiment. A mass balance for nitrogen in the system was obtained. It was evident from the experiment that urea can be retained by maintaining a high pH (>10). Urine drying at 20°C was not a feasible option, since rate of evaporation was very low. The highest retention of inflow nitrogen at 35°C and 60°C were 74% and 54%, respectively, in the produced fertilizer. Reduced evaporation rate, flooding of urine over drying agent, and blockage in airflow influenced nitrogen loss and concentration of nitrogen in the final product.

Key words | eco-san, fertilizer, nitrogen, nutrient recycling, source separated urine

INTRODUCTION
Separate collection and treatment of human urine has opened up a new path for safe and sustainable recycling of plant nutrients in the environment. Urine has a good fertilizer value and it contains substantial amounts of plant nutrients found in wastewater (flush water is included) and grey water (Jönsson 1997; Johansson et al. 2001; Vinnerås et al. 2006).

Human urine is a liquid by product of the body that is constituted of mainly water (95%), urea, cations (Na+, K+, NH4+, Ca2+) and anions (Cl−, SO42−, PO43− and HCO3−), creatinine and organic compounds (Kirchmann & Pettersson 1995). Urine accounts for approximately 1% by volume of the total domestic wastewater flow but it is the dominating source of main agricultural nutrients, nitrogen (80%), phosphorus (50–55%) and potassium (60%) (Johansson et al. 2001; Vinnerås et al. 2006). Urine contains 80–90% of the nitrogen, 50–80% of the phosphorus and 80–90% of the potassium in the total food consumption (Berger 1960). At an average, 400–500 L of urine is excreted by an adult per year, which contains 4.0 kg of nitrogen, 0.4 kg of phosphorus and 0.9 kg of potassium (Jönsson 1997; Esrey et al. 1998).

The pH of freshly excreted urine varies from 4.8 to 8.2 (Diem & Lentner 1970; Lentner et al. 1981). The total nitrogen concentration in undiluted fresh urine ranges from 7–9 g/L (Guyton 1986), the main form of nitrogen in urine is urea (80%) and the remaining portion can be found as ammonia (7%), creatine (6%), shorter peptides and free amino acids (Lentner et al. 1981; Kirchmann & Pettersson 1995). Phosphorus is mostly found as inorganic phosphates (PO43−P) (>95%) and potassium mainly as free ions (K+) (Berger 1960; Lentner et al. 1981). Nutrients are found in highly available plant form and uptake by a plant is essentially as good as chemical fertilizer (Kirchmann & Pettersson 1995; Jönsson et al. 2004). On the other hand, the content of heavy metals (copper, zinc, chromium, nickel, lead and cadmium) in urine is very low compared to other categories of waste, for instance faeces, kitchen waste, farmyard manure and commercially available fertilizer and, therefore, urine is considered a very clean

In diverted urine, the urea is hydrolyzed by bacteria produced urease (urea amidohydrolase) within the collection system (Jönsson et al. 2000; Udert et al. 2003). Consequently, the nitrogen in stored, source-separated urine mostly exists as ammonia nitrogen (92–99%) and this process contributes to an alkaline pH (9–9.3) in urine (Equation (1)) (Udert et al. 2003).

\[
\text{NH}_2\text{(CO)}\text{NH}_2 + 2\text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{NH}_4^+ + \text{HCO}_3^{-} \tag{1}
\]

The relatively large urine volumes of 3–500 L per person and year and then low plant nutrient concentration 0.7% N make it difficult to treat urine and recycle nutrients particularly in low- and mid-income countries. Different researchers used drying techniques to reduce the volume and to concentrate urine for nutrient recovery (Mayer 2002; Pahore et al. 2010; Antonini et al. 2012; Udert & Wächter 2012). Mayer (2002) and Udert & Wächter (2012) used distillation reactor, Pahore et al. (2010) tested a volume reduction system based on water evaporation from a vertical gauge sheet and Antonini et al. (2012) constructed a photo-reactor (solar still) for solar thermal evaporation of human urine.

