

1  
2  
3  
4  
5 Flexible Electrochemical Stripping for Wastewater Ammonia Recovery  
6 with Real-Time Product Tunability  
7

8 Anna Kogler<sup>1</sup>, Meili Gong<sup>2</sup>, William A. Tarpeh<sup>1,2\*</sup>  
9

10 <sup>1</sup> Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, 94305, USA

11 <sup>2</sup> Department of Chemical Engineering, Stanford University, Stanford, CA, 94305, USA

12 \*Corresponding author, Email: [wtarpeh@stanford.edu](mailto:wtarpeh@stanford.edu). Address: 443 Via Ortega, Room 387, Stanford  
13 CA, 94305. Telephone: 650-497-1324  
14  
15

16 Abstract: 179 words

17 Word Count (without figures/tables): 2,385 words

18 Figures: 3 (200 word equivalents each = 600 word equivalents)

19 Word Count: 2,985 words  
20  
21

## Abstract

Nitrogen in wastewater can be recovered to prevent negative environmental, human health, and economic impacts and to enable distributed chemical manufacturing. We developed novel flexible electrochemical stripping (FECS) for tunable recovery of ammonia/ammonium (total ammonia nitrogen, TAN) from urine as  $(\text{NH}_4)_2\text{SO}_4$  and aqueous  $\text{NH}_3$ . Batch and continuous experiments demonstrated that product speciation could be readily controlled by modifying electrochemical cell operation frequency, duration, and applied current without affecting TAN removal. During continuous experiments, FECS recovered  $\text{NH}_3$  solutions with concentrations similar to ready-to-use cleaners (1% and 2%  $\text{NH}_3$  (w/w) or 8.22 and 16.4 g/L TAN) and cleaner concentrates (5%  $\text{NH}_3$  (w/w) or 41.1 g/L TAN), as well as  $(\text{NH}_4)_2\text{SO}_4$  solutions between 5 and 18.4 g/L TAN, approaching commercial fertilizer concentrations (28.4 g/L TAN). Beyond modifying applied current, future process engineering and operating condition optimization should reduce energy consumption, increase recovery efficiency, and enhance economic viability of FECS. Our findings will enable development and deployment of electrochemical nitrogen recovery in contexts with varying needs for ammonia-based products, paving the way for circular economies that integrate distributed chemical manufacturing with sanitation systems.

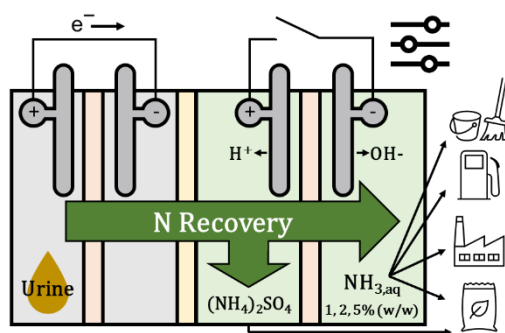
## Keywords

circular economy, electrodialysis, membrane distillation, nitrogen, product diversification, resource recovery, urine

## Statement of Environmental Relevance and Significance

Tunable electrochemical nitrogen recovery enables distributed manufacturing of ammonia and derived products, reducing environmental impacts of wastewater treatment and chemical industries.

## TOC Art



## 1 Introduction

Innovation in wastewater treatment and resource recovery can yield urgently needed solutions that manage humanity's transgression of multiple planetary boundaries (e.g., climate change, nitrogen/phosphorus biochemical flows).<sup>1,2</sup> Traditional wastewater nitrogen removal approaches are energy- and chemical-intensive. Transitioning to wastewater nitrogen recovery can prevent the negative environmental, human health, and economic impacts of nitrogen discharges,<sup>3-5</sup> while reducing greenhouse gas emissions from wastewater treatment<sup>6</sup> and Haber-Bosch ammonia production<sup>7</sup> and rebalancing the nitrogen cycle. At the same time, expanding sanitation access requires radical innovations in wastewater management, such as distributed treatment with resource recovery.<sup>8-10</sup> Rapid and transformative innovation enabling resource-efficient wastewater management and circular economies is crucial to preventing irreversible, catastrophic changes around the globe.<sup>11-13</sup>

Expanding product portfolios and increasing process tunability can accelerate scale-up and deployment of circular wastewater technologies. Most nitrogen recovery processes generate fertilizer products.<sup>14</sup> Two main challenges associated with recovered fertilizers are their low economic value and the breadth of formulations required to meet variable, regional, and crop-specific needs.<sup>9,15-17</sup> Co-generating multiple products can improve the economic viability of recovery technologies.<sup>18-20</sup> Some nitrogen recovery processes co-generate fertilizers and non-

65 nutrient products, such as fuel (e.g.,  $\text{H}_2$ ,<sup>21–24</sup>  $\text{CH}_4$ <sup>25,26</sup>), electricity,<sup>21,25,27,28</sup> caustic solutions,<sup>25</sup>  
66 acids,<sup>23</sup>  $\text{H}_2\text{O}_2$ ,<sup>18,25</sup> organics,<sup>25,26</sup> and clean water.<sup>29,30</sup> Multi-process systems have also been  
67 demonstrated to generate multiple separate fertilizer products (e.g., struvite,  $(\text{NH}_4)_2\text{SO}_4$ , potash).<sup>31</sup>  
68 However, recovering non-fertilizer nitrogen products (e.g., microbial protein for use as animal  
69 feed<sup>22</sup>) and controlling generation of multiple nitrogen products in a single reactor remain under-  
70 explored. These advances could facilitate tailoring fertilizer formulations to soil or crop  
71 characteristics,<sup>32</sup> create more opportunities for nitrogen recovery (e.g., when fertilizer demand is  
72 low), and enable recovery of higher-value products. For example, a process that can switch  
73 between generating  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_3$  could have advantages for economic viability and  
74 equitable resource access. While  $(\text{NH}_4)_2\text{SO}_4$  is primarily used as a fertilizer,<sup>33</sup>  $\text{NH}_3$  is not only a  
75 fertilizer<sup>34</sup> but also a disinfectant,<sup>35–38</sup> precursor in chemical synthesis (e.g., plastics),<sup>34</sup> and  
76 fuel.<sup>39,40</sup> While the price of  $\text{NH}_3$  is similar to or lower than that of  $(\text{NH}_4)_2\text{SO}_4$ , products made from  
77  $\text{NH}_3$  (e.g., acrylonitrile, hexamethylenediamine, caprolactam) are significantly higher-value  
78 (Figure S1-1, Table S1-1). Real-time tunability of product identity and composition can enable  
79 distributed applications by responding to changes in product users' needs.<sup>20,41</sup> Electrochemical  
80 processes, which are modular and easily scalable, automatable, low in chemical inputs, and well-  
81 suited for decentralized wastewater treatment and chemical production,<sup>16,42–44</sup> can facilitate tunable  
82 multi-product recovery that meets specific chemical, public health, and environmental needs.<sup>16</sup>

