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Laboratory Demonstration and Preliminary Techno-Economic Analysis of an Onsite Wastewater Treatment System

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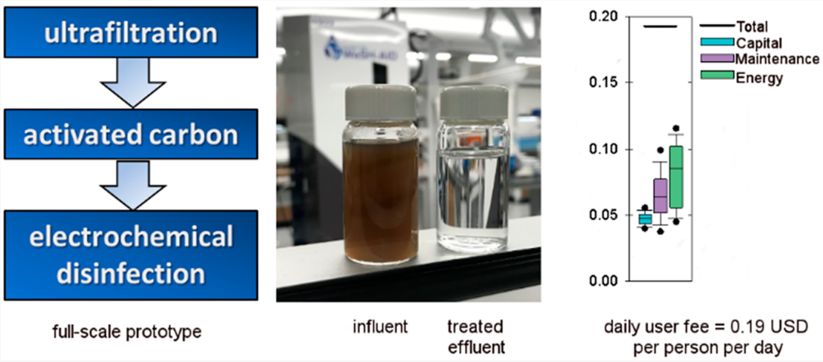

ABSTRACT: Providing safe and reliable sanitation services to the billions of people currently lacking them will require a multiplicity of approaches. Improving onsite wastewater treatment to standards enabling water reuse would reduce the need to transport waste and fresh water over long distances. Here, we describe a compact, automated system designed to treat the liquid fraction of blackwater for onsite water reuse that combines cross-flow ultrafiltration, activated carbon, and electrochemical oxidation. In laboratory testing, the system consistently produces effluent with $6 \leq \text{pH} \leq 9$, total suspended solids (TSS) < 30 mg L^{-1}, and chemical oxygen demand (COD) < 150 mg L^{-1}. These effluent parameters were achieved across a wide range of values for influent TSS (61−820 mg L^{-1}) and COD (384−1505 mg L^{-1}), demonstrating a robust system for treating wastewater of varying strengths. A preliminary techno-economic analysis (TEA) was conducted to elucidate primary cost drivers and prioritize research and development pathways toward commercial feasibility. The ultrafiltration system is the primary cost driver, contributing to >50% of both the energy and maintenance costs. Several scenario parameters showed an outsized impact on costs relative to technology parameters. Specific technological improvements for future prototype development are discussed.

KEYWORDS: *blackwater, techno-economic analysis, granular activated carbon (GAC), ultrafiltration, electrochemical disinfection, ISO 30500, nonsewered sanitation system (NSSS), onsite wastewater treatment system (OWTS)*

INTRODUCTION

It is estimated that 2 billion people lack access to basic sanitation services, and as many as 4.2 billion lack access to safely managed sanitation services.[1] Basic services can be provided by low-cost facilities, such as communal pit latrines, though the long-term maintenance and off-design use of such facilities are frequently points of failure.[2,3] Moreover, the World Health Organization's definition of "safely managed sanitation services" requires that improved sanitation facilities not be shared with other households and that the excreta produced must either be safely treated in situ or transported and treated off-site.[1] In other words, communal toilets do not meet this definition, as access to facilities is not always controlled by the people who need to use them. While transport of waste from the household (either by sewers or pump trucks) is often prohibitively expensive (and safe treatment far from guaranteed), treatment of excreta at the household level presents significant challenges particularly for urban settings, as available technologies require a large footprint and/or considerable maintenance.[4]

Due to a variety of reasons, including perceptions of odor, comfort, and social status, there is a strong user preference for flush toilets over dry toilet options, even in environments

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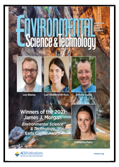

where water is often scarce.[5] Standard commercially available toilets will consume around 30 L of water per person per day (6 L flush volume, five flush events).[6] With a minimum of 15 L of water required daily per person for survival (drinking, domestic hygiene, and cooking),[7] toilet flushing alone can result in a substantial fraction of per capita potable water consumption. A distinct but related challenge in providing safe sanitation thus lies in the ever increasing prevalence of water scarcity. Recent studies show that two-thirds of the world's population currently live in areas that experience water scarcity for at least one month each year.[4] With the global demand for water expected to grow up to 30% by 2050,[8] the ability to conserve and recycle water for sanitation uses will be critical to ensuring access to safe water and sanitation for resource-constrained populations.

Sewered sanitation requires considerable amounts of water to move waste from the household to centralized treatment facilities, and often the water supplied to homes for this purpose is potable. A critical component in making flush toilets sustainable is to minimize the inputs of potable water and the distance waste and wastewater must travel. Decentralized, nonsewered sanitation systems (NSSS) can be designed such that the wastewater point-of-generation and point-of-treatment are very close to each other. NSSS can therefore enable maximal reuse of nonpotable, pathogen-free, reclaimed water under appropriate conditions.[8] Improving NSSS for deployment in rural areas and low- and middle-income countries has been the subject of intensive investigation in the past decade, and a variety of approaches have been demonstrated in laboratory and field testing, including systems employing electrochemical disinfection, membrane bioreactors, and anaerobic–aerobic biodigesters.[6,9−20] Widespread deployment and commercialization of these technologies is desired but remains challenging for a variety of reasons, including cost, limited scope of pilot testing, and regulatory hurdles. The newly introduced ISO 30500 for NSSS[21] establishes an international standard that many countries are using to inform their own requirements for NSSS. The goal of ISO 30500 is to establish the requirements for safe onsite treatment and nonpotable water reuse, and includes threshold values and/or percent reductions for specific pathogens and several effluent water quality parameters, including chemical oxygen demand (COD), total suspended solids (TSS), pH, and nutrients (see Table S1 of the Supporting Information, SI).

