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 agent 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 °, 35 °, 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

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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^+, NH_4^+, Ca^{2+}) and anions (Cl^-, SO_4^{2-}, PO_4^{2-} and HCO_3^-), 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 (PO_4-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

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fertilizer (Kirchmann & Pettersson 1995; Jönsson 1997; Johansson *et al*. 2001; Vinnerås 2002).

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).

$$NH_2(CO)NH_2 + 2H_2O \rightarrow NH_3 + NH_4^+ + HCO_3^- \quad (1)$$

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 by inactivation of enzymatic activity of urease by high pH (pH > 10) of 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 dm^2 and 5 L/min, 3.61 dm^2) 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 (NH_3) 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 25–35 years in sterile plastics bottles and applied in the drying box daily as undiluted and fresh. Urine from different donors

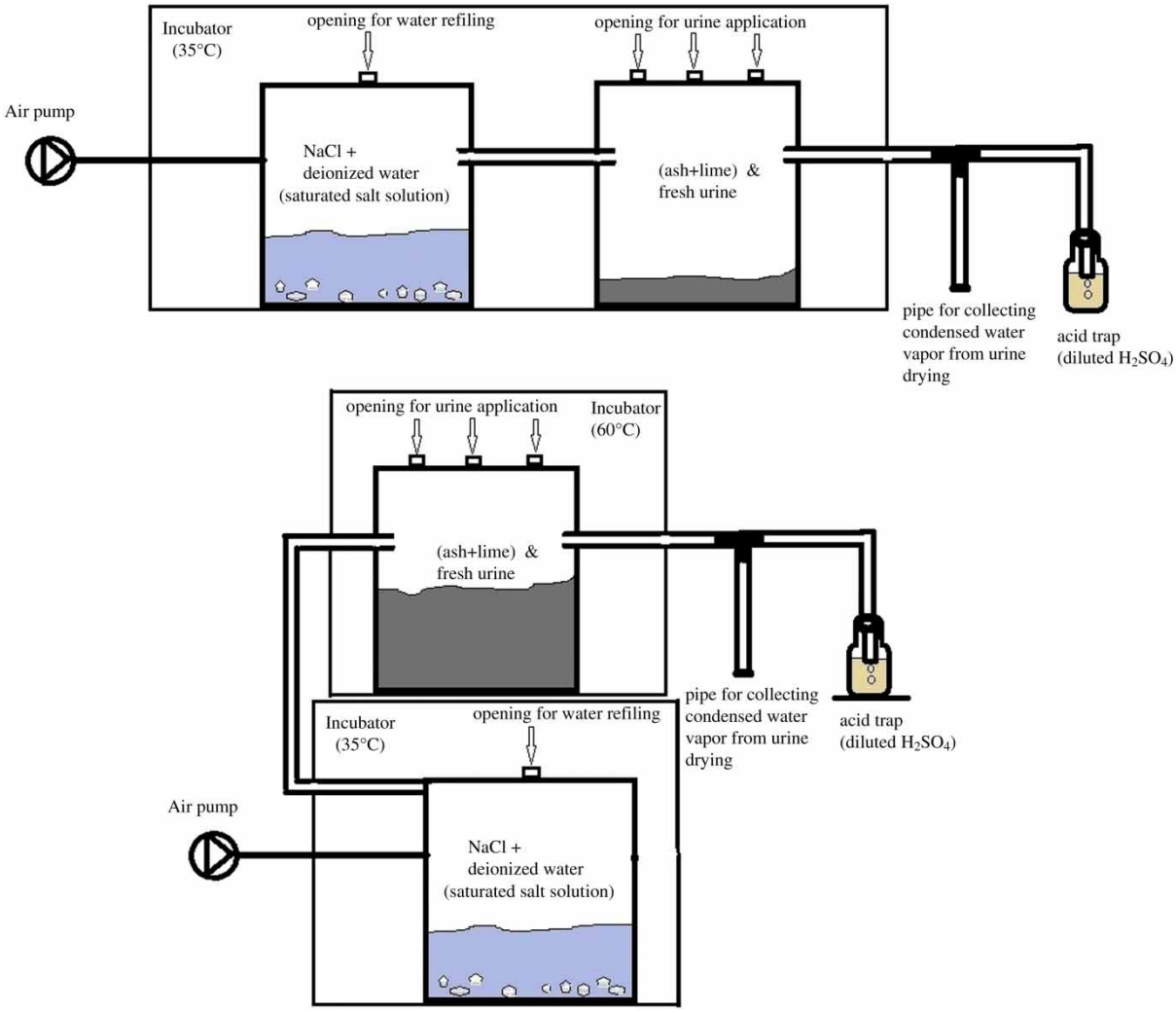

Figure 1 | A diagram showing simplified system design for urine drying at 35 and 60 °C.

Table 1 | Estimated daily urine loading rate in different treatments

Treatment	Temperature of moisture control box (°C)	Temperature of drying box (°C)	Airflow (L/min)	Rate of water loss (L/m², day)	Total water loss from the drying box (ml/day)	80% of average daily water loss (ml)	Total urine load in a week (ml)	Urine load (when applied 5 days/ week) (ml/day)
T-1	35	60	5	6.20	223	179	1,250	250
T-2	35	60	1	3.40	124	99	695	140
T-3	35	35	1	0.64	23	19	130	26
T-4	20	20	1	0.20	7	*	*	*

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

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, T_2R_2 (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 T_2R_2 did not recover; so, the box was cleaned and refilled with ash and lime that means T_2R_2 got a new start and, afterwards, urine was applied according to the capacity of system.

On the fifth week, T_1R_2 and both replicates of treatment 3 (T_3R_1 and T_3R_2) 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 T_3R_1 and T_3R_2, 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 T_1R_2, 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 T_1R_2.