83 In this study, we demonstrated tunable recovery of wastewater total ammonia nitrogen (TAN, sum  
84 of  $\text{NH}_3$  and  $\text{NH}_4^+$ ) as two products –  $(\text{NH}_4)_2\text{SO}_4$  and aqueous ammonia ( $\text{NH}_{3(\text{aq})}$ ) – in a single  
85 flexible electrochemical stripping (FECS) reactor. FECS builds on previously reported  
86 electrochemical stripping (ECS, which recovers  $(\text{NH}_4)_2\text{SO}_4$ )<sup>45–47</sup> to broaden the TAN product  
87 portfolio without dramatically increasing reactor footprint. The specific objectives of this study

were to: (1) develop a novel reactor architecture for producing two separate ammonia-based products in a single reactor; (2) investigate electrochemical operating parameters as a mechanism for controlling product distribution; and (3) demonstrate continuous urine treatment for tunable generation of multiple commercially relevant aqueous ammonia product solutions. In the four-chambered FECS reactor consisting of two electrochemical cells, the operating frequency and current density of the second electrochemical cell controlled product distribution between  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_{3(\text{aq})}$ . Stable, continuous FECS operation treating urine for 16 days generated 1% and 2% (w/w)  $\text{NH}_3$  solutions (8.22 and 16.4 g/L TAN) as ready-to-use cleaners and almost 5% (w/w)  $\text{NH}_3$  solution (41.1 g/L TAN) as a cleaner concentrate, in addition to up to 18.4 g/L TAN  $(\text{NH}_4)_2\text{SO}_4$  fertilizer. Therefore, FECS achieved product diversification beyond fertilizer by recovering two ammonia-based products and enabled tuning product speciation to meet context-specific needs. With these advances, FECS can facilitate distributed sanitation and manufacturing of  $\text{NH}_{3(\text{aq})}$  and chemicals derived from it, reducing the environmental impacts of both industries, fostering more equitable access to resources,<sup>48,49</sup> and promoting waste valorization as a strategy to keep human development within planetary limits.<sup>50</sup>

## 2 Materials and Methods

### 2.1 Urine Collection

Urine was collected from July 3, 2021 to February 9, 2022 at Stanford University's Shriram Center with approximately equal volumetric contributions from adult male and female donors (Internal Review Board Protocol 60601). Urine was stored in a closed container at room temperature (25°C) and allowed to hydrolyze for at least 12 months. Hydrolyzed urine contained below 0.35 mM urea-N compared to  $306 \pm 13$  mM TAN for batch experiments (Section 2.2) and  $353 \pm 20$  mM TAN for continuous experiments (Section 2.3), indicating complete hydrolysis.

## 2.2 Controlling Product Speciation with Electrochemical Operation

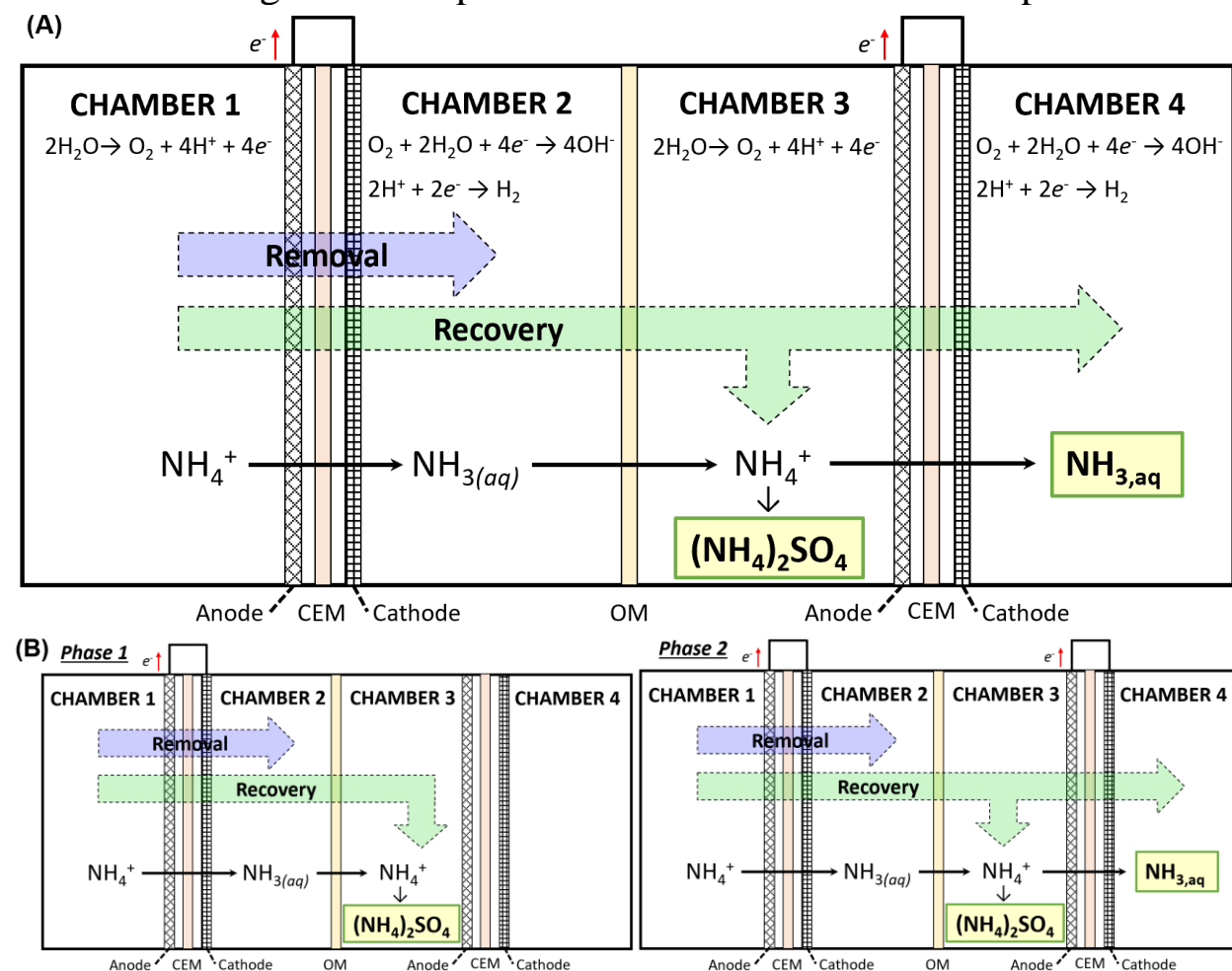


Figure 1. Flexible electrochemical stripping (FECS) process schematic with (A) concurrent electrochemical operation and (B) staggered electrochemical operation. Schematics illustrating flow configuration in batch and continuous experiments are shown in Figure S2-1.

FECS experiments were performed in a four-chambered reactor (Figure 1, Figure S2-1, Table S2-1, Section S2.1). 12-hour batch experiments treating urine (Table S2-2) were conducted in two modes – concurrent (Figure 1A) and staggered (Figure 1B). Staggered experiments were conducted at three currents: 0.64 A (i.e., current density of 100 A/m<sup>2</sup>), 2 A (i.e., 312.5 A/m<sup>2</sup>), and 4 A (i.e., 625 A/m<sup>2</sup>). Experimental details are described in Section S2.2 and analytical procedures

in Section S2.4. Process performance was evaluated by removal and recovery efficiency and energy consumption for removal and recovery (Table S2-4, Equations S5-2 to S5-9).

## 2.3 Continuous Operation for Tunable Product Generation

A continuous FECS experiment treating urine (Table S2-3) in staggered mode was conducted for 16 days as described in Section S2.3 (Figure S2-1B through Figure S2-3). We evaluated the process based on removal and recovery efficiency and energy consumption for removal and recovery (Table S2-4, Equations S5-10 to S5-23).