Here, we describe a treatment system for the liquid fraction of blackwater, which packages previously identified component processes (ultrafiltration, granular activated carbon, and electrochemical disinfection)[22] into a single, automated prototype system for onsite wastewater treatment and reuse. We present data demonstrating functionality of the system per the initial prototype design and provide a critical assessment of the technical and performance gaps with respect to the ISO 30500 standard for NSSS. The results of lab testing were also used to conduct a preliminary techno-economic analysis (TEA) of the system and its subsystem components with respect to three sources of cost (capital, energy, and maintenance). We discuss insights and recommendations for appropriate use-case scenarios and potential paths to viability for this technology.

■ MATERIALS AND METHODS

System Design and Process Logic. The full-scale, prototype system is depicted in Figure 1. The system is designed to treat 200 L of wastewater per day to accommodate the total generation rate for six users, assuming a 6 L flush volume, average of 5 flushes per user per day,[6] and 1.5 L of urine excreted per user per day.[23] The prototype consists of three subsystems operating in series: (1) ultrafiltration (UF) unit for removal of suspended solids; (2) granular activated carbon (GAC) packed bed filter for removal of soluble organic components; (3) electrochemical (EC) oxidation reactor for effluent disinfection. The UF subsystem is comprised of a feed tank plumbed to a 0.75 HP (559.3 W) centrifugal pump [Goulds, LB0712TE, 20 gpm (75.7 L min^{-1})] that delivers

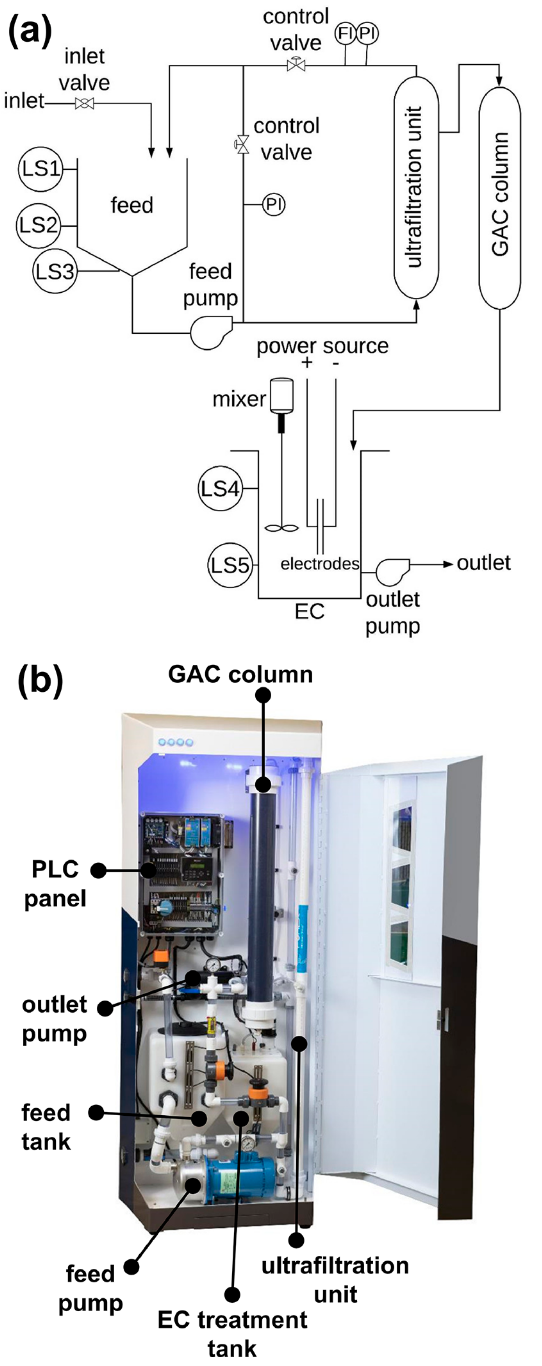

Figure 1. Schematic (a) and photo (b) of the prototype system. The schematic includes locations of level sensors (LS), flow indicator (FI), and pressure indicators (PI). The GAC column is portrayed in the down-flow configuration.

liquid to a Porex tubular membrane filter module (MME2002601VP: porous membrane, polyethylene substrate, 0.5 in. (12.7 mm) tube ID, 0.02 μm pore size, 6 foot (1.83 m) length, polyvinylidene fluoride membrane) and returns the retentate to the feed tank in a closed loop. The GAC filter is based on the design described in ref 16, with charcoal-derived GAC (8−30 mesh size, Evoqua, ~3.5 kg) packed into a 4 in. (10.16 cm) diameter PVC pipe, 100 cm in length. The outlet from the ultrafiltration unit can be connected either to the top of the GAC column to run in a gravity-fed, down-flow configuration or to the bottom of the GAC column to run in an up-flow configuration. The electrochemical cell placed at the bottom of the tank is comprised of two electrode pairs arranged in a bipolar electrode configuration (terminal anode, interstitial bipolar electrode, and terminal cathode). Each electrode was fabricated from a 4.25 × 4.25 in.^{2} (10.795 × 10.795 cm^2) titanium plate with the anode side coated with a mixed-metal oxide (MMO) catalyst. A 12 V DC power supply located within the control panel was used to apply a potential to the electrodes. The system runs on an automated batch treatment cycle consisting of an UF/GAC phase (Phase 1) followed by an EC oxidation phase (Phase 2); system processes are controlled by a programmable logic controller (PLC) based on the status of capacitive level sensors (LS Gems, #230079, L-type, nonembeddable) attached to the outsides of the tanks (Figure S1). Additional details regarding construction and operation of individual subsystems, including a complete bill of materials, can be found in the SI.

