



# Evaluating ion exchange for nitrogen recovery from source-separated urine in Nairobi, Kenya

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## ARTICLE INFO

### Keywords:

Adsorption  
Fertilizer  
Nutrient recovery  
Nitrogen  
Sanitation  
Urine

## ABSTRACT

Rapid population growth in developing world urban centers outpaces provision of essential services such as excreta collection and treatment. Separate collection of urine and feces and decentralized treatment can potentially serve more households at lower energy and cost than conventional waterborne sewers and treatment plants. We conducted a technical validation and preliminary economic modeling to evaluate ion exchange columns, one technical option for recovering nitrogen from urine in Nairobi, Kenya. This technology could be combined with phosphorus recovery and a disinfection step to allow local discharge of the treated urine. Performance, as measured by adsorption density (4.02–4.21 mmol N/g resin) and regeneration efficiency (> 90%) of the adsorbent, was consistent over ten adsorption-regeneration cycles and with columns ten times larger than lab-scale (65 L/d vs. 6.5 L/d). Effluent absorbance and electrical conductivity were identified as indicators of urine and ammonia breakthrough, respectively; both parameters are lower cost and easier to measure on-line than ammonium concentrations. Urine storage containers should be closed to avoid changes in urine composition, including loss of ammonia (and thus potential revenue). Treatment of urine by ion exchange is 40% less expensive than disposal without treatment and urine-derived ammonium sulfate was produced well below market costs of commercial fertilizers.

## 1. Introduction

The majority of people in the developing world live with untreated feces and urine in their communities (Baum et al., 2013). Urban centers in developing countries are expected to experience a disproportionately large share of population growth that is likely to continue to outpace provision of services such as water supply and sanitation (Jacobsen et al., 2012). The proportion of urban residents who live in informal settlements has remained constant at 72% in sub-Saharan Africa (Jacobsen et al., 2012); residents of these high-density, unplanned settlements are particularly vulnerable to water and excreta-related diseases. Excreta collection and treatment can improve human health and environmental quality by reducing the transmission of these diseases and avoiding nutrient discharges that irreversibly alter aquatic environments (Nelson and Murray, 2008). Globally, estimated costs to society from inadequate sanitation are \$260 billion per year due to associated health care, premature deaths, and productivity losses

(Hutton, 2012).

With only 10% of sub-Saharan Africans connected to sewer systems and less than 50% expected by 2050 (Larsen et al., 2016; Morella et al., 2008), universal coverage with conventional sewers and centralized wastewater treatment is an unrealistic proximate goal. Decentralized collection and treatment may be less costly and require less energy while providing opportunities for revenue generation through resource recovery from waste (Nansubuga et al., 2016). An approach in which sanitation providers aim to improve public health, environmental quality, and profit may accelerate and sustain sanitation access. Valuable nutrients (e.g., nitrogen, phosphorus, potassium) can be extracted from human excreta. They are especially valuable near Nairobi, Kenya, where agricultural soil nutrient levels are low due to over-farming, population density, and poor water quality (Stoorvogel et al., 1993). These constraints create high demand for manufactured fertilizers, which the Kenyan government has subsidized since 2009 (Kenya Fertilizer Assessment, 2012; Shimeles et al., 2015). Despite these

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subsidies, fertilizers are often underutilized by the average Kenyan farmer because of high import and transport costs (Van den Bosch et al., 1998), limited fertilizer supply (Ochola and Fengying, 2015), distance to fertilizer distribution channels (Jayne et al., 2003), and cumulative soil degradation (Marenya and Barrett, 2009).

Separate collection of urine facilitates nutrient recovery and fertilizer production because urine contains the majority of excreted macronutrients but is typically only 1% of wastewater volume (Friedler et al., 2013). Phosphorus is an increasingly scarce fertilizer component that can be recovered from urine through precipitation of struvite (magnesium ammonium phosphate,  $\text{MgNH}_4\text{PO}_4$ ) (Etter et al., 2011). Nitrogen can be recovered from urine using several techniques, including urea stabilization (Randall et al., 2016), electrochemical stripping (Tarpeh et al., 2018a), nitrification-distillation (Udert and Wächter, 2012), and ion exchange (Tarpeh et al., 2017). During urine storage, nitrogen in the form of urea is hydrolyzed to ammonium ( $\text{NH}_4^+$ ) (Udert et al., 2003), which is retained on the ion exchange adsorbent's negatively charged sites. Once loaded with  $\text{NH}_4^+$ , cation exchange adsorbents could be applied as solid fertilizers (if naturally derived) or regenerated to produce liquid fertilizer and reusable adsorbent. In this study, ammonium sulfate fertilizer was produced; other options include ammonium nitrate and ammonium chloride, which can be generated by varying the compound used to elute the adsorption columns. Ion exchange can be applied at various scales, from individual toilets or households to centralized urine collection depots. A previous comparison of adsorbents showed that Dowex Mac 3, a cation exchange resin, has high adsorption density and regeneration efficiency that make it well-suited for ammonium recovery from urine (Tarpeh et al., 2017).