Since loss of nitrogen due to ammonia volatilization is an issue during evaporation, Udert & Wächter (2012) used biological nitrification to stabilize nitrogen in urine prior distillation, and Antonini et al. (2012) mentioned that urine acidification prior to treatment improved fertilizer value but they did not recommend the method for developing countries because of extra cost and handling risks.

This study was intended to develop a low-tech system for drying of fresh human urine added to drying agent – that is the combination of sieved ash and slaked lime at temperatures of 20 to 60 °C, and to produce a solid urine fertilizer containing nitrogen in the form of urea, which can be used as an alternative to commercially available chemical fertilizer. Our study tested the alkaline pH of drying agents as an inhibitor of urea hydrolysis for preventing nitrogen loss. Urea was kept to an alkaline pH (9–10) in the drying agent (sieved ash and slaked lime). Kabdasli et al. (2006) reported in an experiment that no hydrolysis occurs in untreated human urine above pH 10. The objective was to evaluate urine drying at three temperatures in a controlled environment with controlled airflow.

Source separated human urine is already in use for agricultural production (Jönsson & Vinnerås 2007). Use of treated urine in a field as fertilizer contributes in two ways: prevention of environmental pollution from human waste and reducing the application of chemical fertilizer, which leads to a more sustainable agriculture (Esrey et al. 1998).

METHODS

The experimental setup

The urine drying experiment was planned to run at three different temperatures, room temperatures 20 °C (Sweden), 35 °C (representing tropical summer) and 60 °C (representing the temperature that can be reached in solar toilets in tropical countries) with controlled airflow (1 L/min, 3.61 dm² and 5 L/min, 3.61 dm²) and controlled moisture content (relative humidity 70%). The desired amount of moisture was achieved by air pumped through a box containing sodium chloride (NaCl) solution. A mixture of ash and lime (1:1) was used as drying agent. Exhaust air from urine drying box was passed through diluted sulfuric acid solution that trapped ammonia (NH₃) from the air. Each treatment consisted of an air pump, a moisture control box, a urine-drying box, a pipe for collecting water vapor from urine drying and an acid trap (Figure 1).

Pilot test and estimated urine loading rate

A pilot test was carried out with only water in the drying box (without any drying agent and urine added) to quantify the drying capacity of the system. The amount of water evaporated per day from each treatment was measured (Table 1) and considered as the urine drying capacity of the system with specific temperature and airflow.

Total daily water loss (Table 1) was highest in T1 (223 mL), where the drying box was placed in an incubator with 60 °C temperature and provided with 5 L/min airflow; the loss was lowest for T4, where the drying box was in room temperature (20 °C) and airflow was 1 L/min. The daily urine-loading rate was estimated from the water loss test. Aimed at the actual urine drying experiment, it was decided to keep the daily urine loading rate as 20% less than the actual daily drying capacity of the system, so that there would not be any risk of urine flooding on the drying agent. Daily urine load (5 days/week) was 250 mL for T1, 140 mL for T2 and 26 mL for T3. Treatment T4 was aborted due to very low evaporation rate.

Urine collection and sampling

Urine was collected every day in the morning from people aged 25–55 years in sterile plastics bottles and applied in the drying box daily as undiluted and fresh. Urine from different donors
was mixed before application and sample was taken from the mixed urine; the sample represented 1% of the total applied urine in a specific day. Urine samples taken during the first three weeks of the experiment were stored in one bottle and samples from the rest of the experiment were stored in a separate bottle and analyzed for measuring ammonia nitrogen.