Blackwater Generation. Procedures for collection of human feces and urine from healthy donors were approved by the Duke University Institutional Review Board. Unless otherwise specified, blackwater was generated using a ceramic pedestal toilet (Glacier Bay), with 6 L tap water per flush and assuming ~1.5 L urine (divided among four flushes) and ~150 g feces (in one additional flush) per person per day,[23] for a total of five flush events.[6] Typically, blackwater was stored in a 50 L tank prior to use, which enabled some gravity settling of larger solid particles. However, advanced solids settling techniques, such as those described in our previous work,[24] were not used in this study. The liquid fraction of blackwater (i.e., the supernatant) from this 50 L tank was used for prototype testing.

Analytical Methods. Single influent and effluent samples were collected from the feed and effluent tanks, respectively, using sterile disposable serological pipettes and stored in sterile polypropylene centrifuge tubes. Total suspended solids (TSS) were measured according to EPA method 160.2. Conductivity and pH were measured using a Myron L 6PFC^E Ultrameter II. Water chemistry analyses were performed using the appropriate HACH reagent kits and methods (chemical oxygen demand, COD, HACH method 8000; total P, HACH method 8190, measured as mg L^{-1} PO_4^{3-}; reactive P, HACH method 8048, measured as mg L^{-1} PO_4^{3-}; total N, HACH method 10072; and NH_3, HACH method 10031), and results were measured with a HACH DR 900 colorimeter. A HACH DRB200 reactor was used for methods requiring digestion (COD, total P, and total N). Ultrapure water was used for samples requiring dilution prior to analysis. Samples for a three-tube most probable number (MPN) assay[25,26] were collected from the feed tank and treated water tank using clean, sterile pipettes and stored at 4 °C. See the SI for details.

Techno-Economic Analysis. A techno-economic analysis (TEA)[27] was conducted with a discounted cashflow analysis to link system performance to cost using the breakeven point. In this case, the breakeven point represents the minimum daily fee users would need to pay for the system to cover all expenses over the course of the system's lifetime. The model tracks the performance of each unit process within the system: UF, GAC, EC disinfection, controls, and miscellaneous. Categories of system costs that were included in this analysis are initial capital, operation and maintenance (O&M, excluding energy), and energy.

Model inputs included data from laboratory tests (e.g., GAC lifetime; EC power requirement), assumptions from literature (e.g., discount rate; daily flushes per person), and values that were fixed by the system design and/or product specifications (e.g., membrane surface area; GAC volume; see Tables S3−S8 for complete model inputs). Initial capital costs came primarily from construction materials (Table S9). A price adjustment was made for several items currently included in the design (Table S10) based on anticipated cost reduction through component replacement without altering performance (e.g., replacing the current pump with a smaller one). Construction materials were separated into two categories: specialized items purchased from global suppliers (using data from vendors in the United States) and items that are widely available that can be purchased in local settings where the toilet is deployed. The cost (in USD) of materials purchased locally in different countries was assumed to follow general trends captured by the Price Level Ratio (PLR).[28] The PLR estimates how many dollars are needed in the local context to buy a set of goods that would cost one dollar in the United States. For example, if the PLR is 0.4, it would cost an average of \$0.40 to purchase something locally that costs \$1 in the U.S.A. For all country-specific parameters (PLR, income tax rate, electricity price, etc.), the value(s) specific to India, the anticipated location for field testing, were used.

The system was modeled using a series of algebraic equations (see SI). Daily influent load was calculated based on the number of users and the assumed average flush volume for each user. The daily system permeate flow (through UF membranes) was fixed to be equal to the daily influent load. The number of membranes in the UF system, the GAC volume, and the energy demand for the UF, EC, and miscellaneous unit processes all vary according to the daily influent load. For example, as the influent load increases, the GAC media reaches its maximum removal capacity quicker, thus increasing the annual media consumption. The costs of media and electricity were factored into the overall system cost along with other expenses such as materials and labor. To estimate annual net profit, annualized initial capital costs (materials and construction labor), O&M costs (replacement materials and labor), and energy costs (electricity) were subtracted from the income generated by a daily user fee. An annual discount rate (3%−6%)[29] was used to adjust for the decreasing value of money over time. An income tax rate (22.5%−27.5%)[28] was applied to the gross profit (income minus expenses), with a tax credit being allotted for the depreciation of system materials. Linear depreciation was assumed for all components, and material lifetimes were assumed to be the same as the overall system unless otherwise specified (Table S11).

