Feasibility of anaerobic membrane bioreactors (AnMBR) for onsite sanitation and resource recovery (nutrients, energy and water) in urban slums

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ABSTRACT

Slums are challenging locations for sanitation technologies. High population densities, a lack of water and electricity infrastructure, and space constraints combine to ensure that many traditional waste treatment technologies fail when implemented in this context. This paper proposes the use of anaerobic membrane bioreactors (AnMBRs) for slum sanitation. AnMBRs allow for localized water reuse, high quality treatment, and energy production at the point of treatment. A water, energy, nutrient, and mass balance was conducted on a theoretical AnMBR directly coupled to a public toilet. The combined system would be capable of recycling its water for use in toilet flushing and would be capable of providing enough energy to power both the toilet and AnMBR operation. The addition of food waste to the feed would help to ensure process stability and energy production by the AnMBR. Ammonia accumulation within the system would have to be managed through struvite precipitation, ion exchange, oxidation, plant uptake or other means. Generated biogas can be converted into heat and/or electricity using small scale gas generators. AnMBR technology has high potential for success in slum settings, if considerations for maintenance and supplies are made as part of the design and system delivery.

Key words | anaerobic membrane bioreactor, AnMBR, public toilets, slum sanitation

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INTRODUCTION

Slum dwellers are some of the most vulnerable and impoverished citizens of urban centres in developing countries. Greater job prospects and the amenities of cities lure rural residents into urban areas where they often find themselves living in the squalid conditions of slums. This trend can be observed in countries such as Rwanda, Nigeria, Uganda, and Bangladesh where more than 50% of the urban population live in informal housing settlements (United Nations 2013). Slum dwellers are at high risk of the transmission of waterborne diseases due to inadequate water and sanitation infrastructure (Holden 2008), a problem that is compounded by high population densities. Development of appropriate sanitation technologies needs to take into consideration the unique challenges found within slums. These challenges include: high user rates of individual and shared sanitation facilities, insufficient water and electricity connections, and land scarcity leading to the requirement of small systems. In Kibera, a slum in Nigeria, it was reported that up to 150 people per day share a single pit latrine (Schouten & Mathenge 2010). Higher rates of up to 650 people were observed using a single toilet block (eight or nine toilets per toilet block) in Kampala, Uganda (Katukiza *et al.* 2010). High user rates, as observed in these two studies, easily overwhelm traditional decentralized wastewater treatment systems such as pit latrines, leach pits, composting toilets, and septic tanks. Due to a lack of government investment, most slums have unreliable or non-existent water and electricity infrastructure. This makes pour-flush and active treatment systems almost impossible to implement. An additional constraint that impedes adequate sanitation is land scarcity. Treatment systems that require larger footprints, such as wastewater lagoons, are impractical due to space limitations.

While most toilets and treatment systems fail within slums, this unique context offers an opportunity for the development of a completely off-grid treatment system that is capable of handling high user-loads within a small footprint. Anaerobic membrane bioreactors (AnMBRs) have a high potential for achieving this desired goal. Defined simply, an

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AnMBR is a combination of an anaerobic bioreactor coupled with a membrane filtration process. AnMBRs are able to concentrate and retain the microbial biomass within the reactor, which leads to more active and efficient microbial performance. This trait allows AnMBRs to be used in areas where space is a major constraint. AnMBRs are also capable of treating high-strength, particulate-laden wastewaters which are expected from public toilets, as they contain little to no dilution water coming from appliances and other grey water sources (Liao *et al.* 2006; Fenner *et al.* 2007).

Decentralized AnMBRs allow for localized reuse of wastewater for flushing toilets or irrigation purposes. Reusing wastewater for toilet flushing would allow pour-flush toilets to be used in arid areas or in areas lacking reliable water connections. The generation of biogas and use of solar energy can allow the system to work in areas that lack electricity infrastructure. AnMBRs also enable localized reuse of water and nutrients, thereby decreasing the environmental impact of providing sanitation. This study investigates the theoretical feasibility of a completely integrated off-grid AnMBR and public toilet for decentralized water, energy and nutrient recovery within the context of a slum. The purpose of this study was to calculate the energy, water, mass and nutrient balance of a combined public toilet and AnMBR. The balance was used to determine if the energy content within wastewater can fully support the operation of the AnMBR and to highlight any potential problems related to their complete integration.