The goal of this investigation was to determine if producing ammonium sulfate from urine via ion exchange is a viable business model for container-based, source-separated excreta collection and treatment services. Our objectives were to: (i) demonstrate proof-of-concept and measurement methods in the field, (ii) evaluate the implications of urine composition, process indicators, and scalability for urine collection and treatment, and (iii) compare the cost of nitrogen recovery via ion exchange to current excreta management and fertilizer production practices in the study region.

## 2. Materials and methods

### 2.1. Description of field site

The field site for the research was Nairobi, Kenya, where the social enterprise Sanergy operates more than 1000 dry, source-separating, toilets in several informal settlements, as of August 2017. The toilets, branded as Fresh Life Toilets (FLT), are primarily owned and operated by local entrepreneurs via a franchise business model. These toilets are used over 50,000 times a day and revenues from user payments go to franchisees (Auerbach, 2016). While most toilets are open to the public, some are located at schools and multi-family dwellings. Sanergy charges toilet operators for daily collection of the waste and generates revenue from the sale of excreta-derived products (O'Keefe et al., 2015). The user interface is a squat plate with separate holes for urine and feces; urine and feces containers (25 L urine, 30 L feces) are collected and replaced daily by Sanergy employees. The containers are taken to a central transfer station where urine and feces are processed separately. The fecal waste is transported 30 km by truck to a processing facility where it is converted into several value-added products: a soil additive branded as *Evergrow* through a co-composting process, biogas through an anaerobic digestion process, and a black soldier fly animal feed. Urine from the toilets is stored in 1000-L tanks at the transfer station, which are emptied every 2–3 days and the urine is trucked 20 km to a wastewater treatment facility.

### 2.2. Synthetic and real urine composition

Synthetic stored urine was used to validate column operation because its composition was known (Table S1) and constant between locations (Table S2 for preparation method) (Tarpeh et al., 2017; Udert et al., 2003). Real urine from different locations (Nairobi, Kenya; Dubendorf, Switzerland; Berkeley, California, USA) and collection systems was compared to determine the effects of varying urine composition and collection methods on urine treatment. In Berkeley, urine from participants was collected individually from approximately 20 volunteers (male and female), homogenized in sterile containers, and stored in closed containers (Committee for Protection of Human Subjects, Protocol 2016-10-9284). In Nairobi, source-separated urine from eight urine-diverting dry toilets and centralized collection tanks was analyzed. In Dubendorf, multiple waterless urinals and urine-diverting flush toilets in a building drained to a single collection tank, from which samples were drawn.

Urea hydrolysis to total ammonia ( $\text{NH}_3/\text{NH}_4^+$ ) proceeded spontaneously in collection systems (Dubendorf (Udert et al., 2003) and Nairobi (this study)); 10 mg/L jack bean urease (Sigma Aldrich, St Louis, MO) was added to Berkeley urine to accelerate the process (Mobley et al., 1995). Berkeley urine was analyzed and used in ion exchange after 5 days of storage, and analyzed again after one month of storage. Magnesium and calcium concentrations were measured as negligible in stored urine via ion chromatography, presumably due to spontaneous struvite and hydroxyapatite ( $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ ) precipitation (Udert et al., 2003).

### 2.3. Column experiments

Columns were constructed and operated according to our previous studies that achieved high ammonium adsorption density and recovery efficiency (Tarpeh et al., 2018b, 2017). Briefly, upflow continuous adsorption experiments were performed in plastic columns (2.54-cm diameter, 16-cm length, PVC plastic) packed with Dowex Mac 3 ( $63.5 \pm 1.5$  g), a cation exchange resin. After pretreatment with 10 mL of 1 M borate buffer per gram of resin, either synthetic or real urine (from closed tanks at transfer station) was pumped at 4.5 mL/min (6.5 L/d, 0.0148 cm/s) through each column for 6 h, and 2-mL effluent samples were collected every 20 min and analyzed for ammonium. Adsorption densities were calculated by numerically integrating breakthrough curves to determine the total mass of ammonium retained by the columns, and dividing by resin mass (Equations S1–S2). The hydraulic performance of columns was verified in experiments with synthetic urine and measurement of chloride as a conservative tracer.

Regeneration experiments were performed using 0.1 M (0.65%)  $\text{H}_2\text{SO}_4$ , pumped at 22.5 mL/min for 2 h, to elute the ammonium from the columns after they were saturated (Tarpeh et al., 2018b, 2017). The total volume of eluent was larger than the volume of urine treated; while this approach is impractical for implementation, it was useful for our goal of identifying the maximum amount of nitrogen that could be recovered. Strategies for generating more concentrated final product, including reusing product as eluent and applying reverse osmosis, are currently being explored. Effluent was combined over the course of the experiment and ammonium concentration was measured in the composite sample. Regeneration efficiencies were calculated by dividing the mass of ammonium eluted (product of composite concentration and effluent volume) by the mass of ammonium adsorbed in the previous cycle (Equation S3).

Ten adsorption-regeneration cycles were conducted in triplicate to evaluate regeneration lifetimes with real urine collected from FLT. For each cycle, adsorption densities and regeneration efficiencies were calculated using the methods above.

Performance at larger scale (scaling factor of 10) was investigated with larger columns (5.08-cm diameter, 40-cm length,  $601 \pm 25.2$  g resin) and flow rates (65 L/d), with the same laboratory set-up and

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