### Preparation of drying agent

The drying agent was prepared by mixing ash and slaked lime (Ca(OH)$_2$) and the ratio was 1:1 by weight. Prior to use in the experiment, wood ash was sieved and fine ash was used in the experiment. The density and pH of sieved

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**Table 1** | Estimated daily urine loading rate in different treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Temperature of moisture control box (°C)</th>
<th>Temperature of drying box (°C)</th>
<th>Airflow (L/min)</th>
<th>Rate of water loss (L/m$^2$ day)</th>
<th>Total water loss from the drying box (ml/day)</th>
<th>80% of average daily water loss (ml)</th>
<th>Total urine load in a week (ml)</th>
<th>Urine load (when applied 5 days/week) (ml/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>35</td>
<td>60</td>
<td>5</td>
<td>6.20</td>
<td>223</td>
<td>179</td>
<td>1,250</td>
<td>250</td>
</tr>
<tr>
<td>T-2</td>
<td>35</td>
<td>60</td>
<td>1</td>
<td>3.40</td>
<td>124</td>
<td>99</td>
<td>695</td>
<td>140</td>
</tr>
<tr>
<td>T-3</td>
<td>35</td>
<td>35</td>
<td>1</td>
<td>0.64</td>
<td>23</td>
<td>19</td>
<td>130</td>
<td>26</td>
</tr>
<tr>
<td>T-4</td>
<td>20</td>
<td>20</td>
<td>1</td>
<td>0.20</td>
<td>7</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

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**Figure 1** | A diagram showing simplified system design for urine drying at 35 and 60 °C.
ash was measured; de-ionized water was mixed with sieved ash and pH of the solution was measured by using a pH meter (pH electrode Blueline 14, Germany).

The mixture was supposed to act as a buffer during the drying process and thereby maintain the pH 10 or higher, since addition of fresh urine is likely to lower the pH every day.

**Urine drying experiment**

The treatment at 20 °C was aborted after the pilot test since drying capacity was too low. The actual urine drying experiment was started with three different treatments, one at 35 °C and two others at 60 °C (with two different airflows) but in all cases moisture control boxes were set in 35 °C temperature. Each treatment had two replicates and drying experiment was carried out for seven weeks.

Amount of urine applied in the system per day was based on drying capacity of the system that was measured during the pilot test. The amount of urine applied per day was 20% less than the drying capacity (as a cautionary approach). During the experiment, no urine was applied during weekends; therefore, daily urine application rate was adjusted, so that the total amount of urine applied in 5 days equaled to the total amount if urine was applied 7 days per week. The amount of drying agent used in a treatment was five times (by weight) of the average daily application rate of urine over the week in that specific treatment (Table 2).

**Additional changes in the experiment**

As the experiment was started, it was observed that all the acid traps were increasing by volume since they started to receive evaporated water from urine drying (Table 3). There was a chance of spilling acid solution out of the bottle that contains acid. Therefore, T-connections were used to install pipes before the acid traps (Figure 1), which could retain a part of water vapor before it entered the acid trap. The pipes with T-connections were installed for all treatments, so that those could be removed every day for collecting condensate from urine drying and then connected back.

On the third week of the experiment, T₂R₂ (it should be read as Treatment-2, Replicate-2) became moist and, consequently, urine flooded over the drying agent. It was stirred well; sometimes urine was not applied and observed if the treatment gets back good drying condition. During the fourth week, the experiment was paused for the whole week (for a personal reason) that means the system was running but no urine was applied to any treatment. It is needed to mention that T₂R₂ did not recover; so, the box was cleaned and refilled with ash and lime that means T₂R₂ got a new start and, afterwards, urine was applied according to the capacity of system.

On the fifth week, T₁R₂ and both replicates of treatment 3 (T₃R₁ and T₃R₂) became moist and the material was mixed well to facilitate the drying process. As mixing did not help, some more drying agent was added to those treatments. For T₃R₁ and T₃R₂, the amount of drying agent was doubled, which means 95 g more (47.5 g ash and 47.5 g lime) were added to those two replicates and for T₁R₂, 300 g more (150 g ash and 150 g lime) was added in addition with the old material. Afterwards, urine loading was reduced by 50% for T₁R₂.

On the seventh week, all the six treatments became moist, especially T₁R₂ and T₂R₂, and, therefore, urine loading rate was reduced by 30% and materials were mixed well in all the boxes. A reduced loading rate and mixing did help to improve the drying condition of treatments, except for T₁R₂, T₂R₁ and T₂R₂, so 100 g, 150 g and 150 g more drying agent was added to T₁R₂, T₂R₁ and T₂R₂, respectively.