A preliminary scenario analysis was conducted before running an uncertainty analysis. Because the precise use scenario (one small household, multiple households, etc.) and the length of time the system will last are unknown, a

Table 1. Experimental Conditions and Initial Influent Characteristics for Datasets 1−3; Values Are Given as the Mean ± Standard Deviation, With the Range Shown in Parentheses

data set (*n*)	GAC flow	batch size (L)	pH	COD (mg L^{-1})	total N (mg L^{-1})	total P (mg L^{-1})	TSS (mg L^{-1})
1 (12)	down	10−15	8.17 ± 0.14 (7.88−8.34)	1115 ± 175 (754−1391)	277 ± 91 (130−410)	298 ± 101 (177−457)	611 ± 152 (325−820)
2 (12)	down	7.5−10	7.80 ± 0.13 (7.58−8.10)	1298 ± 104 (1073−1455)	206 ± 20 (158−234)	75.6 ± 6.1 (66.0−85.0)	98 ± 20 (81−143)
3 (14)	up	7.5−10	8.27 ± 0.30 (7.77−8.64)	757 ± 468 (384−1505)	183 ± 35 (122−248)	71.4 ± 5.8 (66.5−83.5)	126 ± 37 (61−173)
total (38)		7.5−15	*8.09 ± 0.29* *(7.58−8.64)*	*1041 ± 379* *(384−1505)*	*220 ± 68* *(122−410)*	*144 ± 119* *(66−457)*	*270 ± 250* *(61−820)*

preliminary analysis was conducted to determine the quantitative effects of changes in these parameters. The number of users was varied from 5 to 20 to represent different contexts and evaluated under four different lifetime scenarios (5, 10, 15, 20 years), while all uncertain parameters were held constant at their median value. When the number of users increased from 5 to 20, the required daily user fee decreased by $0.91. When the system lifetime was increased from 5 to 20 years, the required daily user fee decreased by $0.49. When both the number of users and the system lifetime were set to their highest values, the lowest daily user fee results ($0.27). In the second stage of the analysis (presented below), the number of users and system lifetime were both set to 20, and a full uncertainty analysis was conducted via Monte Carlo simulation with Latin Hypercube Sampling. The model was run 10 000 times, assigning random values to uncertain parameters in each run. The sensitivity of daily user fee to individual parameters was assessed via Spearman's Rank correlation coefficients.

RESULTS AND DISCUSSION

System Performance. Three data sets collected between Dec. 2018 and Feb. 2020 are presented to demonstrate performance of the system. Each data set consists of 12−16 experiments with batch volumes between 7.5−10 L. Complete data logs for each experiment can be found in the SI. Data set 1 was collected with the GAC column in the down-flow configuration immediately after commissioning of the prototype, i.e., when the GAC media was fresh. Data set 2 was also collected in the down-flow configuration, but after the GAC media had been exposed to over 1400 L of UF-treated wastewater. Data set 3 was collected in the up-flow configuration, also after the GAC media had been exposed to over 1400 L of UF-treated wastewater; data set 3 was collected to determine whether the GAC flow direction affected the effluent quality.

Table 1 summarizes the experimental conditions and initial influent characteristics for each data set; batch-to-batch differences in composition can be expected due to differences in individual excreta composition.[23] The characteristics measured here are consistent with the ranges observed in our previous studies,[24,26] given that we used a larger tap water flush volume (6 L) in this work than in those studies. The influent used in data set 1 included some liquid supernatant pulled directly from other tanks used for separate sludge settling studies, which increased the overall fecal load as reflected in the higher concentrations of TSS and total N and P compared to the other data sets. The average initial bacterial population in the influent was on the order of 10^7 MPN mL^{-1}, but ranged from 10^4 − 10^8 MPN mL^{-1} (see SI).

Figure 2 contains plots for influent and effluent pH, TSS, and COD values recorded for each experiment. Dashed lines in each plot indicate the ISO 30500 standard threshold for each parameter. The different data sets are distinguished in the plots by color, with data set 1 in black, data set 2 in orange, and data set 3 in blue. Figure 2a shows that all experiments (100%) met the ISO 30500 requirement for effluent pH (6 ≤ pH ≤ 9). The influent pH ranged from 7.58−8.64, with an average value of 8.09 ± 0.29. Effluent pH values ranged from 7.62−8.39, with an average value of 8.09 ± 0.15. A correlation (Pearson's *r* = −0.627) was observed between influent pH and effluent pH

