

Urea recovery from fresh human urine by forward osmosis and membrane distillation (FO-MD)

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SUPPLEMENTAL MATERIALS

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MATERIALS

Materials

Forward osmosis and membrane distillation set-ups. Cole-Parmer Acrylic In-Line

Flowmeter, 1 GPM Water, 3/8" NPT (F) were used to monitor the flow of the solution in the FO and MD systems. Cole-Parmer console drive, 115 VAC, 50/60 Hz pumps were used to circulate the solutions in the system. Cole-Parmer Masterflex platinum-cured silicone tubing, L/S 17, was used throughout the FO and MD setup. A Cole-Parmer Polystat recirculator, 17 L/min, 250W cooling capacity, 115V 60 Hz chiller was used for the FO and MD experiments, and a Cole-Parmer Polystat Standard 6.5 L heated bath, 150 °C, 115VAC/60Hz was used for MD experiments. A Sartorius microbalance was used to track the increase in weight during the experiment to determine the flux of the FO and MD systems. WinWedge, a computer software, connected the balance to Microsoft Excel to log the data. pH and conductivity readings were taken for all samples using an Orion Dual Star Multiparameter Meter, an Orion 9156BNWP Combination pH probe, and Orion Star A212 conductivity probe.

Analytical methods. Urea was analyzed using a urea assay kit (Bioassay Systems, DUR-100) and a BioTek Synergy H1 Hybrid Multi-Mode Reader plate reader following the procedure detailed in the assay manual. However, a 1000 mg/L standard was used to increase the calibration curve from 500 to 1000 mg/L. Three check standards were used for every plate reading: 800, 500, and 100 mg/L in duplicate to ensure accuracy. Total organic carbon (TOC) and TN were both analyzed using a Shimadzu Total Organic Carbon/Nitrogen Analyzer. Four check standards were used for each TOC/TN run: TN 5, TN 1, TOC 10, and TOC 5 mg/L.

TABLES

Table S1: The composition of the synthetic urine used for all synthetic urine experiments

| Synthetic fresh urine composition | |
|--------------------------------------|---------------------|
| Compound | Concentration (g/L) |
| Urea | 15.0075 |
| NaCl | 2.5715 |
| Na ₂ SO ₄ | 2.1305 |
| KCl | 2.982 |
| MgCl ₂ ·6H ₂ O | 0.813 |
| NaH ₂ PO ₄ | 2.3995 |
| CaCl ₂ ·2H ₂ O | 0.588 |
| pH | 6 |

Table S2: The saturation indices for magnesium minerals in synthetic urine at pH 12.5

| Visual MINTeq Saturation Indices | |
|--|------------------|
| Mineral | Saturation index |
| Mg(OH) ₂ | 4.05 |
| Mg(OH) ₂ active | 2.35 |
| Mg ₂ (OH) ₃ Cl·4H ₂ O | 2.57 |
| Mg ₃ (PO ₄) ₂ | 3.89 |

Table S3: The TOC content in the FO draw solution at t = 24 h that is not accounted by the urea concentration. All units are mg/L C.