MATERIAL AND METHODS

A steady-state water, energy and mass balance, along with an elemental carbon, nitrogen and phosphorus balance, was performed for an integrated system of an AnMBR treating wastewater from a public toilet. For the model, water treated by the AnMBR is then used for toilet flushing in the public toilet. The combined toilet-AnMBR system is powered by the combination of solar and biogas energy. Public toilet data were acquired from Eram Scientific Solutions (ESS), a company based out of Kerala, India, which manufactures and installs automated public toilets (eToilets). At the time of writing, ESS had installed over 400 eToilets servicing urban populations throughout India. These eToilets have a number of sensors installed on them to monitor usage and toilet cleanliness. This information is reported to the company's headquarters in Thiruvananthapuram, Kerala. From these headquarters, maintenance crews are dispatched in the event of a user's complaint or a system malfunction. The sensor data also activate automated cleaning procedures that help to reduce the need for human labour. Urination and defecation events were distinguished by ESS according to the duration of each individual event. Events lasting more than 5 min were assumed to be defecation events and anything under 5 min was assumed to be a urination event. For this study, it was assumed that defecation events also included urine addition. On average, 40% of public toilet users used the facility to defecate, while 60% of events were urination events. Based on eToilet usage records, it was assumed that up to 100 discrete events occurred per day per toilet. For each event, 1 L of rinse water was used for personal hygiene (toilet paper was not used). The assumptions and characteristics of the wastewater can be found in Table 1.

The volume of water used for toilet flushing, platform rinsing and ablution were obtained from ESS and combined with the volumes that would be added from the defecation and urination events. The daily flow from the toilet was estimated at 628 l/day. The chemical oxygen demand (COD), nitrogen, and phosphorus loadings to the system were then calculated using the daily per capita waste characteristics, number of events per toilet, and the fraction of waste left per person per event (termed the 'event wastage fraction'). From the loading and volume estimations a final wastewater strength was calculated to be 2.7 g COD/L, making it much higher than typical domestic wastewater (0.4–0.6 g COD/L). In addition to being stronger than traditional wastewater, this wastewater is estimated to have a higher percentage of biodegradable COD due to its proximity to the waste source and due to the lack of toilet paper and cleaning chemicals entering the system.

Once the final wastewater characteristics were estimated, an AnMBR was designed to treat the wastewater of the eToilet while recovering energy, water and nutrients. The primary purpose of the AnMBR was to recycle water to supply the needs of the eToilet, with a secondary aim of delivering enough energy to power the AnMBR and the electronic toilet. For reactor sizing, a moderate organic loading rate (OLR) of 1 gram of COD/L/d was used to help ensure biological stability. The reactor biomass concentration was assumed to be 35 g/L as total solids (TS). Additional parameters used for the reactor design can be found in Table 2.

To enhance pathogen destruction and disintegration/hydrolysis of waste material within the reactor, the feed was designed to be pre-heated using incoming solar radiation. Average solar insolation values for Thiruvananthapuram, Kerala were used to estimate the surface area required to heat all incoming feed to 60 °C for a minimum of 20 minutes. Average winter temperatures for Kerala were used to

Table 1 | Feed characteristics for the AnMBR

Feed assumptions and characteristics (100 events per day per toilet)