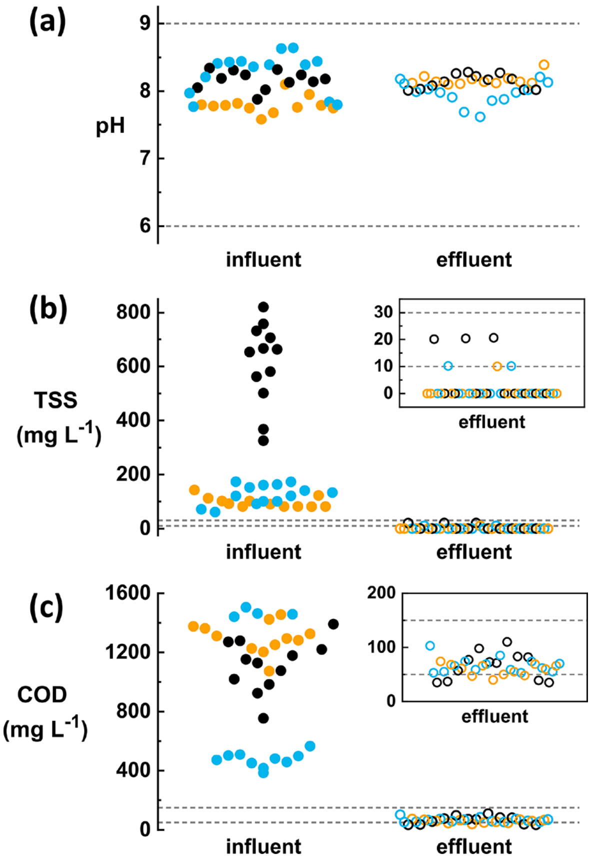

Figure 2. Measured values for (a) pH, (b) total suspended solids (TSS), and (c) chemical oxygen demand (COD) in influent (left, filled circles) and effluent (right, open circles). Insets in (b) and (c) show expanded views of the effluent plots. Individual data sets are differentiated by color (black = data set 1; orange = data set 2; blue = data set 3). Dashed horizontal lines indicate the threshold values as set by ISO 30500. Position along the *x* axis is not meaningful; points are offset from one another along the *x*-direction for clarity.

(Figure S2). The effluent TSS for all experiments (100%) met the ISO 30500 threshold for Category B reuse (≤30 mg L^{-1}), and met the threshold for Category A reuse (≤10 mg L^{-1}) for all but six experiments (88.9%).

Effluent values of COD (Figure 2c) met the ISO 30500 threshold for Category B reuse (≤150 mg L^{-1}) for all experiments (100%). Seven experiments (19.4%) met the COD threshold for Category A reuse (≤50 mg L^{-1}). There was no correlation observed between influent COD and effluent COD (see Figure S4). However, experiments meeting the Category A threshold were all performed with the GAC column in a down-flow configuration. It is interesting to note, however, that the vast majority of COD is separated from the effluent during the ultrafiltration process (see Table S2).

Reduction of total N and total P are shown in Figure 3; unlike the water quality parameters discussed previously, the ISO 30500 standards for N and P reduction are set using percent reduction values, and plots for percent reduction for each component are also included. The average total N reduction (Figure 3a) was 36.6% ± 17.1%, and the average total P reduction (Figure 3b) was 34.7% ± 8.9%. There was a strong correlation (r = 0.933; Figure S5) between the influent and effluent total N concentrations. A weaker correlation was observed for influent and effluent total P concentrations, and was lower for data sets 2 and 3 (data set 1, r = 0.782; data set 2 + data set 3, r = 0.516; see Figure S6). For both total N and total P, no experiments met the ISO 30500 % reduction standard.

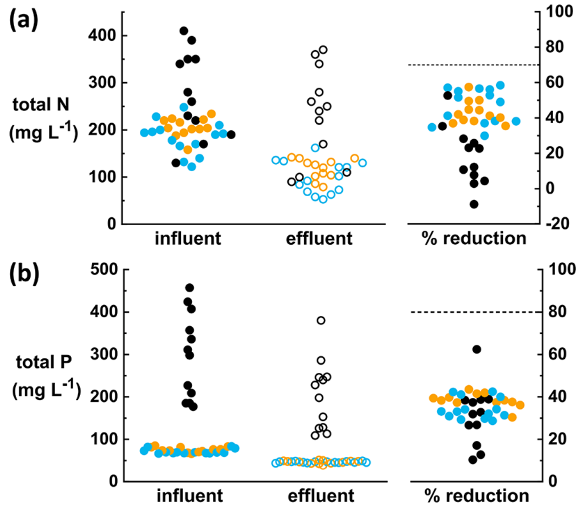

Figure 3. Measured concentrations of (a) total N and (b) total P in influent (left, filled circles) and effluent (center, open circles). Percent reduction values for the same data are plotted on the right. Individual data sets are differentiated by color (black = data set 1; orange = data set 2; blue = data set 3). Dashed horizontal lines indicate the minimum reduction values for total N and total P as set by ISO 30500. Position along the x axis is not meaningful; points are offset from one another along the x-direction for clarity.

Of particular note is that after ultrafiltration, the total N and NH_3 concentrations are nearly identical, and likewise, the total P and reactive P values are very similar (see Table S2). This means that essentially the entire organic fractions of N and P are removed during ultrafiltration, leaving almost exclusively NH_3 and orthophosphate in the effluent. The average NH_3 reduction (Figure S7) was 28.5% ± 14.1%, with a strong correlation (r = 0.806) between influent and effluent NH_3 concentrations. Reduction in reactive P (Figure S7) was fairly consistent across all the samples tested, averaging 20.0% ± 1.9%. In summary, the system falls short of the ISO 30500 requirements for reductions in total N and P, as is the case with many NSSS which rely on nonbiological treatment processes.[30] Given that UF removes the organic fractions of N and P, we are currently focused on investigating nonbiological sorptive materials and membrane separation processes for inorganic N and P reduction to meet the ISO 30500 requirements and enhance suitability of this system for water reuse applications.