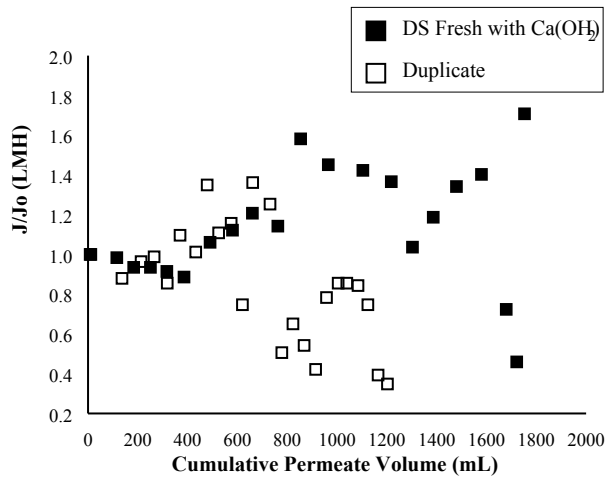
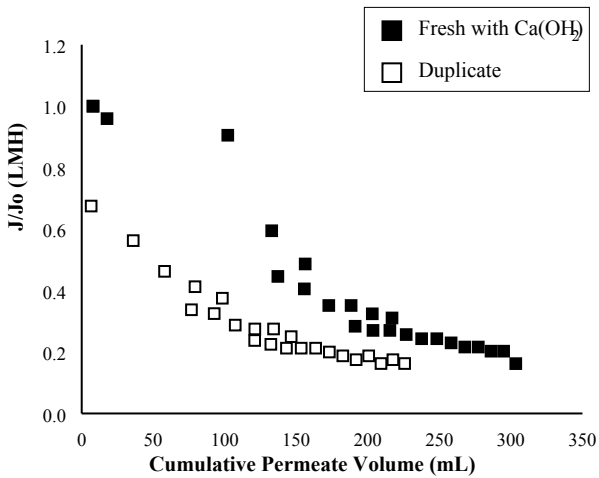
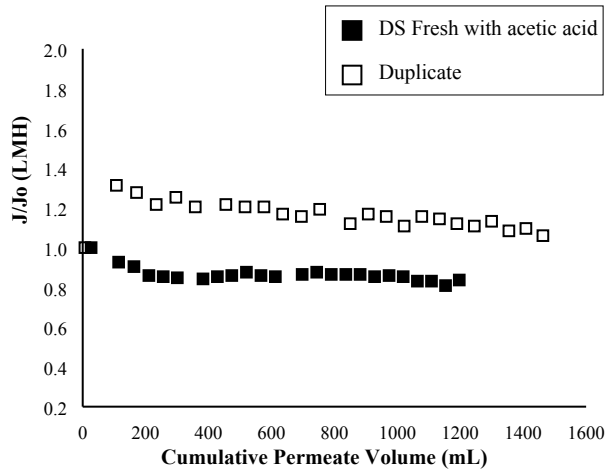
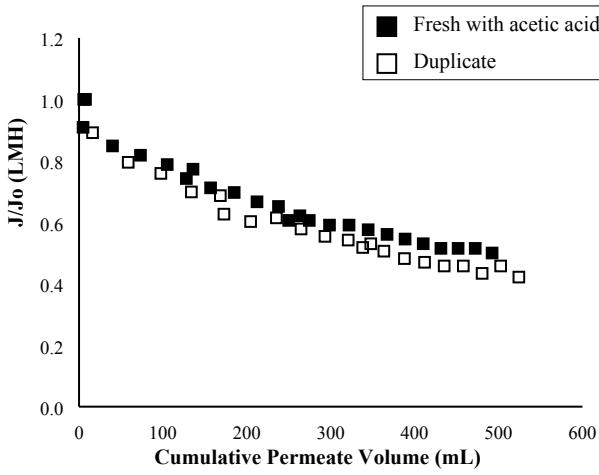
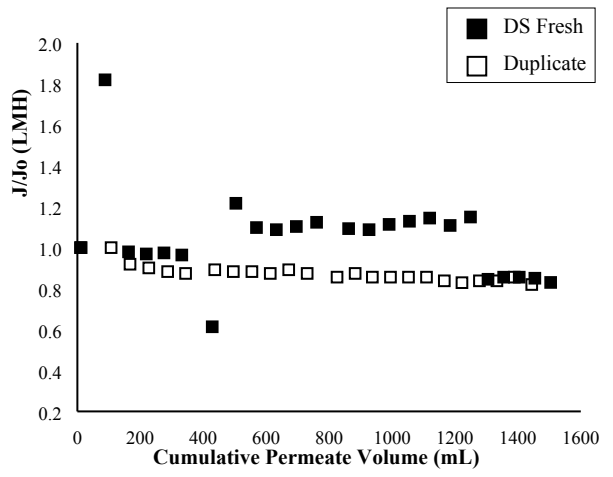
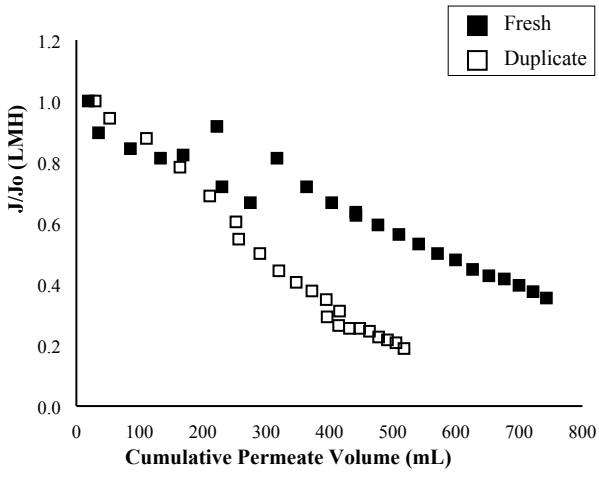
| Forward osmosis TOC content | | | |
|---|---|----------------------|------------------------------------|
| Urine Condition | TOC in Draw at t = 24 h minus urea content | Duplicate Run | Average % Permeation of TOC |
| Fresh | 391 | 43 | 6 |
| Fresh with acid | 100 | 85 | 3 |
| Fresh with base (Ca(OH)₂) | 107 | 70 | 2 |
| Fresh with base (NaOH) | 103 | 106 | 4 |
| Synthetic fresh with base (NaOH) | 24 | 35 | 5 |