Parameter	Value	Unit	Ref
% Users defecating	40.0%	Of total events	
% Users urinating	95.0%	Of total events	
Moisture content of faeces	73.0%		Nishimuta *et al.* (2006)
Avg. defecation water volume	0.11	L/capita/d	Jönsson *et al.* (2005)
Avg. urination water volume	1.4	L/capita/d	Jönsson *et al.* (2005)
Total COD of urination	8.5	g/capita/d	Jönsson *et al.* (2005)
Soluble & biodegradable COD of urination	7.23	g/capita/d	Jönsson *et al.* (2005)
Total nitrogen of urination	11	g/capita/d	Jönsson *et al.* (2005)
Total COD of defecation	37.3	g/capita/d	Jönsson *et al.* (2005)
Total phosphorus from urination	0.9	g/capita/d	Jönsson *et al.* (2005)
Soluble & biodegradable COD of defecation	5.2	g/capita/d	Jönsson *et al.* (2005)
Total nitrogen of defecation	1.5	g/capita/d	Jönsson *et al.* (2005)
Total phosphorus from defecation	0.5	g/capita/d	Jönsson *et al.* (2005)
% Defecation captured by toilet	100%	Of daily generation	Heaton *et al.* (1992)
% Urination captured by toilet	25%	Of daily waste	
Flush volume for urination	1	L/event	
Flush volume for defecation	4	L/event	
Rinse water for personal hygiene	1	L/event	
Wastewater characteristics based on assumptions			
Total solids	3.5	g TS/L	
Total suspended solids	2.4	g TSS/L	
Total dissolved solids	1.1	g TDS/L	
Volatile solids	1.8	g VS/L	
Volatile suspended solids	1.1	g VSS/L	
Volatile dissolved solids	0.7	g VDS/L	
Total COD	2.7	g COD/L	
Soluble biodegradable COD	0.6	g COD/L	
Soluble inert COD	0.05	g COD/L	
Particulate biodegradable COD	1.9	g COD/L	
Particulate inert COD	0.18	g COD/L	

determine the minimum solar collector footprint required (Hegde & Ramachandra 2012). Beyond the pretreatment, the bioreactor was operated at ambient temperatures to minimize additional energy inputs. Biological performance, biogas production, and waste rates were determined using microbial kinetics from Rittman & McCarty (Rittmann & McCarty 2001). A multiple barrier approach is used to enable multi-log pathogen destruction to ensure maximum microbial safety for water reuse: (1) thermal pretreatment of feed; (2) pathogen elimination during anaerobic digestion; (3) filtration through 0.03 μm ultrafiltration (UF) membrane; (4) post-chlorination of permeate (to suppress microbial regrowth during storage); and (5) biosolids and trash destruction via occasional onsite incineration. While this level of processing may seem excessive, a multiple barrier approach ensures that the wastewater can be safely reused at a decentralized level. Many decentralized technologies lack constant supervisor oversight, so a stronger reliance on multiple barriers is necessary.

The design of the membrane filtration unit was modelled after the external tubular UF membranes used by Prieto *et al.* (2013). These membranes were selected due to their ease of maintenance and robust performance in the industrial

Table 2 | AnMBR system design and operation parameters used for the mass and elemental balance

Anaerobic membrane bioreactor system design and operational parameters	
Reactor type	Plug flow – partially stirred
Reactor volume	1,714 L
Design organic loading rate	1 g COD/L/d
Design hydraulic retention time	2.1 d
Design solids retention time	140 d
Initial seed biomass concentration	20 g/L
Membrane unit design flux	2 L/m^2/h (LMH)
Membrane material, pore size	PVDF, 0.03 μm
Membrane location, type	External, tubular
Membrane fouling control	Backwash, gas sparging, relaxation
Thermal pretreatment temperature	60 °C
Reactor solids concentration	35 g/L as total solids
Waste biosolids concentration	50 g/L as total solids
Reactor solids wasting flow rate	8.7 L/d

wastewater treatment sector. To guarantee membrane performance, a low flux of 2 LMH was used to calculate the required membrane surface area of 13.2 m^2. To reduce the energy demand associated with membrane feed pumping, a low cross-flow velocity (CFV) of 0.02 m/s was selected, with additional measures implemented to prevent clogging of the membrane tubes. The energy demand required for pumping was calculated according to the membrane surface area and the required CFV, as well as for permeate pumping and the system feed pumping. To ensure electricity demand was met during reactor start-up, a photovoltaic (PV) system with battery storage was designed to supply the system with its electrical needs. The PV system was designed using the National Renewable Energy Lab's Solar Advisory Model program (SAM) and typical solar insolation values found in Kerala, India. Biogas produced by the reactor was assumed to be stored within a 1 m^3 gas bag and was periodically used to fuel a 600 watt generator with an overall energy efficiency of 20%. Accumulated biosolids were disposed of through occasional solar drying and onsite incineration. Many of the assumptions used to calculate the energy values can be found in Table 3.