To assess the ability of the system to inactivate pathogens, we employed a most probable number (MPN) serial dilution method (Figure 4a). In a majority (23/38) of experiments the effluent MPN was below 5 mL^{-1}, with 18 experiments falling below the detection limit of the assay (3 mL^{-1}). Among the remainder of the experiments, there is a strong relationship between the effluent conductivity and effluent MPN (Figure 4b), with effluent MPN values increasing as the conductivity drops below ~2 mS cm^{-1}. This is likely attributable to a lower chloride concentration available for conversion to chlorine in the EC process. We have found in separate experiments (data not shown) that the EC process can be made to consistently achieve disinfection to the detection limit with low chloride concentrations by running at higher voltages and/or for longer periods of time. We plan to modify the control algorithm accordingly in future embodiments of this technology, as well as test the system for efficacy in inactivation of the specific pathogen surrogates indicated by ISO 30500.[21]

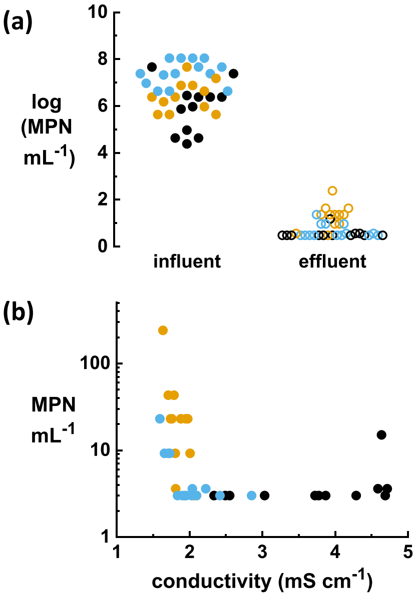

Figure 4. (a) Measured bacterial counts in influent (left, filled circles) and effluent (right, open circles). Individual data sets are differentiated by color (black = data set 1; orange = data set 2; blue = data set 3). Position along the x axis is not meaningful; points are offset from one another along the x-direction for clarity. (b) Plot demonstrating the relationship between effluent conductivity and effluent bacterial count.

Energy Consumption. Table 2 summarizes energy consumption measured during operation. The energy required to run the UF and EC subsystems is shown, along with the total energy requirement which is the sum of these two

Table 2. Energy Consumption of the Prototype System and Its Subsystems[a]

data set (n)	UF (kJ L^{-1})	EC (kJ L^{-1})	system total (kJ L^{-1})
1 (12)	498 ± 140 (358–722)	14 ± 2 (10–15)	512 ± 141 (368–736)
2 (12)	711 ± 125 (584–932)	17 ± 3 (15–20)	728 ± 125 (599–951)
3 (14)	728 ± 206 (538–1171)	19 ± 1 (18–20)	747 ± 206 (557–1190)
total (38)	*650 ± 191 (358–1171)*	*17 ± 3 (10–20)*	*667 ± 192 (368–1190)*

[a] Values are given as the mean ± standard deviation, with the range shown in parentheses.

subsystems. The prototype is connected to electrical supply through a standard U.S. wall outlet (120 V). The typical electrical power consumed during UF (1.28 kJ s^{-1}) and EC (75 J s^{-1}) stages was measured using a digital outlet power meter and used to estimate energy consumed per volume processed based on run times. The UF subsystem requires an average of 650 kJ to process each L of wastewater. The energy consumption for UF in data set 1 is much lower (498 kJ L^{-1}) than for data sets 2 and 3 (711 and 728 kJ L^{-1}, respectively). As data set 1 was collected just after commissioning of the prototype, this increase in UF energy for later data sets is likely due to partial fouling of the UF membrane after prolonged use. Operation of the EC oxidation process requires 17 kJ L^{-1} on average, accounting for ~2.5% of the total energy.

It is important to note that for the first experiment run on any given day in up-flow configuration (data set 3), the UF runtime increases by about 35 min, which is the amount of time required to fill the interstitial volume in the GAC column. Despite this, the average UF run time is not dramatically higher than in a down-flow configuration (data set 2). The batch-to-batch variation in UF run time is greater in the down-flow configuration (60–112 min; n = 12) when compared to that for the up-flow configuration once the GAC column is full of liquid (56–65 min; n = 10), perhaps due to the somewhat random path taken by liquid as is travels via gravity down through the GAC column. To increase consistency of the UF run time, liquid could be fed through the GAC column in an up-flow configuration with a one-way check valve added before the column influent port to prevent draining of the column when the system is idle.

Techno-Economic Analysis. A techno-economic analysis was performed to examine viability of the system in its current form and to prioritize areas for improvement. We assessed the daily user fee, which includes capital, maintenance, and energy costs, for the overall system, as well as for individual subsystem components. In addition to the water treatment subsystem components (UF, GAC, and EC oxidation), two additional subsystem components were included in the TEA (controls and miscellaneous items, including housing, air vent, power connector, etc.). A bill of materials is included in the SI and indicates the component category for each item.

As designed, the median required daily user fee is approximately \$0.19 per user per day (\$0.13–5th percentile, \$0.26–95th percentile; Figure 5). The overall cost is distributed relatively evenly among the three cost categories. The UF subsystem is the most expensive component, making up about 58% (50%–5th percentile, 63%–95th percentile) of the total cost. As expected, the UF subsystem is the largest contributor to energy cost, making up 71% (58%–5th percentile, 83%–95th percentile) of the total. The UF subsystem also drives the cost of maintenance, making up 61% (48%–5th percentile, 72%–95th percentile) of the total maintenance cost. No single subsystem drives the capital cost. Capital costs from the UF subsystem make up 31% (29%–5th percentile, 32%–95th percentile) of total capital costs, while capital costs from the controls system make up 24% (23%–5th percentile, 26%–95th percentile). Although material costs are highest for the miscellaneous subsystem, a large portion of the miscellaneous materials can be purchased in the local context where items can be purchased for less than they would cost in the U.S.