On the seventh week, all the six treatments became moist, especially T_1R_2 and T_2R_2, 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 T_1R_2, T_2R_1 and T_2R_2, so 100 g, 150 g and 150 g more drying agent was added to T_1R_2, T_2R_1 and T_2R_2, 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 T_3R_1 and T_3R_2. 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 2 | System specification for urine drying experiment

Treatment	Temperature for moisture control box (°C)	Temperature for urine drying box (°C)	Airflow (L/min)	Urine application (5 days/week) (mL)	Amount of drying agent (ash + lime) (g)	Estimated exchange of air volume (times/h)
T_1	35	60	5	250	900	200
T_2	35	60	1	140	500	30
T_3	35	35	1	26	95	20

Table 3 | Summary of additional changes during the experiment

Treatment repetition	Changes occurred during the experiment									
	Day-14	Day-15	Day-22 to 28	Day-29	Day-31	Day-33	Days-38 to 40	Day-43	Day-45	Day-48	Day-39
T_1R_1			The experiment was paused that means the system	Became moist	300 g drying agent was added	Urine loading was reduced by 50%	No urine applied	All the treatments became moist and urine loading was reduced by 30% for all treatments	100 g drying agent was added	150 g drying agent was added	
T_1R_2											
T_2R_1											
T_2R_2	Be-came moist	No urine applied	was running but no urine was added to any treatment	Replaced with new drying agents							
T_3R_1		Became moist			95 g drying agent was added						50 g drying agent was added
T_3R_2		Became moist									

application, and, for dried urine, pH was measured every second week during the experiment.

Ammonium test kit 1.00683.0001 (Merck, Germany) was used to prepare samples for measuring ammonium nitrogen (NH_4-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-NH_3 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 NH_4-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 ($pH \geq 13$) 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 ($pH \leq 2$) 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

Table 4 | Measured characteristics of collected urine

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

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 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 T_1R_1, 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 T_1R_2, storage was 34%, loss is 43%, and in this case, loss is higher than storage. For T_2R_1 and T_2R_2, 51% and 57% of input TAN + u was stored in dried urine and loss was 39% and 35%, respectively; for T_3R_1 and T_3R_2, 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 5 | Mass balance of TAN + U in the urine drying system