Table S4: Urea concentrations and mass balance for forward osmosis and membrane distillation

Table S4 - Urea Recovery for FO and MD

| Urine Condition | FO Initial Feed (mg/L urea) | FO Initial Feed (mg urea) | FO Product (mg/L urea) | FO Product (mg urea) | FO %Recovery | MD Initial Feed (mg urea) | MD Product (mg/L urea) | MD Product (mg urea) | MD %Recovery | Concentration Factor | Final MD Concentration Compared to Urine (%) |
|---|-----------------------------|---------------------------|------------------------|----------------------|--------------|---------------------------|------------------------|----------------------|--------------|----------------------|--|
| Fresh | 9027 | 36108 | 2930 | 8204 | 23 | 6711 | 5327 | 6179 | 92 | 1.8 | 59 |
| Duplicate | 6427 | 25710 | 1670 | 4459 | 17 | 4421 | 4004 | 4084 | 92 | 2.4 | 64 |
| Fresh with acetic acid | 8826 | 35304 | 1815 | 4792 | 14 | 4002 | 2711 | 3362 | 84 | 1.5 | 31 |
| Duplicate | 6170 | 24680 | 1471 | 4008 | 16 | 4101 | 3474 | 3682 | 90 | 2.4 | 60 |
| Fresh with base (Ca(OH)₂) | 10601 | 42404 | 2179 | 5230 | 12 | 5306 | 5877 | 3802 | 72 | 2.7 | 55 |
| Duplicate | 10834 | 43336 | 2036 | 4744 | 11 | 4467 | 3832 | 3698 | 83 | 1.9 | 35 |
| Fresh with base (NaOH) | 8137 | 32548 | 1571 | 3737 | 11 | 3483 | 5958 | 2985 | 86 | 3.8 | 73 |
| Duplicate | 7894 | 31576 | 1544 | 3629 | 11 | 3279 | 4466 | 3037 | 93 | 2.9 | 57 |
| Synthetic fresh with base (NaOH) | 13732 | 54928 | 4379 | 11385 | 21 | 8730 | 9786 | 6968 | 80 | 2.2 | 71 |
| Duplicate | 13108 | 52432 | 4277 | 11098 | 21 | 9506 | 8433 | 7421 | 78 | 2.0 | 64 |

FIGURES



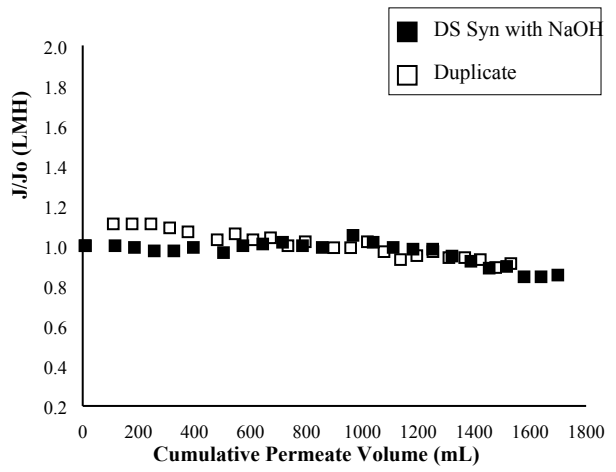
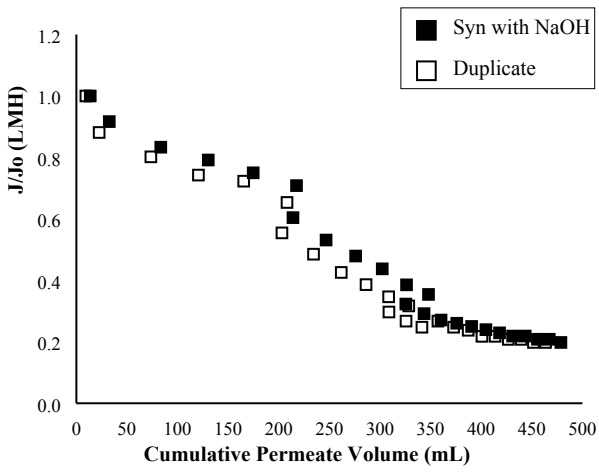
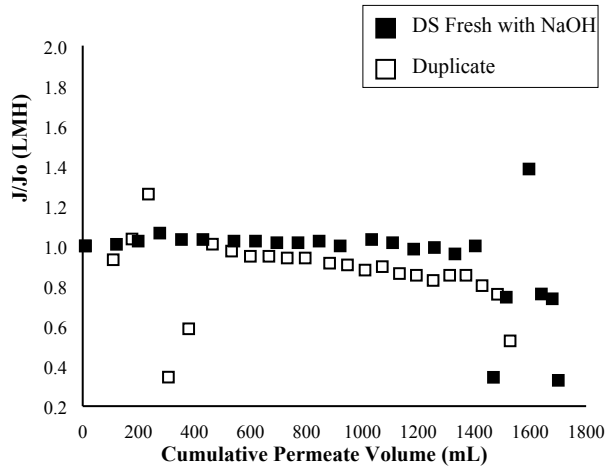
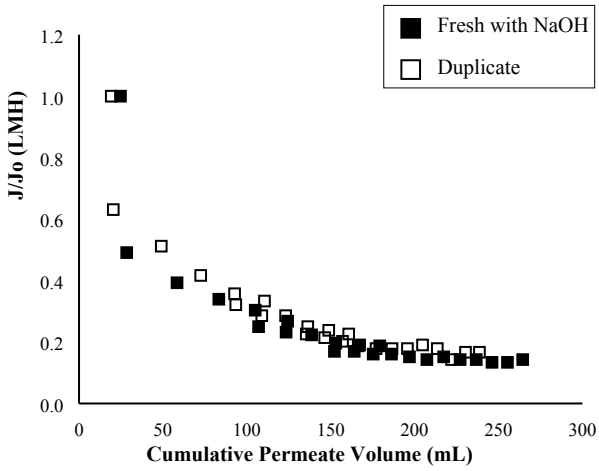