Table 3 | Energy assumptions and calculations used to determine the energy balance of the combined system

Energy assumptions			
COD electron equivalent	0.125	mol e/g COD	
Avogadro's number	6.02E + 23	atoms/mol	
Ampere electron equivalent	6.24E + 18	e/s	
Fraction of electrons reserved for energy (fe)	0.95	–	Rittmann & McCarty (2001)
% CH_4 in biogas	65%	–	Lettinga (1995)
CH_4 yield	0.350	L CH_4/g COD	Rittmann & McCarty (2001)
Heating value of CH_4	52.8	kJ/g	
Biogas mean molecular weight	25.8	g/mol	
Peak daylight hours (winter)	4	h	Hegde & Ramachandra (2012)
Peak daylight hours (average)	6.5	h	Hegde & Ramachandra (2012)
Solar PV yield	193.17	W/m^2	Goswami *et al.* (2000)
Solar PV performance ratio	0.7	–	Goswami *et al.* (2000)
Density of wastewater	1.01	kg/L	
Feed preheating temperature	60	°C	
Heat exchange efficiency	80%	–	
Specific heat capacity of water	4.1813	J/g/K	
Solar insolation (average)	5.6	kWh/m^2/d	Hegde & Ramachandra (2012)
Solar insolation (winter)	4.8	kWh/m^2/d	Hegde & Ramachandra (2012)
Solar thermal efficiency	65%	–	Goswami *et al.* (2000)

In addition to this base scenario, a second scenario was simulated in which food waste was added to the AnMBR for co-digestion. Food waste addition is beneficial as it improves biogas yields and reduces the environmental impact of inadequate food waste disposal. Increasing biogas yields improves the overall energy balance of the combined system while making it more resilient to environmental perturbations that would affect photovoltaic energy production. Food waste generation, availability, and composition is highly site specific. In some locations, existing solid waste disposal practices will compete for this resource, while in other locations it will be easily accessible. For this scenario, food waste was assumed to be readily available and highly biodegradable. For this scenario, the food waste was added to the same sized reactor as described in Scenario 1, which increased its design organic loading rate to 8 g COD/L/d. The food waste characterization can be found in Table 4.

RESULTS AND DISCUSSION

The mass, energy and water balance shows favourable results in that an AnMBR is theoretically capable of providing enough energy to sustain itself and the electronic toilet, under the conditions stated, as an off-grid process. Assuming stable state performance of the anaerobic reactor, permeate quality and volume should be adequate in providing the flush water used within the public toilet. A summary of the water–energy–mass balance for Scenario 1 can be found in Figure 1. The majority of the energy required for the combined system comes from preheating the incoming feed to 60 °C. During the summer months, this heating demand is 4.3 kWh/day and increases to 5.0 kWh/day during the winter months. To provide for this heating requirement, a solar heater would have to be a minimum of 0.8 m^2 in size. To guarantee adequate heating, other low-grade heat sources can be combined to heat the feed water. For example, the use of exhaust heat from the biogas generator can help reduce the footprint required for a solar thermal collector. The total electricity requirements of the AnMBR amounted to 3 kWh/day while the electricity requirement of the toilet was 3.6 kWh/day. The total energy demand for the AnMBR would be 8 kWh/day; this figure includes the 5 kWh/day thermal requirement and the 3 kWh/day electrical demand.