At the end of seventh week, it was decided to run the experiment for one week more. On the eighth week, 50 g drying agent was added to T₁R₁ and T₃R₂. So, the experiment was run for eight weeks in total including a one-week break (urine was applied for seven weeks). All additional changes in the experiment are summarized in Table 3.

**Analytical measurements**

The pH of fresh urine and dried urine was measured during the experiment (pH electrode Blueline 14, Germany). In case of fresh urine, pH was measured every day before

<table>
<thead>
<tr>
<th>System specification for urine drying experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatment</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>T₁</td>
</tr>
<tr>
<td>T₂</td>
</tr>
<tr>
<td>T₃</td>
</tr>
</tbody>
</table>
Ammonium test kit 1.00683.0001 (Merck, Germany) was used to prepare samples for measuring ammonium nitrogen (NH₄-N) in urine, dried urine fertilizer, acid solution and in condensed water vapor (from urine drying) by using a spectrophotometer (Model-4001/4, CAT-4001-03, Thermo Electron Corporation, USA). The method is analogous to EPA 350.1, US Standard Methods 4500-NH3 D, and ISO 7150/1.

Samples were taken from fresh urine, dried urine, condensate and acid trap for total ammonium nitrogen (TAN) analysis. Fresh and dried urine samples were taken after urea hydrolyzation (TAN+ u is used in the document to indicate total ammonium nitrogen in hydrolyzed urine sample). For dried urine, samples were taken randomly to ensure unintentional sampling from treatments.

For urea hydrolyzation, the amount of urea in diluted fresh urine samples was estimated and 5,000 units of urease enzyme was added per gram of urea to those samples. Prepared samples were shaken overnight for complete breakdown of urea by urease. After that, ammonia test kit and spectrophotometer were used to measure NH₄-N in samples. For dried urine fertilizer, the procedure was the same as for fresh urine, except that the pH of dried urine samples was very alkaline (pH > 13) and so, it was adjusted by adding diluted (0.01 ML⁻¹) hydrochloric acid (HCl). Samples from acid trap and condensate were also analyzed using ammonia test kit. The pH of acid solution sample was very low (pH ≤ 2) and, therefore, it was adjusted by adding diluted (0.1 ML⁻¹) sodium hydroxide (NaOH).

**Calibration of TAN values by using acid and drying agent**

As there was, a mal-fit in the results in the mass balance for some treatments (higher output than input). Therefore, photometric analysis only with acid solution (with no added ammonia from urine drying) and with ash and lime dissolved in water (no urine added) by using the ammonia test kit. These data were then used for calibration of the ammonia analysis of acid trap and dried urine samples.

## RESULTS

### Characteristics of collected fresh urine and ash

The average pH of urine (mixed urine from different donors) applied to the system was 6.1 (Table 4). The range of pH of every day urine mixture was 5 to 7.5. Fresh urine samples...
were collected in different bottles for the first half and the second half of the experiment and total ammonia TAN was measured after enzymatic degradation with urease (TAN + u) and it was 6.84 ± 0.02 g/L (weeks 1–3.5, 1st half of the experiment) and 8.24 ± 0.09 g/L of wet mass of urine (Table 4), respectively. The pH of sieved ash was 12 as measured before the drying experiment.

**Mass balance for TAN + u**

After calculating the total amount of TAN + u in fresh urine, dried urine, condensate and acid trap, all the values are put together to make a mass balance of TAN + u in the whole urine drying system (Table 5). Here, we considered fresh urine application as the input of TAN + u, the output includes two parts: one is storage in the dried urine, and the other part is loss from the system, which represents the TAN found in condensate and acid trap.

For T1R1, the total input is 63.51 g and total output (storage + loss) is 50.03 g where 40.90 g is stored in dried urine (Table 5). For this treatment, the difference between total input and total output is 13.48 g, 64% of the input TAN + u was stored in dried urine meanwhile 14% of TAN + u was found in condensate and in acid trap. For T1R2, storage was 34%, loss is 43%, and in this case, loss is higher than storage.