## 3 Results and Discussion

### 3.1 Controlling Product Speciation with Electrochemical Operation

FECS recovered both  $\text{NH}_{3(\text{aq})}$  and  $(\text{NH}_4)_2\text{SO}_4$  from urine containing  $4.29 \pm 0.19$  g/L TAN during batch experiments. Modifying operation of the second electrochemical cell enabled tuning product speciation (Figure 2). TAN removal and total TAN recovery were similar for concurrent and staggered operation at 0.64 A ( $100 \text{ A/m}^2$ ) (Figure 2A, Table S3-1). The product distribution was similar for both modes when the second electrochemical cell was on;  $(\text{NH}_4)_2\text{SO}_4$  in Chamber 3 dominated with  $46.4 \pm 9.1\%$  recovery efficiency for  $(\text{NH}_4)_2\text{SO}_4$  and  $30.6 \pm 6.6\%$  for  $\text{NH}_{3(\text{aq})}$  after 12 hours ( $2.15 \pm 0.33$  g/L TAN as  $(\text{NH}_4)_2\text{SO}_4$  vs.  $1.42 \pm 0.34$  g/L TAN as  $\text{NH}_{3(\text{aq})}$ ). Longer operation up to 24 hours did not shift product speciation toward  $\text{NH}_{3(\text{aq})}$  (Figure S3-1, Figure S3-2). While concurrent operation recovered a combination of  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_{3(\text{aq})}$  at all times, staggered operation at 0.64 A recovered only  $(\text{NH}_4)_2\text{SO}_4$  when the second electrochemical cell was off (first 6 hours,  $75.4 \pm 7.0\%$  recovery efficiency for  $(\text{NH}_4)_2\text{SO}_4$  vs.  $0.68 \pm 0.3\%$  for  $\text{NH}_{3(\text{aq})}$ ). Because staggered operation at 0.64 A facilitated control over the start of  $\text{NH}_{3(\text{aq})}$  recovery (i.e., by turning on the second electrochemical cell) but still primarily recovered  $(\text{NH}_4)_2\text{SO}_4$ , further

144 modified staggered operation of the second electrochemical cell was needed to target more tunable  
145 TAN recovery.

146 Changing the current applied to the second electrochemical cell influenced product distribution  
147 (Figure 2B). Across three applied currents (0.64 A or 100 A/m<sup>2</sup>, 2 A or 312.5 A/m<sup>2</sup>, and 4 A or  
148 625 A/m<sup>2</sup>), we observed consistent removal efficiency (Table S3-2), indicating that operation of  
149 the second electrochemical cell did not affect the removal process occurring in the first  
150 electrochemical cell. Total recovery efficiency was also similar across the three staggered  
151 conditions (Table S3-2) except when TAN mass balance closure differed (Figure S3-3). (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>  
152 was the dominant product after 6 hours in all cases, but after 12 hours, the ratio of NH<sub>3(aq)</sub> to  
153 (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> varied directly with applied current. In fact, NH<sub>3(aq)</sub> was the dominant product within  
154 2 hours of turning on the second electrochemical cell (8 hours of total operation) at 2 A and 4 A.  
155 After 12 hours, recovery efficiencies were 57.1 ± 7.6% as NH<sub>3(aq)</sub> versus 17.5 ± 3.1% as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>  
156 at 2 A and 65.9 ± 1.9% as NH<sub>3(aq)</sub> versus 14.2 ± 1.9% as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> at 4 A. Therefore, increasing  
157 current applied to the second electrochemical cell relative to the first cell prioritized NH<sub>3(aq)</sub> over  
158 (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> production, enabling applications of recovered TAN beyond fertilizer.