Table 4 | Food waste characteristics and assumptions

Food waste characteristics and assumptions

Parameter	Value	Unit
Total solids	309.0	g/L
Total suspended solids	256.6	g/L
Total dissolved solids	52.4	g/L
Volatile solids	263.5	g/L
Volatile suspended solids	224.0	g/L
Volatile dissolved solids	39.5	g/L
Total COD	482.2	g/L
Soluble COD	231.5	g/L
Soluble biodegradable COD	214.9	g/L
Soluble inert COD	16.5	g/L
Particulate COD	250.7	g/L
Particulate biodegradable COD	233.3	g/L
Particulate inert COD	17.4	g/L

Source: Zhang *et al.* (2007).

The nutrient and element balance, featured in Figure 2, shows an estimated 331.3 grams of nitrogen entering the system per day. As most of this nitrogen would be converted to ammonia, which would accumulate within the reactor, ammonia inhibition would be of serious concern to the biological performance of the system. Odour in the recycled water is another potential concern. Chemical recovery, including the use of zeolite for ion exchange, is a potential avenue for removing ammonia from the system. The ammonia laden zeolite could then be sustainably used as a fertilizer. Another strategy for ammonia removal via plant uptake is fertigation, i.e. direct coupling of membrane permeate with hydroponics or algae cultivation (Prieto *et al.* 2013; Calabria 2014). The majority of the incoming 629.3 grams of carbon would be routed into biogas and biomass production. Through combustion of the biogas and incineration of the waste biosolids, all of the biodegradable carbon will be routed towards flue gas. Of the 42.4 grams of phosphorus entering the system on a daily basis, 37.7 grams can be captured for reuse as struvite. While struvite precipitation would also help to reduce nitrogen concentrations, it would require the constant addition of magnesium. Because the water is constantly recycled by the combined system, other minerals and salts should also be modelled as they would eventually accumulate within the reactor and have the potential to affect the biological treatment or cause scaling in plumbing.

Under Scenario 2, with the addition of food waste, the energy balance shifts towards excess energy production. Under this scenario, the energy demand of the AnMBR increases as it has to account for heating and processing of the food waste. The total energy demand for the AnMBR