For T2R1 and T2R2, 51% and 57% of input TAN + u was stored in dried urine and loss was 39% and 35%, respectively; for T3R1 and T3R2, storage was 98% and 100%, respectively, where also 16% and 17% of loss was found.

**New mass balance for TAN + u after considering calibration values**

A new mass balance for TAN + u was obtained (Table 6) after considering the influence of calibration values on photometric analysis of acid trap samples and dried urine samples. In case of acid traps, values from TAN + u calibration were deducted from respective TAN + u values measured for different treatments. For dried urine, average value from TAN + u calibration was deducted from measured TAN + u values of all dried urine samples. Output of TAN + u in different treatments were calculated according to new values for dried urine samples and acid trap samples and, eventually, percentages of stored and lost TAN + u were calculated to obtain the corrected mass balance.

**The final product and concentration factor**

The final product: the dried urine was a soil-like material; it was dark in color and smelt like a mixture of urine and lime and the smell was not the same as fresh or stored urine. The fertilizer contained a considerable amount of moisture since it went through consecutive dry and moist phases during the experiment. The pH of the fertilizer was measured and it was 12.

The amount of urine treated per gram of drying agent was calculated after the experiment was finished. Total amount of urine applied was divided by total amount of drying agent that gives amount of urine treated per gram of drying agent. A concentration factor was also calculated

### Table 4

<table>
<thead>
<tr>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average pH 6.1 (range: 5 to 7.5)</td>
</tr>
<tr>
<td>TAN + u 6.84 ± 0.02 g/L (weeks 1–3.5, 1st half of the experiment)</td>
</tr>
<tr>
<td>TAN + u 8.24 ± 0.09 g/L (weeks 3.5–7, 2nd half of the experiment)</td>
</tr>
</tbody>
</table>

### Table 5

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Input (TAN + u)</th>
<th>Storage dried urine</th>
<th>Loss</th>
<th>Total output (storage + loss)</th>
<th>Unaccounted TAN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fresh urine (g)</td>
<td>dried urine (g)</td>
<td>Condensate (g)</td>
<td>Acid trap (g)</td>
<td>input-output (g)</td>
</tr>
<tr>
<td>T1R1</td>
<td>63.51</td>
<td>40.90</td>
<td>0.17</td>
<td>8.97</td>
<td>50.03</td>
</tr>
<tr>
<td>T1R2</td>
<td>49.55</td>
<td>17.03</td>
<td>0.40</td>
<td>20.97</td>
<td>38.40</td>
</tr>
<tr>
<td>T2R1</td>
<td>36.46</td>
<td>18.65</td>
<td>0.18</td>
<td>14.15</td>
<td>32.98</td>
</tr>
<tr>
<td>T2R2</td>
<td>25.47</td>
<td>14.42</td>
<td>0.10</td>
<td>8.74</td>
<td>23.27</td>
</tr>
<tr>
<td>T3R1</td>
<td>6.22</td>
<td>6.09</td>
<td>0.01</td>
<td>1.01</td>
<td>7.11</td>
</tr>
<tr>
<td>T3R2</td>
<td>6.89</td>
<td>6.90</td>
<td>0.01</td>
<td>1.19</td>
<td>8.10</td>
</tr>
</tbody>
</table>

*T2R2 was replaced with new material after 3rd week.
that indicates the proportion of weight of urine treated and the final dry weight of the fertilizer.

Table 7 shows that T1R1 is the treatment which treated the largest amount of urine per gram of drying agent (9.4 mL) and that treatment represents the highest concentration factor (6.2) that means it was the most efficient treatment in terms of urine concentration. T2R1 had a higher concentration factor compared to T2R2 since T2R2 was replaced with new material after the third week. On the other hand, T3R1 and T3R2 have similar concentration factors that goes with their similar condition throughout the experiment.