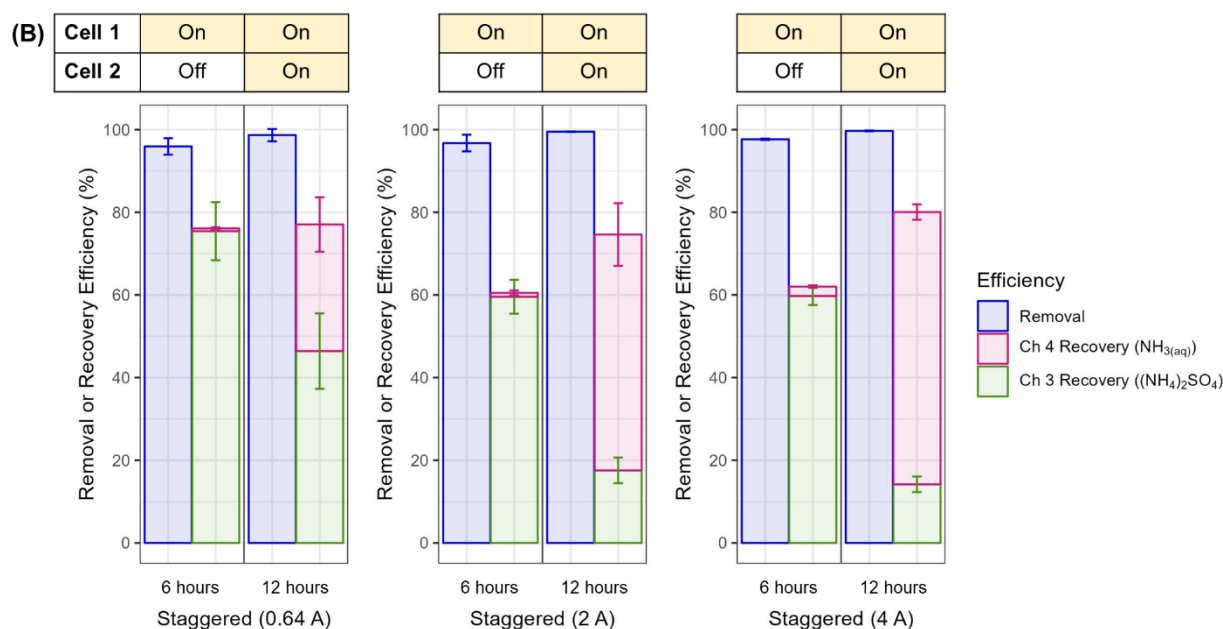
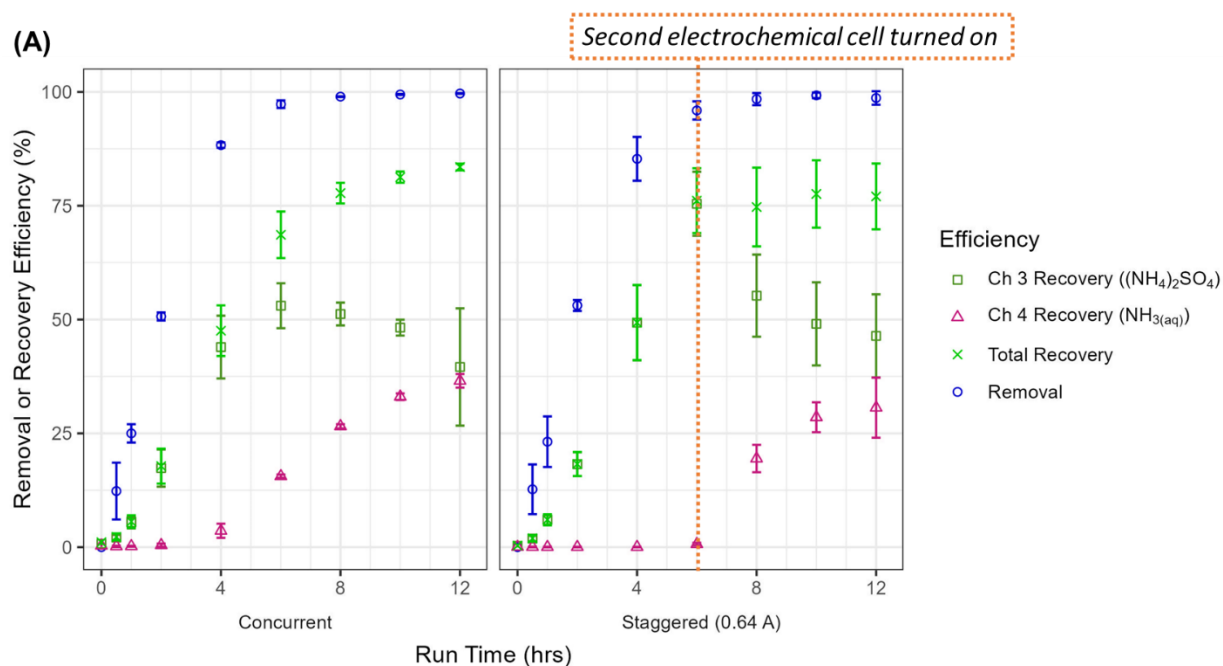
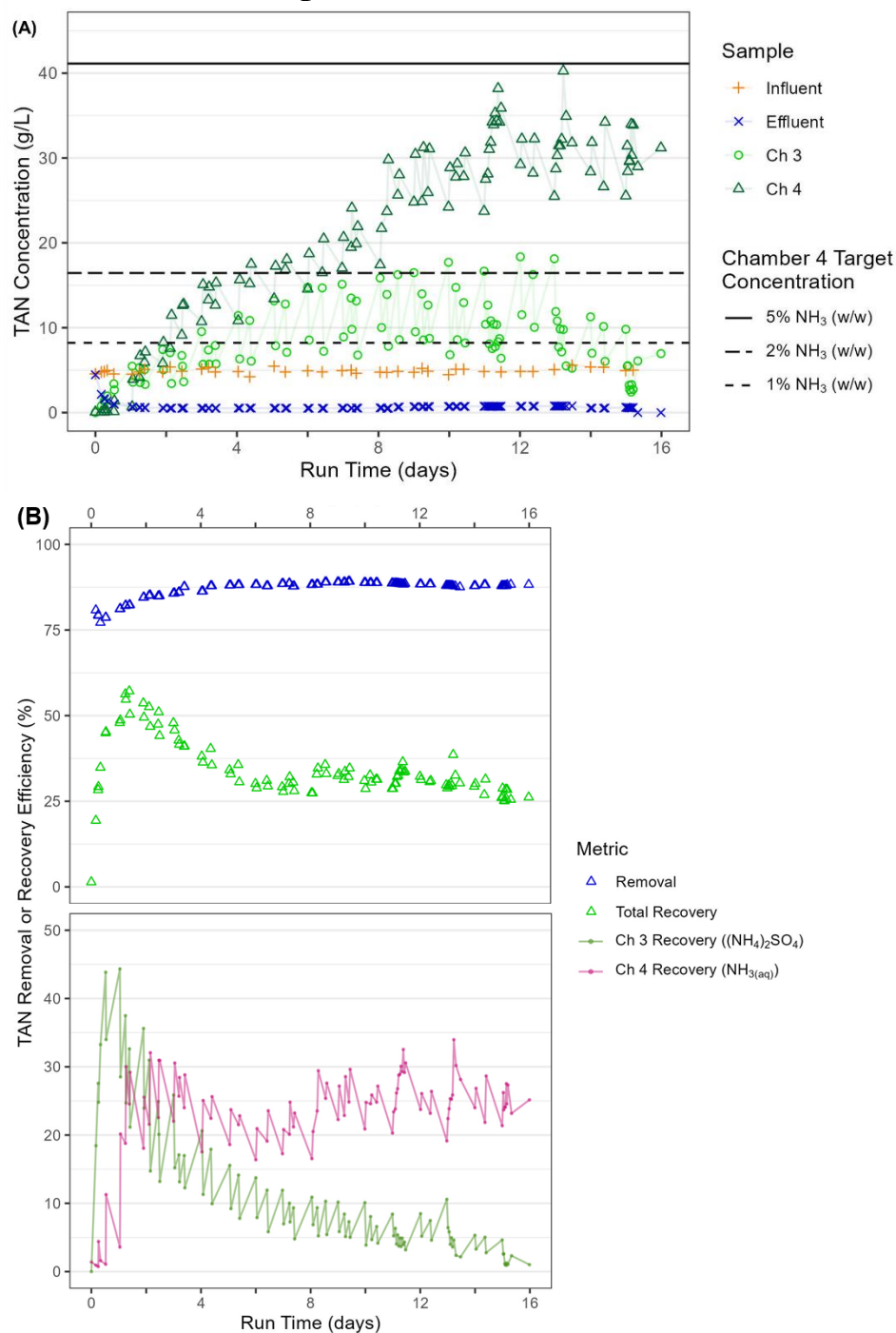


Figure 2. Batch flexible electrochemical stripping (FECS) experiments treating urine using concurrent and staggered electrochemical operation. (A) Removal and recovery efficiency over time during concurrent and staggered operation with the second electrochemical cell operating at 0.64 A. Figure S3-1 shows removal and recovery efficiency for 24-hour experiments in concurrent mode and staggered mode at 0.64 A. (B) Removal and recovery efficiency during staggered operation at different currents. Performance at 6 hours represents the end of Phase 1 of staggered operation when only electrochemical cell 1 is on; data at 12 hours illustrate performance at the end of Phase 2 when both cells are on. The grid above the plots indicates which electrochemical cells are on at the time points shown.

## 168 3.2 Continuous Operation for Tunable Product Generation



170  
171 *Figure 3. Performance of continuous flexible electrochemical stripping (FECS) with staggered electrochemical cell operation*  
172 *while treating urine. (A) Total ammonia nitrogen (TAN) concentrations over time. (B) Removal efficiency, total recovery efficiency,*  
173 *and recovery efficiency as ( $\text{NH}_4$ )<sub>2</sub>SO<sub>4</sub> in Chamber 3 and NH<sub>3(aq)</sub> in Chamber 4. Recovery efficiencies shown in panel B consider*

only TAN present in the reactor chambers and recirculation bottles; Figure S3-4 shows analogous metrics accounting for TAN captured in acid traps as well as TAN present in the reactor chambers and recirculation bottles.