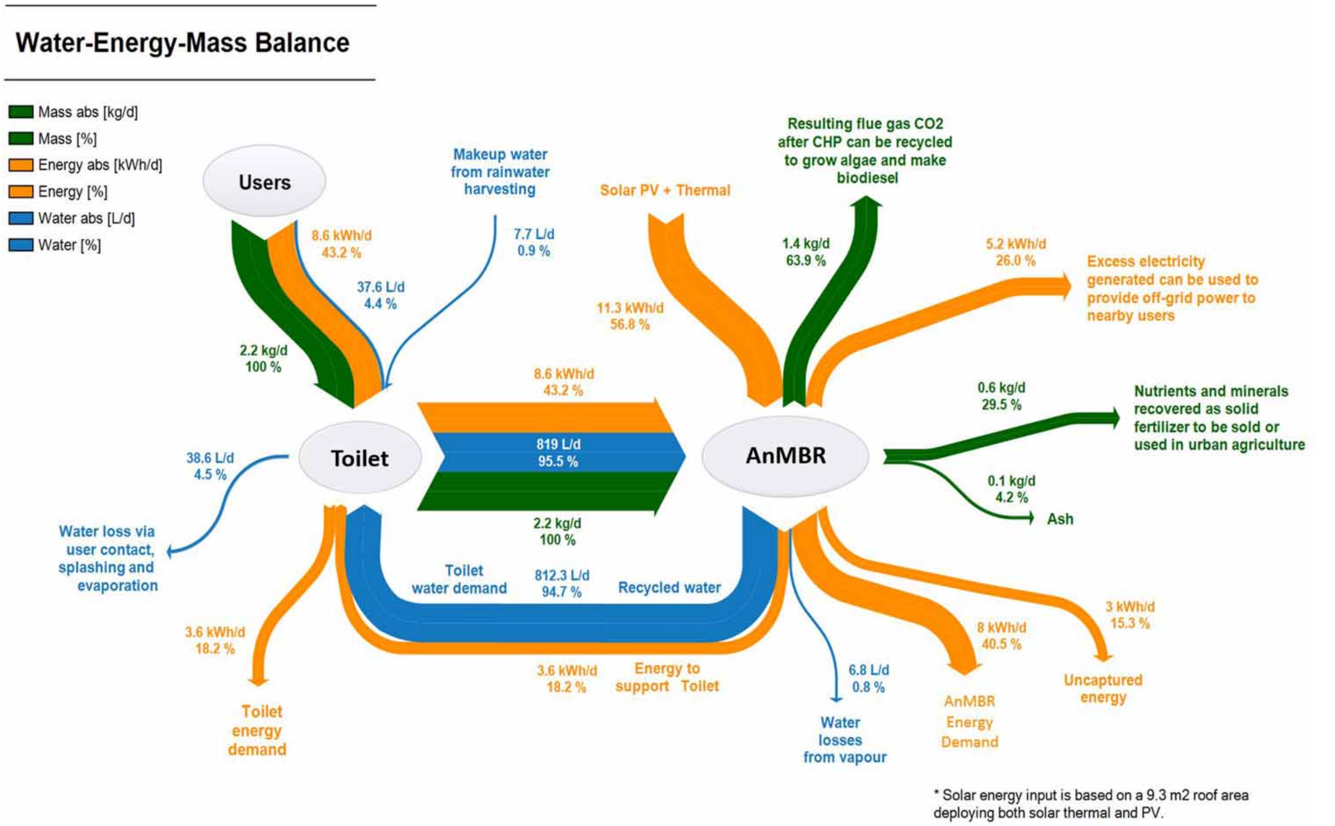

Figure 1 | Water–energy–mass balance summary for the combined eToilet and AnMBR system (Scenario 1).

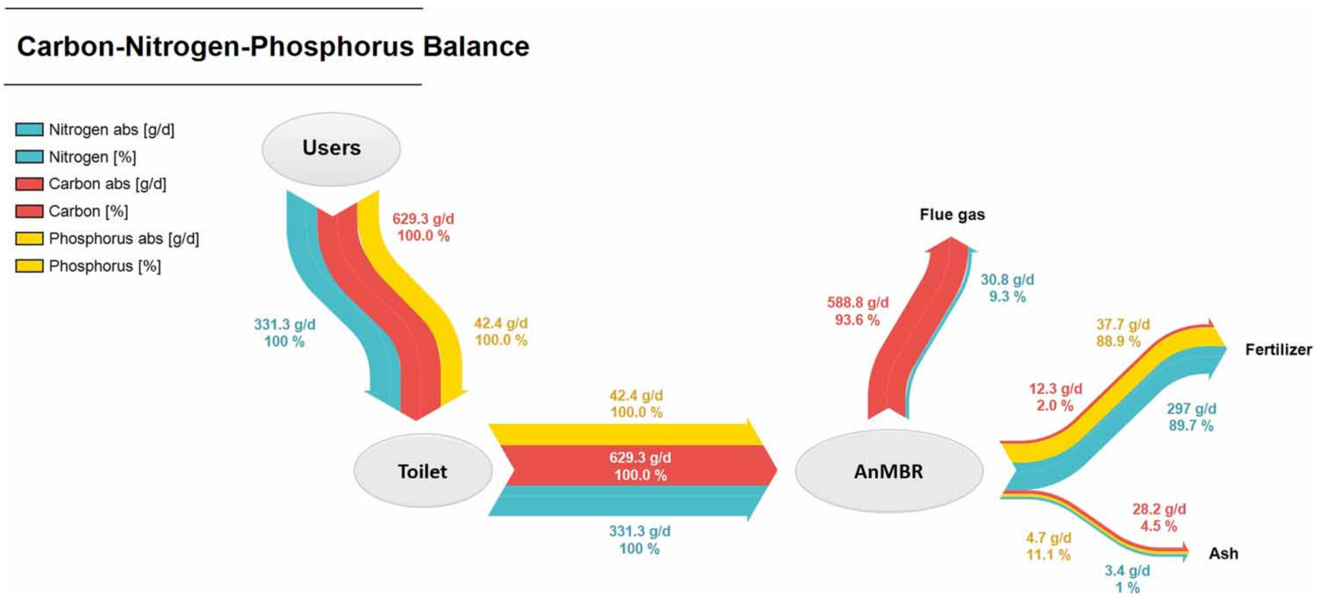

Figure 2 | Nutrient and element analysis for combined electronic toilet and AnMBR system. The diagram shows nutrient flows and recycling between the system components.