DISCUSSION

Drying capacity of the system

It was evident from the water loss test that temperature and airflow both were important factors influencing the amount of water loss from the system. In accordance with the steam capacity of the air at different temperatures, the water lost per day was highest at 60°C temperature (T1 and T2) and it was lower at 35°C (T3) and lowest at room temperature (T4). When increasing the airflow at 60°C five times it resulted in 80% more water loss per day in T1 where the amount of daily water loss in T1 and T2 were 223 mL and 124 mL, respectively. According to Table 1, the rate of water loss for T1, T2, T3 and T4 were 6.20, 3.40, 0.64 and 0.20 L/m² per day, respectively. This means that for a person urinating 1.5 L per day it requires a drying bed corresponding to 0.24, 0.44, 2.34 and 7.5 m² for each of the treatment alternatives, T1–T4, respectively.

Urine application and TAN + u input into the system

Measured average values of pH and TAN + u in urine (Table 4) in this experiment were found to be compatible with the values found in literatures (Diem & Lentner 1970; Lentner et al. 1981). For treatment T1R1 and T1R2, the theoretical volume of urine application was expected to be 8.75 L but the actual volumes applied to those two treatments were 8.43 L and 6.71 L, respectively. The difference between actual and expected volume of urine application was not big for T1R1, but the difference is big for T1R2. This occurred because of an unexpected bad drying condition throughout the experiment.

A general observation about the experiment was that all treatments were drying very well during the first and the second weeks and at the end of the second week all treatments became slightly moist. Besides, different treatments became moist at different periods of the experiment and the degree of wetness was different for different treatments, some were less moist and some were more. Some amendments were done to recover the drying condition and

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Table 6 | New mass balance for TAN + u after correcting the influence of acid and drying agent

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Input (TAN + u)</th>
<th>Storage</th>
<th>Loss</th>
<th>Total output</th>
<th>Unaccounted TAN</th>
<th>Stored</th>
<th>Lost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fresh urine (g)</td>
<td>dried urine (g)</td>
<td>Condensate (g)</td>
<td>Acid trap (g)</td>
<td>(storage + loss) (g)</td>
<td>input-output (%)</td>
<td>(%)</td>
</tr>
<tr>
<td>T1R1</td>
<td>63.51</td>
<td>34.13</td>
<td>0.17</td>
<td>7.83</td>
<td>42.13</td>
<td>33</td>
<td>54</td>
</tr>
<tr>
<td>T1R2</td>
<td>49.55</td>
<td>8.33</td>
<td>0.40</td>
<td>19.82</td>
<td>28.54</td>
<td>42</td>
<td>17</td>
</tr>
<tr>
<td>T2R1</td>
<td>36.46</td>
<td>14.41</td>
<td>0.18</td>
<td>12.79</td>
<td>27.38</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>T2R2</td>
<td>25.47</td>
<td>10.16</td>
<td>0.10</td>
<td>7.88</td>
<td>18.14</td>
<td>29</td>
<td>40</td>
</tr>
<tr>
<td>T3R1</td>
<td>6.22</td>
<td>4.20</td>
<td>0.01</td>
<td>0.53</td>
<td>4.75</td>
<td>23</td>
<td>68</td>
</tr>
<tr>
<td>T3R2</td>
<td>6.89</td>
<td>5.11</td>
<td>0.01</td>
<td>0.70</td>
<td>5.82</td>
<td>16</td>
<td>74</td>
</tr>
</tbody>
</table>

*T2R2 was replaced with new material after 3rd week.