When treating hydrolyzed urine, FECS generated: (1)  $\text{NH}_{3(\text{aq})}$  in Chamber 4 with concentrations similar to ready-to-use cleaners (1% and 2%  $\text{NH}_3$  (w/w)) and cleaner concentrates (5%  $\text{NH}_3$  (w/w)) and (2)  $(\text{NH}_4)_2\text{SO}_4$  solutions in Chamber 3 with no less than 5 g/L TAN and up to 18.4 g/L TAN, approaching commercial fertilizer concentrations (28.4 g/L TAN)<sup>51</sup> (Figure 3). In this study, we prioritized TAN up-concentration into  $\text{NH}_3$  solutions over  $(\text{NH}_4)_2\text{SO}_4$  to advance tunable FECS product distribution compared to previous ECS studies focused on  $(\text{NH}_4)_2\text{SO}_4$  recovery.<sup>47</sup> Continuous FECS removed  $88.1 \pm 0.72\%$  of TAN from urine with an influent concentration of  $4,950 \pm 290$  mg/L TAN (effluent composition shown in Table S3-3). Although continuous FECS achieved removal similar to ECS ( $83.4 \pm 1.5\%$ ),<sup>47</sup> the steady-state recovery efficiency ( $30.7 \pm 2.8\%$  at 5 days onward) was lower than for ECS ( $73.0 \pm 2.9\%$ )<sup>47</sup> and lower than removal in FECS. Fluctuating pH in Chamber 3 decreased recovery efficiency in FECS compared to ECS by causing an inconsistent  $\text{NH}_3$  concentration gradient driving diffusion from Chamber 2 to 3 and thus, TAN accumulation in Chamber 2 (Figure S3-4, Figure S3-5**Error! Reference source not found.**). Given alkaline conditions in Chambers 3 and 4 (Figure S3-4; intermittently alkaline in Chamber 3, always alkaline in Chamber 4), better sealing these chambers would reduce  $\text{NH}_3$  transfer to acid traps and improve recovery efficiency ( $46.5 \pm 3.3\%$ , Figure S3-6). Additional factors contributing to low FECS recovery included (Figure S3-7 through Figure S3-9, Section S3.2.1): TAN transfer to the Chamber 2 acid trap; TAN oxidation to  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and possibly un-measured gaseous species (e.g.,  $\text{N}_2$ ); potential losses due to  $\text{NH}_3$  volatilization; and possible interference of mesh supports around the omniphobic membrane with TAN mass transfer to and through the membrane. While FECS achieved steady TAN removal and recovery, future improvements are needed to

increase TAN recovery as  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_{3(\text{aq})}$  (e.g., preventing TAN oxidation) or enable recovery of additional products (e.g., gaseous  $\text{NH}_3$ ,  $\text{NO}_3^-$ ).

Despite low recovery efficiency, TAN concentrations in Chambers 3 and 4 generally increased over time, and TAN concentrations and product distribution between Chambers 3 and 4 showed short-term fluctuations that reflected operation of the second electrochemical cell (Figure 3). When the second electrochemical cell was on, the TAN concentration in Chamber 3 decreased and the TAN concentration in Chamber 4 increased due to electromigration of  $\text{NH}_4^+$  from Chamber 3 to 4. When the second electrochemical cell was off, the TAN concentration in Chamber 4 decreased and the TAN concentration in Chamber 3 increased due to  $\text{NH}_3$  back-diffusion from Chamber 4 to 3. Chamber 4 TAN concentration seemed to plateau (i.e., fluctuated between 23.7 and 31.2 g/L each day) starting at about 8 days. On Days 11 and 13, we achieved higher Chamber 4 concentrations (up to 40.3 g/L TAN, 4.89%  $\text{NH}_3$  (w/w)) and greater product distribution toward  $\text{NH}_{3(\text{aq})}$  over  $(\text{NH}_4)_2\text{SO}_4$  by increasing the operation frequency of the second electrochemical cell (i.e., 1-hour on vs. 1-hour off periods instead of 1-hour on vs. 6- to 12-hour off periods) to limit back-diffusion (Figure S3-10). Reactor modifications (e.g., using a thicker CEM in the second electrochemical cell,<sup>52</sup> alternative architectures like electrocatalyst-in-a-box (ECaB)<sup>53</sup>) in combination with the demonstrated operational strategy could further enhance  $\text{NH}_{3(\text{aq})}$  recovery.

Long-term FECS operation revealed water transfer from Chamber 3 to 4 (due to osmosis and electro-osmosis) as a second challenge to  $\text{NH}_{3(\text{aq})}$  up-concentration (Figure S3-11, Figure S3-12). While water transfer did not drastically affect the time needed to reach ready-to-use cleaner concentrations (1% and 2% (w/w)  $\text{NH}_3$ ), reaching 5% (w/w)  $\text{NH}_3$  could have been achieved in 9.4 rather than 13.2 days without water transfer (Figure S3-13). This detrimental effect of water transfer was most noticeable at the highest target concentration because greater concentration

differences across the second CEM resulted in more osmotic water transport.<sup>54,55</sup> Mitigating water transfer likely requires material innovations, like tuning membrane properties (e.g., polymer and fixed charge group identity, pore size and connectivity, coating).<sup>56–58</sup> Therefore, integrated optimization of reactor architecture, materials, and operation is needed to achieve more complete TAN recovery and higher  $\text{NH}_{3(\text{aq})}$  concentrations in FECS.

The tunability that FECS offers had significant energy and monetary costs (Figure S3-14). TAN removal via FECS required about  $166 \pm 8.2$  MJ/kg N compared to  $61.2 \pm 4.2$  MJ/kg N for ECS.<sup>47</sup> Energy consumption for recovery was  $470 \pm 56$  MJ/kg N compared to  $69.6 \pm 3.2$  MJ/kg N recovered for ECS,<sup>47</sup> 32 MJ/kg N for conventional ammonia stripping,<sup>59</sup> 31.6 MJ/kg N for the Haber-Bosch process,<sup>60</sup> and 77.9 MJ/kg N for conventional nitrogen management via the Haber-Bosch process and nitrification-denitrification (Figure S3-15, Table S3-4).<sup>46,60</sup> Despite the high energy demand of FECS, *in situ* acid and base generation minimized chemical inputs, which can contribute significantly to life-cycle costs and environmental impacts for nitrogen recovery technologies.<sup>61</sup> Each electrochemical cell contributed almost equally to total energy consumption (Figure S3-16). Modifying the applied current for the second electrochemical cell could reduce energy demand (Figure S3-17, Figure S3-18, Table S3-5, Table S3-6, Section S3.2.2). Altering the operation frequency of the second electrochemical cell and reactor architecture could improve energy efficiency by maintaining more consistent migration from Chamber 2 to 3 and reducing  $\text{NH}_3$  back-diffusion from Chamber 4 to 3. Additional energy consumption and reactor components (e.g., two anodes in FECS vs. one in ECS<sup>47</sup>) entail significant costs for the additional functionality that FECS enables, motivating future studies on low-cost, durable materials; alternative reactor configurations that reduce TAN losses and increase recovery efficiency; and further tuning

operating parameters to reduce energy consumption, improve recovery, and enhance product control.

## 4 Implications

We demonstrated a novel reactor, FECS, that facilitates tunable recovery of ammonia/ammonium from urine as both  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_3(\text{aq})$ . While  $(\text{NH}_4)_2\text{SO}_4$  is mainly used as a fertilizer,  $\text{NH}_3$  is more versatile, with uses as a disinfecting cleaner,<sup>35–38</sup> green fuel,<sup>39,40</sup> and industrial feedstock for plastic, rubber, and fiber synthesis.<sup>34</sup> With minimal chemical inputs and real-time control over product distribution, FECS can integrate distributed wastewater treatment and chemical manufacturing in diverse settings with changing local needs and markets. Simpler, lower-cost, and lower-energy systems like ECS may be more suitable in cases where TAN removal is the primary goal (e.g., due to regulatory limits on environmental discharges). However, FECS is valuable if  $\text{NH}_3(\text{aq})$  or switching between  $(\text{NH}_4)_2\text{SO}_4$  and  $\text{NH}_3(\text{aq})$  is desirable. For instance, FECS could supply  $\text{NH}_3$  to nearby industries reducing dependence on long-distance supply chains and provide both fertilizers and cleaners to remote rural agricultural communities. Therefore, integrating FECS into sanitation systems can promote more equitable resource access, improve food security and health, and lower environmental impacts of chemical industries while contributing to re-engineering the nitrogen cycle toward circularity.

