Recovery of ammonium, phosphorus, and potassium from source-separated urine using Donnan Dialysis

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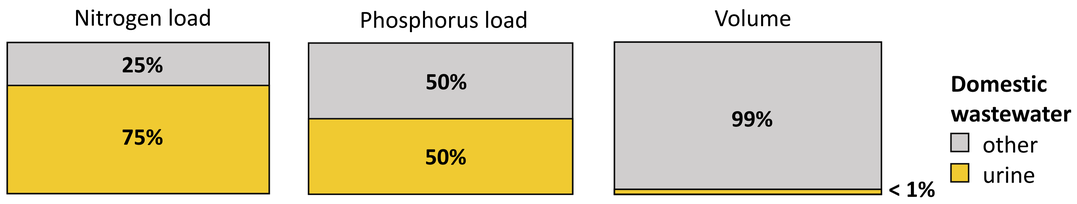
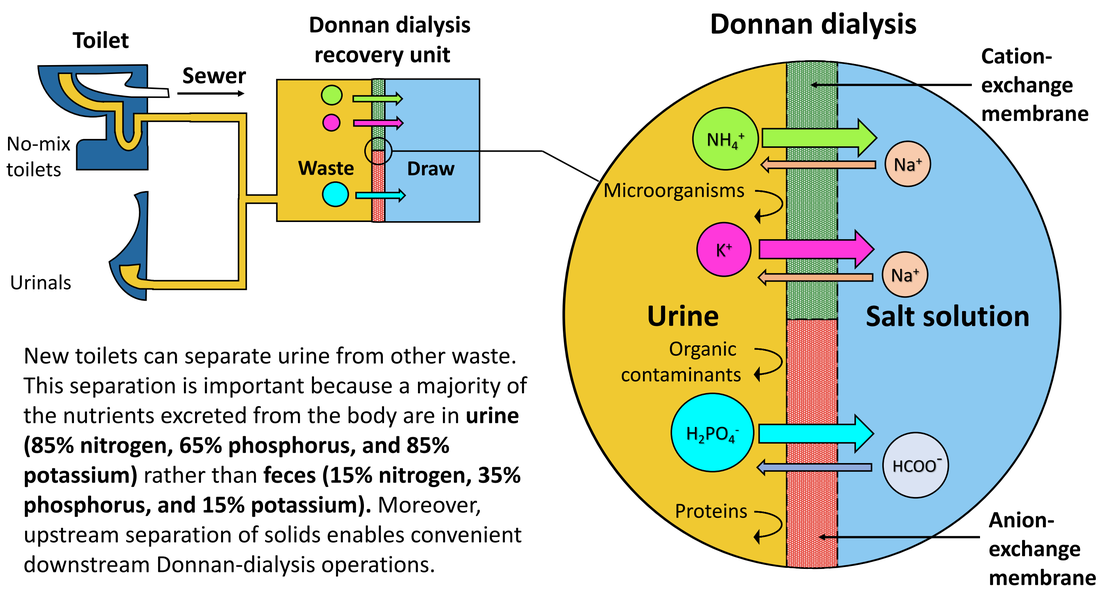
Motivation

Human urine contributes a high nutrient load (but small volume) to WWTPs



Human urine is a nutrient-rich waste stream that can be cost-effectively treated at the source through innovative processes. Currently, urine contributes the majority of nitrogen (75%) and phosphorus (50%) entering wastewater treatment plants (WWTPs), but urine is less than one percent of the total wastewater volume. Decentralized nutrient recovery from source-separated urine can relieve the burden on WWTPs and ensure food and water security. In this study, we investigated the potential for Donnan dialysis to recover ammonium (NH_4^+), phosphorus (P(V)), and potassium (K^+) from synthetic and real urine.