Table 7 | Concentration factor for different treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total amount of urine applied (ml)</th>
<th>Total amount of drying agent (g)</th>
<th>Urine treated per gram of drying agent (ml)</th>
<th>Final dry weight (kg)</th>
<th>Concentration factor (weight of urine treated, kg/final dry weight, kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1R1</td>
<td>8,430</td>
<td>900</td>
<td>9.4</td>
<td>1.35</td>
<td>6.2</td>
</tr>
<tr>
<td>T1R2</td>
<td>6,710</td>
<td>1,300</td>
<td>5.2</td>
<td>1.76</td>
<td>3.8</td>
</tr>
<tr>
<td>T2R1</td>
<td>4,900</td>
<td>650</td>
<td>7.5</td>
<td>0.93</td>
<td>5.3</td>
</tr>
<tr>
<td>T2R2</td>
<td>3,210</td>
<td>650</td>
<td>4.9</td>
<td>0.83</td>
<td>3.9</td>
</tr>
<tr>
<td>T3R1</td>
<td>840</td>
<td>240</td>
<td>3.5</td>
<td>0.28</td>
<td>3.0</td>
</tr>
<tr>
<td>T3R2</td>
<td>930</td>
<td>240</td>
<td>3.9</td>
<td>0.32</td>
<td>2.9</td>
</tr>
</tbody>
</table>
those were described in the materials and method section (Table 3). While searching for reasons behind such a moist condition, it was found that sometimes airflow was obstructed in the pipe because of water vapor condensed and remained in pipes, both in between moisture control box and drying box and drying box and acid trap, so air could not pass to the drying box. Throughout the experiment, it was observed that maintaining a good airflow in the system was crucial to keep a good drying condition. Therefore, the actual volume of air passing over the drying bed was less than compared to what was expected and thereby slowing down the drying process.

**Nitrogen distribution in the drying system**

Treatment 1 replicates behaved very differently from each other. In case of T₁R₁, the acid trap captured 7.83 g (12.53%) of TAN⁺u in total (Table 6) where the total TAN⁺u input was 63.51 g (Table 6) and for T₁R₂ the acid trap captured 19.82 g (40%) (Table 6) of TAN⁺u, where the total input was 49.55 g (Table 6). It was evident from the study that the loss of TAN⁺u was significantly higher in T₁R₂. In the case of Treatment 2, replicate T₂R₁ had higher (5%) losses compared to T₂R₂ where, in the case of Treatment 3, ammonia loss was similar for both replicates.

As airflow was obstructed due to condensing water in pipes, the system could not run at its full potential, that means evaporation was less. That condition made the drying agent saturated with urine and, consequently, urine flooded on top of the drying agent since urine was applied regularly (except for the second half of the experiment when urine application was reduced by some percent for a period and even sometimes urine was not applied at all to some treatments). This shows the importance of good ventilation of the system to avoid pooling of urine, that later on may be hard to dry as the urine contains some peptides (Lentner et al. 1983) forming a lipid surface layer that may block the steam evaporation.

Data from TAN⁺u concentration in dried urine (Table 6) showed that TAN⁺u was actually stored in drying agent (in the form of urea), so our hypothesis was right. TAN⁺u concentration was higher in some treatments compared to others, however, it was evident that the idea behind using the mixture of ash and lime as drying agent and thereby inactivating enzymatic activity of urease by maintaining high pH was correct and proved by the experiment.

When calibrating the ammonia analysis with background TAN value of the acid in the acid trap and putting it into the mass balance (Table 6), T₁R₁ showed higher TAN⁺u collection capacity (54%) compared to the replicates of the same treatment T₁R₂ (17%). This difference between replicates can be explained by the drying condition that occurred throughout the experiment, as T₁R₁ was drying well throughout the experiment, except for the sixth and the seventh week, while T₁R₂ was not drying well most of the time. A substantial amount of ammonia was lost from T₁R₂ that was captured by the acid trap (19.82 g). This indicates the importance of constantly holding the urine level below the drying bed during the drying process.

If we consider all replicates from all the treatments, both replicates in Treatment 3, T₃R₁ and T₃R₂ showed higher TAN⁺u retaining capacity and smallest losses compared to all the treatments set up in 60 °C drying temperature. This indicates the importance of keeping the temperature of the drying system at a moderate level as the chemical degradation of the urea increases too much for keeping the nitrogen within the drying system (Randall et al. 2016).