## Supporting Information

The supporting information includes text describing reactor setup and operation; tables describing influent and effluent streams, reactor component properties, statistical analysis of performance metrics, and product prices; equations for efficiencies and energy demand; and figures showing reactor setup, temporal trends in performance metrics and composition, and product prices.

## Acknowledgements

We thank the Tarpeh lab for productive discussions in developing this work. The project was funded by the Stanford University King Center on Global Development, Stanford University Center for Innovation in Global Health, and the Sustainability Accelerator from the Stanford Doerr School of Sustainability. Authors also acknowledge the following additional support: AK – Stanford University Vice Provost for Graduate Education; MG – National Alliance for Water Innovation (NAWI); and WAT – Camille and Henry Dreyfus Foundation. NAWI is funded by the U.S. Department of Energy, Energy Efficiency and Renewable Energy Office, Advanced Manufacturing Office under Funding Opportunity Announcement DE-FOA-0001905. Funding has been provided in full or in part through an agreement with the California State Water Resources Control Board using funds from Proposition 1. The contents of this document do not necessarily reflect the views and policies of the foregoing, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

## References

- (1) Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F. S.; Lambin, E. F.; Lenton, T. M.; Scheffer, M.; Folke, C.; Schellnhuber, H. J.; Nykvist, B.; De Wit, C. A.; Hughes, T.; Van Der Leeuw, S.; Rodhe, H.; Sörlin, S.; Snyder, P. K.; Costanza, R.; Svedin, U.; Falkenmark, M.; Karlberg, L.; Corell, R. W.; Fabry, V. J.; Hansen, J.; Walker, B.; Liverman, D.; Richardson, K.; Crutzen, P.; Foley, J. A. A Safe Operating Space for Humanity. *Nature* **2009**, *461* (7263), 472–475. <https://doi.org/10.1038/461472a>.
- (2) Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S. E.; Fetzer, I.; Bennett, E. M.; Biggs, R.; Carpenter, S. R.; de Vries, W.; de Wit, C. A.; Folke, C.; Gerten, D.; Heinke, J.; Mace, G. M.; Persson, L. M.; Ramanathan, V.; Reyers, B.; Sörlin, S. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347* (6223), 1259855. <https://doi.org/10.1126/science.1259855>.
- (3) Dodds, W. K.; Bouska, W. W.; Eitzmann, J. L.; Pilger, T. J.; Pitts, K. L.; Riley, A. J.; Schloesser, J. T.; Thornbrugh, D. J. Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environ. Sci. Technol.* **2009**, *43* (1), 12–19. <https://doi.org/10.1021/es801217q>.
- (4) Burow, K. R.; Nolan, B. T.; Rupert, M. G.; Dubrovsky, N. M. Nitrate in Groundwater of the United States, 1991–2003. *Environ. Sci. Technol.* **2010**, *44* (13), 4988–4997. <https://doi.org/10.1021/es100546y>.
- (5) Falconer, I. R. An Overview of Problems Caused by Toxic Blue–Green Algae (Cyanobacteria) in Drinking and Recreational Water. *Environmental Toxicology* **1999**, *14* (1), 5–12. [https://doi.org/10.1002/\(SICI\)1522-7278\(199902\)14:1<5::AID-TOX3>3.0.CO;2-0](https://doi.org/10.1002/(SICI)1522-7278(199902)14:1<5::AID-TOX3>3.0.CO;2-0).



- (6) Juli IacuanIELlo; Orianna Bretschger. *Decentralizing wastewater treatment can help corporations achieve climate goals*. World Economic Forum.  
<https://www.weforum.org/agenda/2022/10/wastewater-corporations-climate-goals/> (accessed 2024-01-09).
- (7) Kyriakou, V.; Garagounis, I.; Vourros, A.; Vasileiou, E.; Stoukides, M. An Electrochemical Haber-Bosch Process. *Joule* **2020**, 4 (1), 142–158. <https://doi.org/10.1016/j.joule.2019.10.006>.
- (8) Larsen, T. A.; Hoffmann, S.; Lüthi, C.; Truffer, B.; Maurer, M. Emerging Solutions to the Water Challenges of an Urbanizing World. *Science* **2016**, 352 (6288), 928–933.
- (9) Larsen, T. A.; Gruendl, H.; Binz, C. The Potential Contribution of Urine Source Separation to the SDG Agenda – a Review of the Progress so Far and Future Development Options. *Environ. Sci.: Water Res. Technol.* **2021**, 7 (7), 1161–1176. <https://doi.org/10.1039/D0EW01064B>.
- (10) Randall, D. G.; Naidoo, V. Urine: The Liquid Gold of Wastewater. *Journal of Environmental Chemical Engineering* **2018**, 6 (2), 2627–2635. <https://doi.org/10.1016/j.jece.2018.04.012>.
- (11) Will Steffen; Angelina Sanderson; Peter Tyson; Jill Jaeger; Pamela Matson; Berrien Moore III; Frank Oldfield; Katherine Richardson; H. John Schellnhuber; B.L. Turner II; Robert J. Wasson. *Global Change and the Earth System: A Planet Under Pressure*, 2nd printing.; Springer-Verlag: Berlin, 2005.
- (12) Lenton, T. M.; Held, H.; Kriegler, E.; Hall, J. W.; Lucht, W.; Rahmstorf, S.; Schellnhuber, H. J. Tipping Elements in the Earth’s Climate System. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, 105 (6), 1786–1793. <https://doi.org/10.1073/pnas.0705414105>.
- (13) Scheffer, M.; Carpenter, S.; Foley, J. A.; Folke, C.; Walker, B. Catastrophic Shifts in Ecosystems. *Nature* **2001**, 413 (6856), 591–596. <https://doi.org/10.1038/35098000>.
- (14) Kogler, A.; Farmer, M.; Simon, J. A.; Tilmans, S.; Wells, G. F.; Tarpeh, W. A. Systematic Evaluation of Emerging Wastewater Nutrient Removal and Recovery Technologies to Inform Practice and Advance Resource Efficiency. *ACS EST Eng.* **2021**, 1 (4), 662–684. <https://doi.org/10.1021/acsestengg.0c00253>.
- (15) J.R. McConville; E. Kvarnström; H. Jönsson; E. Kärrman; M. Johansson. Is the Swedish Wastewater Sector Ready for a Transition to Source Separation? *dwt* **2017**, 91, 320–328. <https://doi.org/10.5004/dwt.2017.20881>.
- (16) Miller, D. M.; Abels, K.; Guo, J.; Williams, K. S.; Liu, M. J.; Tarpeh, W. A. Electrochemical Wastewater Refining: A Vision for Circular Chemical Manufacturing. *J. Am. Chem. Soc.* **2023**. <https://doi.org/10.1021/jacs.3c01142>.
- (17) Hengl, T.; Leenaars, J. G. B.; Shepherd, K. D.; Walsh, M. G.; Heuvelink, G. B. M.; Mamo, T.; Tilahun, H.; Berkhout, E.; Cooper, M.; Fegraus, E.; Wheeler, I.; Kwabena, N. A. Soil Nutrient Maps of Sub-Saharan Africa: Assessment of Soil Nutrient Content at 250 m Spatial Resolution Using Machine Learning. *Nutr Cycl Agroecosyst* **2017**, 109 (1), 77–102. <https://doi.org/10.1007/s10705-017-9870-x>.
- (18) Wang, R.; Yang, K.; Wong, C.; Aguirre-Villegas, H.; Larson, R.; Brushett, F.; Qin, M.; Jin, S. Electrochemical Ammonia Recovery and Co-Production of Chemicals from Manure Wastewater. *Nat Sustain* **2023**, 1–12. <https://doi.org/10.1038/s41893-023-01252-z>.
- (19) Mousset, E.; Fournier, M.; Su, X. Recent Advances of Reactive Electroseparation Systems for Water Treatment and Selective Resource Recovery. *Current Opinion in Electrochemistry* **2023**, 42, 101384. <https://doi.org/10.1016/j.coelec.2023.101384>.
- (20) Pickett, M. T.; Roberson, L. B.; Calabria, J. L.; Bullard, T. J.; Turner, G.; Yeh, D. H. Regenerative Water Purification for Space Applications: Needs, Challenges, and Technologies towards “Closing the Loop.” *Life Sciences in Space Research* **2020**, 24, 64–82. <https://doi.org/10.1016/j.lssr.2019.10.002>.
- (21) Ledezma, P.; Kuntke, P.; Buisman, C. J. N.; Keller, J.; Freguia, S. Source-Separated Urine Opens Golden Opportunities for Microbial Electrochemical Technologies. *Trends in Biotechnology* **2015**, 33 (4), 214–220. <https://doi.org/10.1016/j.tibtech.2015.01.007>.