		Output (TAN + u)							
			Loss			Unaccounted TAN			
Treatment	Input (TAN + u) fresh urine (g)	Storage dried urine (g)	Condensate (g)	Acid trap (g)	Total output (storage + loss) (g)	Input-output (g)	Input-output (%)	Stored (%)	Lost (%)
T_1R_1	63.51	40.90	0.17	8.97	50.03	13.48	21.22	64	14
T_1R_2	49.55	17.03	0.40	20.97	38.40	11.15	22.51	34	43
T_2R_1	36.46	18.65	0.18	14.15	32.98	3.47	9.53	51	39
$T_2R_2^a$	25.47	14.42	0.10	8.74	23.27	2.20	8.65	57	35
T_3R_1	6.22	6.09	0.01	1.01	7.11	−0.89	−14.30	98	16
T_3R_2	6.89	6.90	0.01	1.19	8.10	−1.21	−17.50	100	17

[a]T_2R_2 was replaced with new material after 3rd week.

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

Treatment	Input (TAN + u) fresh urine (g)	Output (TAN + u)					
		Storage dried urine (g)	Loss		Total output (storage + loss) (g)	Unaccounted TAN input-output (%)	Stored (%)	Lost (%)
			Condensate (g)	Acid trap (g)				
T_1R_1	63.51	34.13	0.17	7.83	42.13	33	54	13
T_1R_2	49.55	8.33	0.40	19.82	28.54	42	17	41
T_2R_1	36.46	14.41	0.18	12.79	27.38	24	40	36
$T_2R_2^a$	25.47	10.16	0.10	7.88	18.14	29	40	31
T_3R_1	6.22	4.20	0.01	0.53	4.75	23	68	9
T_3R_2	6.89	5.11	0.01	0.70	5.82	16	74	10

[a]T_2R_2 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 T_1R_1 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. T_2R_1 had a higher concentration factor compared to T_2R_2 since T_2R_2 was replaced with new material after the third week. On the other hand, T_3R_1 and T_3R_2 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/m^2 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 m^2 for each of the treatment alternatives, T1–T4, respectively.

Table 7 | Concentration factor for different treatments

Treatment	Total amount of urine applied (ml)	Total amount of drying agent (g)	Urine treated per gram of drying agent (ml)	Final dry weight (kg)	Concentration factor (weight of urine treated, kg/final dry weight, kg)
T_1R_1	8,430	900	9.4	1.35	6.2
T_1R_2	6,710	1,300	5.2	1.76	3.8
T_2R_1	4,900	650	7.5	0.93	5.3
T_2R_2	3,210	650	4.9	0.83	3.9
T_3R_1	840	240	3.5	0.28	3.0
T_3R_2	930	240	3.9	0.32	2.9

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 T_1R_1 and T_1R_2, 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 T_1R_1, but the difference is big for T_1R_2. 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

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 T_1R_1, the acid trap captured 7.83 g (12.33%) of TAN + u in total (Table 6) where the total TAN + u input was 63.51 g (Table 6) and for T_1R_2 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 T_1R_2. In the case of Treatment 2, replicate T_2R_1 had higher (5%) losses compared to T_2R_2 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.* 1981) 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), T_1R_1 showed higher TAN + u collection capacity (54%) compared to the replicate of the same treatment T_1R_2 (17%). This difference between replicates can be explained by the drying condition that occurred throughout the experiment, as T_1R_1 was drying well throughout the experiment, except for the sixth and the seventh week, while T_1R_2 was not drying well most of the time. A substantial amount of ammonia was lost from T_1R_2 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, T_3R_1 and T_3R_2 showed higher TAN + u storing efficiency (68% and 74%, respectively, Table 6) among all replicates of other treatments, although those became moist several times throughout the experiment. It can be said that those two treatments, T_3R_1 and T_3R_2, which were provided with 35 °C drying temperature and 1 L/min airflow rate, had the best 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 H_3PO_4, 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.* (2012) 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/m^2, day. According to our calculation, the family will need a drying bed that should have an area of 9.4 m^2 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.

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