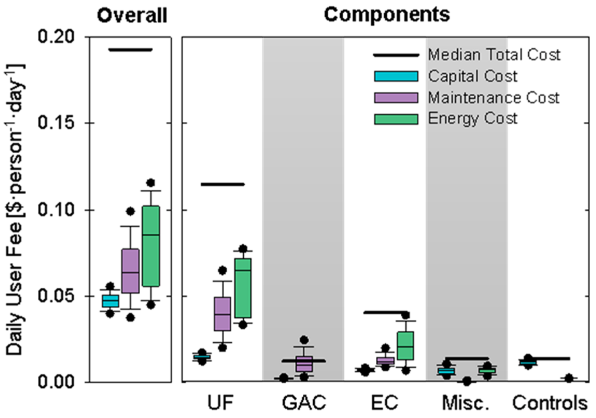

Figure 5. Daily user fee for the overall system (left) is broken down into five components (right). The overall daily user fee and components are separated into three cost categories (differentiated by color). The capital cost (blue) consists of the material and labor costs associated with the construction of the system. The maintenance cost (purple) is made up of the cost of replacement materials and labor for replacement and routine maintenance. The cost of the electricity required to power the system makes up the energy cost (green). The values were gathered by varying uncertain parameters 10 000 times. Boxplot tails represent the 10th and 90th percentiles, and dots represent the 5th and 95th percentiles.

The TEA revealed several clear opportunities to reduce the overall system cost. Given the large contribution of the UF system to the energy cost, alternative filter and pump configurations are being investigated to reduce the energy consumed on a per volume basis, and insights from these studies will be incorporated into the next iteration of this technology. Preliminary results indicate that the energy consumption of the UF system could be reduced by as much as an order of magnitude by increasing the membrane surface area and/or downsizing the pump. While increasing the membrane area is likely to increase the capital cost, this would be offset by significant reductions in energy cost. Similarly, two large contributions to the capital cost are the miscellaneous category (which includes a steel housing) and controls (currently PLC). These costs could be reduced by using less expensive materials for the housing or forgoing a housing in favor of a rack-mounted system, and replacing the PLCs with embedded controls (see Table S10).

The sensitivity analysis identified flush frequency as the most impactful parameter for three of the four outputs (Figure 6). This is due to a high level of uncertainty (1–7 flushes per day)[23] around the parameter and its impact on system sizing

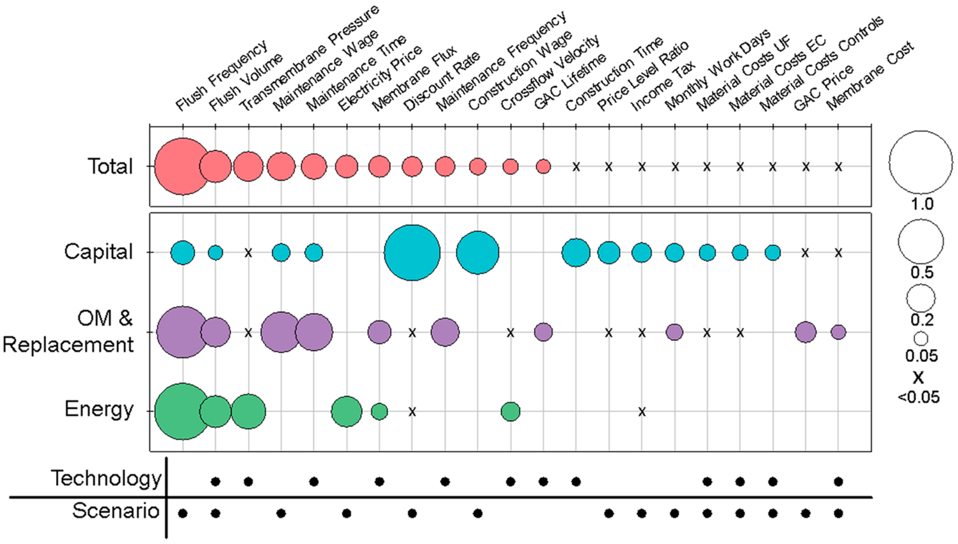

Figure 6. Bubbles represent the magnitude of Spearman's rank correlation coefficients for uncertain parameters with a coefficient ≥0.05 for the overall required daily user fee and the three cost phases. An *x* indicates that the parameter does affect the cost phase but has a Spearman's rank correlation coefficient value lower than 0.05. The parameters are divided into two categories. Technology parameters can be adjusted by design and innovation. Scenario parameters depend on the market, user behavior, or other factors that cannot be adjusted by design. Some parameters are characterized as a technology and scenario parameter. For example, flush volume is classified as a technology and scenario parameter. In this case, the system is designed to require a certain volume of flush water, but users ultimately determine the volume of water dispensed into the system after use.

and energy consumption. While scenario parameters cannot be optimized directly, they can be used to inform decision making regarding the implications of potential deployment sites. For instance, selecting deployment locations that are close together (potentially reducing travel time of maintenance workers) and with lower electricity costs may increase the likelihood of financial viability. Technology parameters, however, can be optimized directly. The flush volume could be reduced by attaching the system to a low-flush/high-efficiency toilet. Simplifying the system could reduce the time and frequency of routine maintenance; thus, decreasing the associated labor cost. For example, the size of the GAC column could be increased to minimize GAC replacement. Streamlining the initial assembly process by providing explicit assembly instructions and/or prefabricated parts could further reduce the cost of labor needed to construct the system.