- (22) Christiaens, M. E. R.; Udert, K. M.; Arends, J. B. A.; Huysman, S.; Vanhaecke, L.; McAdam, E.; Rabaey, K. Membrane Stripping Enables Effective Electrochemical Ammonia Recovery from Urine While Retaining Microorganisms and Micropollutants. *Water Research* **2019**, *150*, 349–357. <https://doi.org/10.1016/j.watres.2018.11.072>.
- (23) Zhang, Y.; Angelidaki, I. Recovery of Ammonia and Sulfate from Waste Streams and Bioenergy Production via Bipolar Bioelectrodialysis. *Water Research* **2015**, *85*, 177–184. <https://doi.org/10.1016/j.watres.2015.08.032>.
- (24) Xie, A.; Papat, S. C. Electrochemical Ammonia Stripping from Non-Nitrified Animal Rendering Wastewater. *Chemical Engineering Journal Advances* **2020**, *3*, 100020. <https://doi.org/10.1016/j.cej.2020.100020>.
- (25) Logan, B. E.; Rabaey, K. Conversion of Wastes into Bioelectricity and Chemicals by Using Microbial Electrochemical Technologies. *Science* **2012**, *337* (6095), 686–690. <https://doi.org/10.1126/science.1217412>.
- (26) Nidheesh, P. V.; Ganiyu, S. O.; Kuppam, C.; Mousset, E.; Samsudeen, N.; Olvera-Vargas, H.; Kumar, G. Bioelectrochemical Cells as a Green Energy Source for Electrochemical Treatment of Water and Wastewater. *Journal of Water Process Engineering* **2022**, *50*, 103232. <https://doi.org/10.1016/j.jwpe.2022.103232>.
- (27) Kuntke, P.; Śmiech, K. M.; Bruning, H.; Zeeman, G.; Saakes, M.; Sleutels, T. H. J. A.; Hamelers, H. V. M.; Buisman, C. J. N. Ammonium Recovery and Energy Production from Urine by a Microbial Fuel Cell. *Water Research* **2012**, *46* (8), 2627–2636. <https://doi.org/10.1016/j.watres.2012.02.025>.
- (28) Koskue, V.; Rinta-Kanto, J. M.; Freguia, S.; Ledezma, P.; Kokko, M. Optimising Nitrogen Recovery from Reject Water in a 3-Chamber Bioelectroconcentration Cell. *Separation and Purification Technology* **2021**, *264*, 118428. <https://doi.org/10.1016/j.seppur.2021.118428>.
- (29) Sutherland, D. L.; Turnbull, M. H.; Craggs, R. J. Increased Pond Depth Improves Algal Productivity and Nutrient Removal in Wastewater Treatment High Rate Algal Ponds. *Water Research* **2014**, *53*, 271–281. <https://doi.org/10.1016/j.watres.2014.01.025>.
- (30) Xie, M.; Nghiem, L. D.; Price, W. E.; Elimelech, M. Toward Resource Recovery from Wastewater: Extraction of Phosphorus from Digested Sludge Using a Hybrid Forward Osmosis–Membrane Distillation Process. *Environ. Sci. Technol. Lett.* **2014**, *1* (2), 191–195. <https://doi.org/10.1021/ez400189z>.
- (31) Jagtap, N.; Boyer, T. H. Integrated, Multi-Process Approach to Total Nutrient Recovery from Stored Urine. *Environ. Sci.: Water Res. Technol.* **2018**, *4* (10), 1639–1650. <https://doi.org/10.1039/C8EW00004B>.
- (32) Trimmer, J. T.; Margenot, A. J.; Cusick, R. D.; Guest, J. S. Aligning Product Chemistry and Soil Context for Agronomic Reuse of Human-Derived Resources. *Environ. Sci. Technol.* **2019**, *53* (11), 6501–6510. <https://doi.org/10.1021/acs.est.9b00504>.
- (33) Speight, J. G. Chapter Three - Industrial Inorganic Chemistry. In *Environmental Inorganic Chemistry for Engineers*; Speight, J. G., Ed.; Butterworth-Heinemann, 2017; pp 111–169. <https://doi.org/10.1016/B978-0-12-849891-0.00003-5>.
- (34) International Energy Agency. *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production*; OECD, 2021. <https://doi.org/10.1787/f6daa4a0-en>.
- (35) Ogunyoku, T. A.; Habebo, F.; Nelson, K. L. In-Toilet Disinfection of Fresh Fecal Sludge with Ammonia Naturally Present in Excreta. *Journal of Water, Sanitation and Hygiene for Development* **2016**, *6* (1), 104–114. <https://doi.org/10.2166/washdev.2015.233>.
- (36) Decrey, L.; Kazama, S.; Udert, K. M.; Kohn, T. Ammonia as an In Situ Sanitizer: Inactivation Kinetics and Mechanisms of the ssRNA Virus MS2 by NH<sub>3</sub>. *Environ. Sci. Technol.* **2015**, *49* (2), 1060–1067. <https://doi.org/10.1021/es5044529>.
- (37) Pecson, B. M.; Nelson, K. L. Inactivation of *Ascaris Suum* Eggs by Ammonia. *Environ. Sci. Technol.* **2005**, *39* (20), 7909–7914. <https://doi.org/10.1021/es050659a>.
- (38) Jenkins, M. B.; Bowman, D. D.; Ghiorse, W. C. Inactivation of *Cryptosporidium Parvum* Oocysts by Ammonia. *Appl Environ Microbiol* **1998**, *64* (2), 784–788.