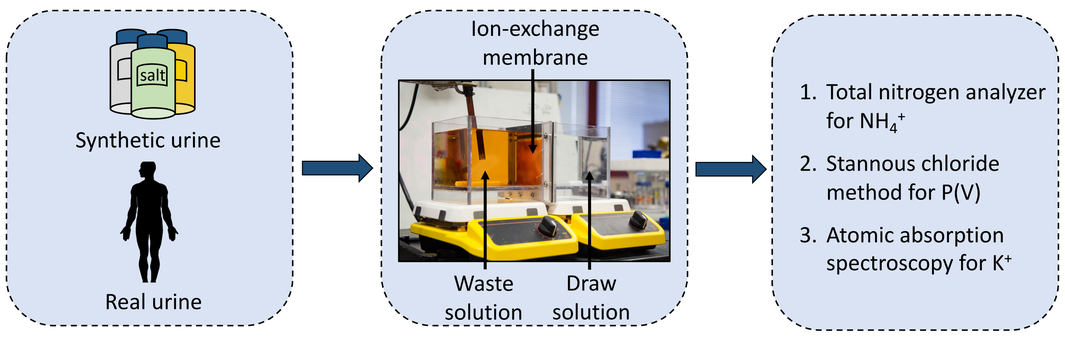
Concept



New toilets can separate urine from other waste. This separation is important because a majority of the nutrients excreted from the body are in **urine (85% nitrogen, 65% phosphorus, and 85% potassium)** rather than **feces (15% nitrogen, 35% phosphorus, and 15% potassium).** Moreover, upstream separation of solids enables convenient downstream Donnan-dialysis operations.

Donnan dialysis establishes equilibrium across an ion-exchange membrane. The ions from the waste solution migrate to the draw solution (and vice versa) until the electrochemical potentials of the ions are equal in both solutions. In the above schematic, NH_4^+ and K^+ ions exchange with Na^+ ions and P(V) (*e.g.*, $H_2PO_4^-$) ions exchange with $HCOO^-$ ions until the chemical potentials of NH_4^+, K^+, and P(V) ions are equal in the waste and draw solutions. The recovery efficiency of NH_4^+, K^+, and P(V) is controlled by the salt ion (*e.g.*, Na^+, $HCOO^-$) concentrations in the draw solution. Higher recovery efficiency can be achieved by employing concentrated draw solutions.

Experimental methods

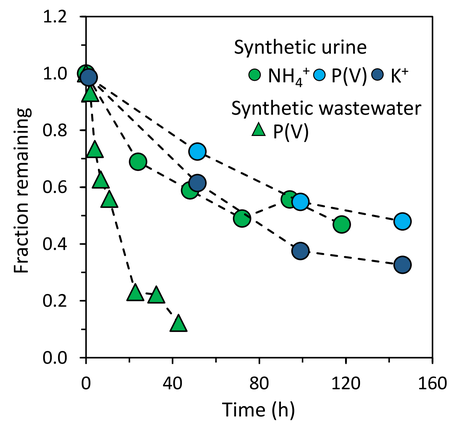


Synthetic urine and wastewater were prepared by dissolving inorganic salts (*e.g.*, NH_4Cl, $MgCl_2$, KCl, $NaHCO_3$, etc.) and NaH_2PO_4 in 2.0 or 0.4 L of deionized (DI) water, respectively. The draw solutions were prepared by adding sodium formate (HCOONa) to DI water. Real urine was collected from a volunteer over an 8-d period. The real urine was dosed with citric acid to prevent hydrolysis, and the measured pH was 4.6. The Donnan dialysis reactor was operated under continuous mixing by magnetic stirrer. Samples (1 mL) were collected and analyzed for NH_4^+, P(V), and K^+ using total nitrogen analysis, the stannous chloride standard method (method# 4500-P D), and flame atomic absorption spectroscopy, respectively. The anion- (AMI-7001) and cation- (CMI-7000) exchange membranes were purchased from Membranes International Inc.

Results

Removal of nitrogen, phosphorus, and potassium from synthetic urine

Synthetic urine composition (mM)	
NH_4^+	34.1
K^+	48.3
Ca^{2+}	2.9
Mg^2	2.4
P(V)	14.8
SO_4^{2-}	3.6
HCO_3^-	0.1
Na^+	102.8
Cl^-	140.2



After 144 h of treatment, the removal efficiencies for NH_4^+ and K^+ from synthetic urine were 51% and 66%, respectively. For 120 h and 43 h of treatment of synthetic urine and wastewater, the P(V) removal efficiencies were 53% and 88%, respectively. For synthetic wastewater, the P(V) removal was much faster than for synthetic urine due to competing effects of other anions (*e.g.*, SO_4^{2-}, Cl^-, HCO_3^-) in synthetic urine.