Figure S1. Duplicate membrane comparisons for each urine condition. The left column is comparisons of FO duplicate experiments. The right column is comparisons of MD duplicate experiments.

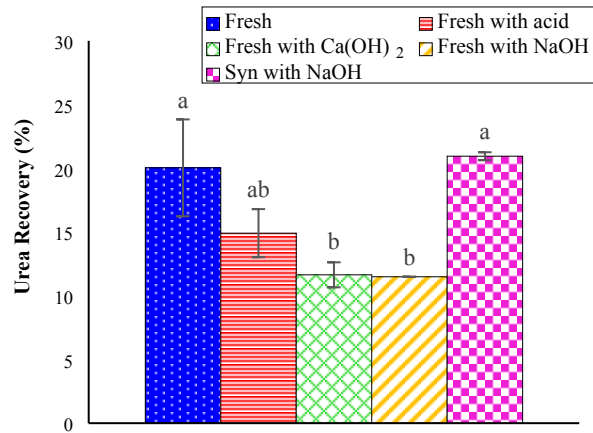
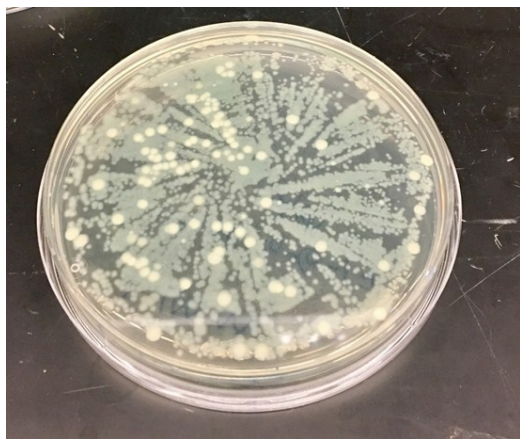
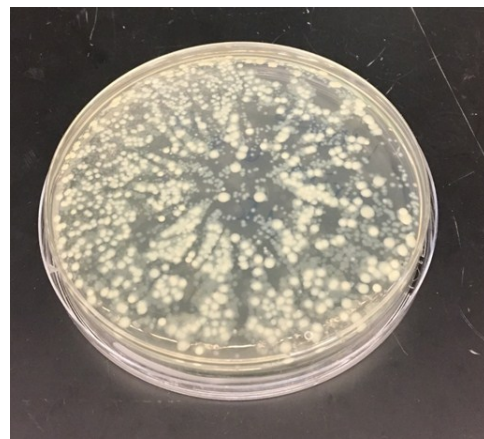


Figure S2. Urea separation percentages by forward osmosis for each urine pre-treatment condition. The graph includes the statistical grouping coming from a One-Way ANOVA test on the separation percentages. The graphed data is mean values \pm one standard deviation for duplicate runs for time 24 h.



1:100,000 = 8.26e9 CFU



1:10,000 = 5.28e9 CFU

Figure S3. Spread plates for bacteria counts from the forward osmosis membrane surface for the real fresh urine condition after 30 hours of operation. Two different dilutions were performed. CFU stands for colony-forming unit.