As measured in the experiment, the highest TAN⁺u retention in this experiment was 54% at 60 °C, and at 35 °C it was 74% (Table 6). Kabdasli et al. (2006) reported a TAN⁺u recovery of 95% through struvite precipitation conducted on enzyme hydrolyzed samples at 20 ± 1 °C; it needs to be noted that the precipitation of 1 kg TAN requires an additional 9.5 kg to 7.1 kg H₃PO₄, 4.0 kg MgO and 1.2 kg NaOH (Siegrist 1996; Munch & Barr 2001). In another experiment, 86% recovery by using clinoptilolite was reported by Beler-Baykal et al. (2011). TAN⁺u retention rate in this urine drying experiment is lower than those more resource-demanding concentration methods. In another experiment, Antonini et al. (2002) reported 70% recovery of input nitrogen by solar thermal evaporation, which is close to the value that we got for the treatment in 35 °C.

In our experiment, urine drying at 35 °C seems promising as 74% of inflow nitrogen could be recovered and this temperature is easily achievable during summer in a tropical country like Bangladesh. In the final product achieved in these trials, the nitrogen content in the product was up to 3%; this is more dilute compared to available fertilisers on the market, but it is considerably more concentrated in comparison to the fresh urine that contains 0.6–0.8% nitrogen.
Additionally, the product is easy to store in a bag until use which simplifies the logistics for the produced fertilizer.

There is no extra energy requirement for evaporation and ash and lime are locally available; this method is very suitable for rural areas in Bangladesh where biomass fuel is frequently used for cooking, thereby, ash can be easily collected from households. Our study proposes that in case of real application, a drying bed can be set up under the toilet and drying agents can absorb urine upon excretion by family members, so there is no need to transfer urine in a different tank for drying. However, large-scale verification is required.

An estimation for practical implementation

This urine drying experiment was done in laboratory scale. For full-scale implementation, we can consider a family of four excretes approximately 6 L of urine per day (1.5 L/person, day). We assume that they live in a tropical country where, in summer, the temperature should reach 35 °C in the drying bed, relative humidity in ambient air is approximately 70% and expected airflow over the drying bed 1 L/min.

According to the calculation in our laboratory experiment, average water loss in above stated situation (35 °C temperature, 70% relative humidity and 1 L/min airflow) is 0.64 L/m², day. According to our calculation, the family will need a drying bed that should have an area of 9.4 m² to dry 6 L of urine that they excrete every day. This is a large area requirement for the treatment and further optimization of the drying system is required.

In this case of a family of four, 30 kg of drying agent (15 kg ash and 15 kg of lime) is required for the drying bed, five times of daily urine excretion. As done in the experiment, once the drying agent is applied in the drying chamber, it can be used for seven weeks or longer and, by this time, it will retain a good amount of TAN + u; after seven weeks or longer, it can be removed and used as fertilizer and the drying chamber needs to be refilled with fresh drying agent. Further research is needed to determine the optimum time after which the drying agent should be replaced.

CONCLUSIONS

The final dried urine fertilizer was partially dried, not completely dried as expected in the experiment due to urine flooding. The experiment showed that it is possible to retain nitrogen from the urine in the form of urea by maintaining a high pH (>10). The concentration of nitrogen in input urine, airflow and drying condition regulates the concentration of nitrogen in the final product. The drying technique needs to be optimized by further research.

Approximate mass balances for nitrogen were obtained for the investigated systems. Obstruction in airflow to the drying chamber and the consequent bad drying condition results in urine flooding over drying agent; urea might be hydrolyzed and cause the loss of input nitrogen. The experiment showed that nitrogen retention rate was higher in treatment at low temperature (35 °C), compared to treatment at high temperature (60 °C); the highest nitrogen retention was 54% of the inflow at 60 °C and it was 74% at 35 °C as the chemical half-life of the urea shortens significantly between the temperatures 35 and 60 °C.

Urine drying in ash or ash/lime beds shows high potential for production of a dry, urine based fertilizer. However, further studies are needed to optimize the systems design and function.

REFERENCES