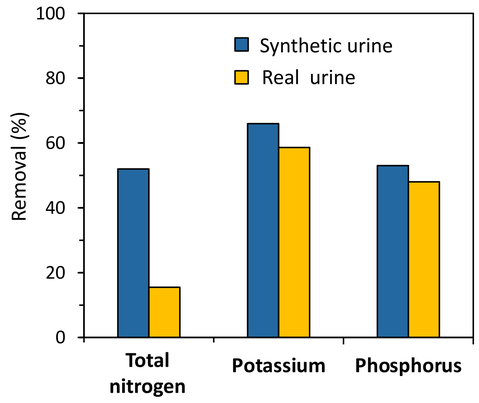
Removal of nutrients from real urine

Composition of real urine (mM)	
Total nitrogen	2500
K^+	64
P(V)	26

Hydrolysis of urea

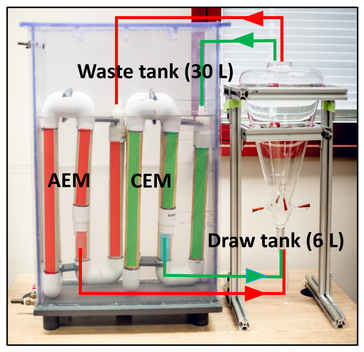
$$CO(NH_2)_2 + H_2O \longrightarrow CO_2 + 2NH_3$$

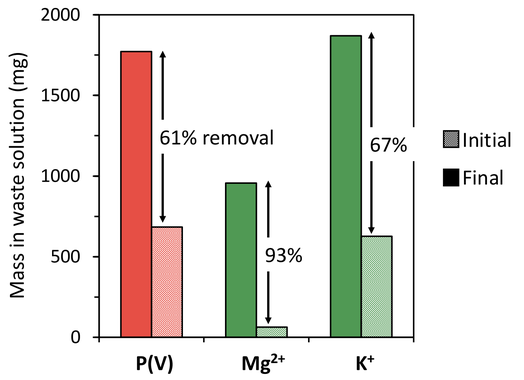
$$CO_2 + 2NH_3 + H_2O + H^+ \rightleftharpoons HCO_3^- + 2NH_4^+$$

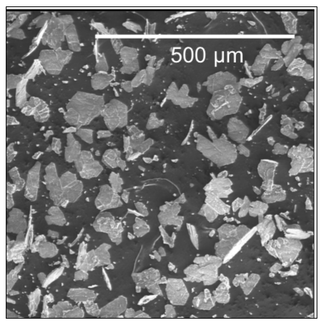


The removal efficiencies for nutrients in real urine after 7 d of Donnan dialysis operation were 16%, 48%, and 57% for nitrogen, phosphorus, and potassium, respectively. The low removal of nitrogen was attributed to the presence of other unrecovered forms, such as urea (a major nitrogen species in real urine). Ongoing work is exploring the impact of hydrolysis, which converts urea to ammonium, on nitrogen removal and recovery.

Simultaneous recovery of anions and cations using tubular ion-exchange membranes







Our lab-scale Donnan dialysis reactor simultaneously recovered P(V), Mg^{2+}, and K^+. The separate waste (30 L) and draw tanks (6 L) allowed treatment of larger waste volumes. The draw solution was continuously circulated through tubular ion-exchange membranes to recover 61% P(V), 93% Mg^{2+}, and 67 K^+ after 50 h. In the draw tank, the pH was adjusted to 9.0 using NaOH to precipitate recovered ions as potassium struvite ($KMgPO_4 \cdot 6H_2O$) and magnesium phosphate ($Mg_3(PO_4)_2$).

Conclusions

- Seven days of Donnan dialysis operation with real urine recovered 57% of potassium, 48% of phosphorus, and 16% of nitrogen.
- The recovery efficiencies for P(V) and K^+ in synthetic and real urine were similar, suggesting negligible matrix effects.
- Using the tubular-ion exchange reactor, a larger volume of wastewater was successfully treated, and 61% P(V), 93% Mg^{2+}, and 67 K^+ was recovered as nutrient-rich solids.

Related Work

Shashvatt, U.; Amurrio, F.; Portner, C.; Blaney, L. (2021) Phosphorus recovery by Donnan dialysis: membrane selectivity, diffusion coefficients, and speciation effects. *Chemical Engineering Journal (in press)*

Acknowledgements

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