- (39) MacFarlane, D. R.; Cherepanov, P. V.; Choi, J.; Suryanto, B. H. R.; Hodgetts, R. Y.; Bakker, J. M.; Ferrero Vallana, F. M.; Simonov, A. N. A Roadmap to the Ammonia Economy. *Joule* **2020**, *4* (6), 1186–1205. <https://doi.org/10.1016/j.joule.2020.04.004>.
- (40) Valera-Medina, A.; Amer-Hatem, F.; Azad, A. K.; Dedoussi, I. C.; de Joannon, M.; Fernandes, R. X.; Glarborg, P.; Hashemi, H.; He, X.; Mashruk, S.; McGowan, J.; Mounaim-Rousellet, C.; Ortiz-Prado, A.; Ortiz-Valera, A.; Rossetti, I.; Shu, B.; Yehia, M.; Xiao, H.; Costa, M. Review on Ammonia as a Potential Fuel: From Synthesis to Economics. *Energy Fuels* **2021**, *35* (9), 6964–7029. <https://doi.org/10.1021/acs.energyfuels.0c03685>.
- (41) Tarpeh, W. A.; Chen, X. Making Wastewater Obsolete: Selective Separations to Enable Circular Water Treatment. *Environmental Science and Ecotechnology* **2021**, *5*, 100078. <https://doi.org/10.1016/j.es.2021.100078>.
- (42) Chaplin, B. P. The Prospect of Electrochemical Technologies Advancing Worldwide Water Treatment. *Acc. Chem. Res.* **2019**, *52* (3), 596–604. <https://doi.org/10.1021/acs.accounts.8b00611>.
- (43) Radjenovic, J.; Sedlak, D. L. Challenges and Opportunities for Electrochemical Processes as Next-Generation Technologies for the Treatment of Contaminated Water. *Environ. Sci. Technol.* **2015**, *49* (19), 11292–11302. <https://doi.org/10.1021/acs.est.5b02414>.
- (44) Kong, L.; Liu, X. Emerging Electrochemical Processes for Materials Recovery from Wastewater: Mechanisms and Prospects. *Front. Environ. Sci. Eng.* **2020**, *14* (5), 90. <https://doi.org/10.1007/s11783-020-1269-2>.
- (45) Tarpeh, W. A.; Barazesh, J. M.; Cath, T. Y.; Nelson, K. L. Electrochemical Stripping to Recover Nitrogen from Source-Separated Urine. *Environ. Sci. Technol.* **2018**, *52* (3), 1453–1460. <https://doi.org/10.1021/acs.est.7b05488>.
- (46) Liu, M. J.; Neo, B. S.; Tarpeh, W. A. Building an Operational Framework for Selective Nitrogen Recovery via Electrochemical Stripping. *Water Research* **2020**, *169*, 115226. <https://doi.org/10.1016/j.watres.2019.115226>.
- (47) Kogler, A.; Sharma, N.; Tiburcio, D.; Gong, M.; Miller, D. M.; Williams, K. S.; Chen, X.; Tarpeh, W. A. Long-Term Robustness and Failure Mechanisms of Electrochemical Stripping for Wastewater Ammonia Recovery. *ACS Environ. Au* **2024**, acsenvironau.3c00058. <https://doi.org/10.1021/acsenvironau.3c00058>.
- (48) Comer, B. M.; Fuentes, P.; Dimkpa, C. O.; Liu, Y.-H.; Fernandez, C. A.; Arora, P.; Realff, M.; Singh, U.; Hatzell, M. C.; Medford, A. J. Prospects and Challenges for Solar Fertilizers. *Joule* **2019**, *3* (7), 1578–1605. <https://doi.org/10.1016/j.joule.2019.05.001>.
- (49) McArthur, J. W.; McCord, G. C. Fertilizing Growth: Agricultural Inputs and Their Effects in Economic Development. *J Dev Econ* **2017**, *127*, 133–152. <https://doi.org/10.1016/j.jdeveco.2017.02.007>.
- (50) Lim, M. M. L.; Søgaaard Jørgensen, P.; Wyborn, C. A. Reframing the Sustainable Development Goals to Achieve Sustainable Development in the Anthropocene - a Systems Approach. *E&S* **2018**, *23* (3), art22. <https://doi.org/10.5751/ES-10182-230322>.
- (51) Rodrigues, M.; Lund, R. J.; ter Heijne, A.; Sleutels, T.; Buisman, C. J. N.; Kuntke, P. Application of Ammonium Fertilizers Recovered by an Electrochemical System. *Resources, Conservation and Recycling* **2022**, *181*, 106225. <https://doi.org/10.1016/j.resconrec.2022.106225>.
- (52) Roman, M.; Roman, P.; Verbeke, R.; Gutierrez, L.; Vanoppen, M.; Dickmann, M.; Egger, W.; Vankelecom, I.; Post, J.; Cornelissen, E.; Keesman, K.; Verliefde, A. Non-Steady Diffusion and Adsorption of Organic Micropollutants in Ion-Exchange Membranes: Effect of the Membrane Thickness. *iScience* **2021**, *24* (2), 102095. <https://doi.org/10.1016/j.isci.2021.102095>.
- (53) Miller, D.; Liu, M.; Abels, K.; Kogler, A.; Williams, K.; Tarpeh, W. Engineering a Molecular Electrocatalytic System for Energy-Efficient Ammonia Production from Wastewater Nitrate. *ChemRxiv* February 8, 2024. <https://doi.org/10.26434/chemrxiv-2023-1s6n8-v2>.
- (54) Galama, A. H.; Saakes, M.; Bruning, H.; Rijnaarts, H. H. M.; Post, J. W. Seawater Predesalination with Electrodialysis. *Desalination* **2014**, *342*, 61–69. <https://doi.org/10.1016/j.desal.2013.07.012>.

- (55) Galama, A. H.; Vermaas, D. A.; Veerman, J.; Saakes, M.; Rijnaarts, H. H. M.; Post, J. W.; Nijmeijer, K. Membrane Resistance: The Effect of Salinity Gradients over a Cation Exchange Membrane. *Journal of Membrane Science* **2014**, *467*, 279–291. <https://doi.org/10.1016/j.memsci.2014.05.046>.
- (56) Kingsbury, R. S.; Zhu, S.; Flotron, S.; Coronell, O. Microstructure Determines Water and Salt Permeation in Commercial Ion-Exchange Membranes. *ACS Appl. Mater. Interfaces* **2018**, *10* (46), 39745–39756. <https://doi.org/10.1021/acsami.8b14494>.
- (57) Rommerskirchen, A.; Roth, H.; Linnartz, C. J.; Egidi, F.; Knepeck, C.; Roghmans, F.; Wessling, M. Mitigating Water Crossover by Crosslinked Coating of Cation-Exchange Membranes for Brine Concentration. *Advanced Materials Technologies* **2021**, *6* (10), 2100202. <https://doi.org/10.1002/admt.202100202>.
- (58) Kamcev, J.; Freeman, B. D. Charged Polymer Membranes for Environmental/Energy Applications. *Annu. Rev. Chem. Biomol. Eng.* **2016**, *7* (1), 111–133. <https://doi.org/10.1146/annurev-chembioeng-080615-033533>.
- (59) Maurer, M.; Schwegler, P.; Larsen, T. A. Nutrients in Urine: Energetic Aspects of Removal and Recovery. *Water Science and Technology* **2003**, *48* (1), 37–46. <https://doi.org/10.2166/wst.2003.0011>.
- (60) Rouwenhorst, K. H. R.; Krzywda, P. M.; Benes, N. E.; Mul, G.; Lefferts, L. Chapter 4 - Ammonia Production Technologies. In *Techno-Economic Challenges of Green Ammonia as an Energy Vector*; Valera-Medina, A., Banares-Alcantara, R., Eds.; Academic Press, 2021; pp 41–83. <https://doi.org/10.1016/B978-0-12-820560-0.00004-7>.
- (61) Kavvada, O.; Tarpeh, W. A.; Horvath, A.; Nelson, K. L. Life-Cycle Cost and Environmental Assessment of Decentralized Nitrogen Recovery Using Ion Exchange from Source-Separated Urine through Spatial Modeling. *Environ. Sci. Technol.* **2017**, *51* (21), 12061–12071. <https://doi.org/10.1021/acs.est.7b02244>.