Prototype Assessment and Outlook for Implementation. When selecting a wastewater treatment technology, it is critical to determine what is the "best fit" for any particular scenario and the given constraints, rather than searching for a "one-size-fits-all" solution.[8,31] This prototype was designed to facilitate nonpotable water reuse through wastewater treatment without requiring changes in user behavior and while meeting the user preference for water-based toilet systems, and is intended for use in conjunction with other systems that provide coarse solid/liquid separation to remove solid objects (e.g., menstrual pads) as well as the bulk of solid fecal material for other modes of treatment. Thus, while the laboratory testing reported here did not include toilet paper during the wastewater generation process—making the results most immediately relevant for "washing" cultures—we expect this system to perform comparably well in "wiping" cultures when paired with appropriate solid–liquid separation and solid treatment. In comparison to some other onsite treatment approaches (e.g., urine diversion; composting toilets), our system is user-interface agnostic, is compatible with commercially available squat or pedestal style toilets, and has potential to be installed as a retrofit to some existing structures.

The biggest shortcomings of the current design are inadequate nutrient removal and the high energy requirement. Many nonbiological technologies struggle to achieve the high water-reuse standards set for nutrient removal,[30,31] and this is an area of ongoing research and development in our group. In its current form, the prototype requires a stable electrical grid or a solar array that is larger than practical for dense urban areas. Further development is required to reduce the overall energy cost, and the preliminary TEA provides guidance for where to focus these efforts (primarily on optimization of the UF system).

Laboratory testing demonstrates that the system consistently produces effluent with $6 \leq \mathrm{pH} \leq 9$, TSS < 30 mg L^{-1}, and chemical oxygen demand COD < 150 mg L^{-1}, even across a wide range of influent values for TSS (61–820 mg L^{-1}) and COD (384–1505 mg L^{-1}). The successful treatment of wastewater of varying strengths indicates that the system will be compatible with a range of solid/liquid separation methods and solid treatment systems, e.g., septic tanks or anaerobic digesters. We expect that our system will have especially high value in markets where water is used for cleansing, due to its ability to handle relatively large volumes of liquid, including in cultures where pour-flushing is practiced. A recent study from our group found that water for pour flushing averaged 7 L per use in India.[32] Our current system was sized to treat 200 L per day, which is slightly oversized assuming a 6 L flush × 6 people × 5 flushes = 180 L, but slightly undersized assuming the same usage in a pour flush scenario with 7 L flush × 6 people × 5 flushes = 210 L. The daily capacity of the system could be increased to meet the needs of a pour-flush scenario by increasing the UF membrane surface area. However, the preliminary TEA identified the flush volume and frequency as high impact factors on the total system costs. The robustness of the system to variable influents means that commercially available low-flush-volume toilets could be used with the current system in order to decrease costs. Due to the lack of biological components which require a constant feed of fresh influent to maintain performance, our system could also be suitable for scenarios where toilet use is infrequent (e.g., remote, sparsely populated areas).

It is also important to acknowledge the limitations of laboratory-based testing for a system that will ultimately be expected to run frequently (or constantly) over a usage lifetime of years, and whose functionality is critical to the health and well-being of its users. In particular, though many of the batch trials reported here were run consecutively on the same days (see raw data logs provided in the SI) to simulate continuous usage, it was not possible to consistently simulate the designed-for daily usage in the laboratory. Field trials are therefore indispensable for testing under sustained realistic and high-use conditions, identifying critical failure modes, and defining maintenance/replacement requirements.[19,20] Of particular concern for this system are the maintenance requirements for the UF subsystem, specifically: (1) the performance of the membrane over time and its recoverability via chemical cleaning and/or backwashing; (2) the frequency with which such maintenance will need to be performed to maintain acceptable performance; (3) the volume of suspended solids accumulated in the feed tank and the frequency with which they will need to be removed, e.g., to a digestor or other solids remediation/containment system; and (4) the specific capacity and maintenance requirements for that solids remediation/containment system. These are the primary areas of focus of a field trial underway that will be reported in a future publication.

Ultimately, adoption of this technology will depend on meeting the needs and preferences of the end-user at an affordable cost. For example, the maintenance tasks noted above will need to be infrequent, of low technical complexity, and require only sustainable and readily available materials. Much of this can be accomplished through automation of processes, e.g., periodic backwashing of the UF subsystem and return of settled solids from the feed tank to a solids remediation system. Data collected from long-term, continuous field testing will inform process automation and refinement of prototype design. In concert, further techno-economic analyses will guide value engineering efforts and careful selection of target markets to achieve the cost reductions required for sustainable deployment.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c02755.

Supplementary details of prototype design, laboratory testing, and techno-economic analysis; Figures S1−S9; and Tables S1−S11 (PDF)

Raw laboratory testing data (XLSX)

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Notes

The authors declare no competing financial interest.

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