increases to 14.8 kWh/d, with the vast majority of this energy demand being used for feed heating. Despite this increase in operational energy demand, the AnMBR is able to route the vast majority of energy content in the food waste towards biogas. In this scenario, 21.3 kWh/d is generated as electricity that can be used by the local community for their energy

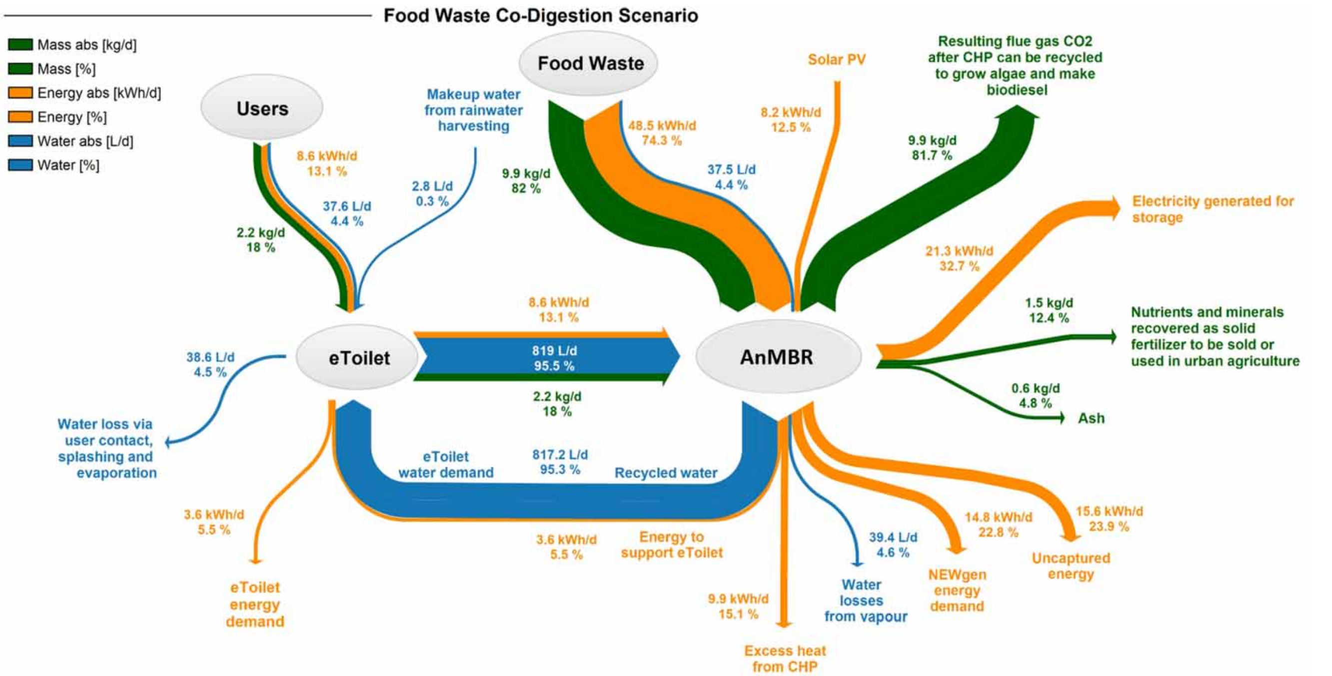

Figure 3 | Water–energy–mass balance summary for the combined eToilet and AnMBR system under Scenario 2 which includes food waste addition.

needs or for ensuring constant charge of the system's batteries. Food waste addition can help to buffer the effects of intermittent toilet usage and changes in the influent composition. A stable source of food waste can also be used to minimize the size of the photovoltaic system and solar thermal collectors, thereby reducing the overall system cost. A summary of the water–energy–mass balance for Scenario 2 can be found in Figure 3.

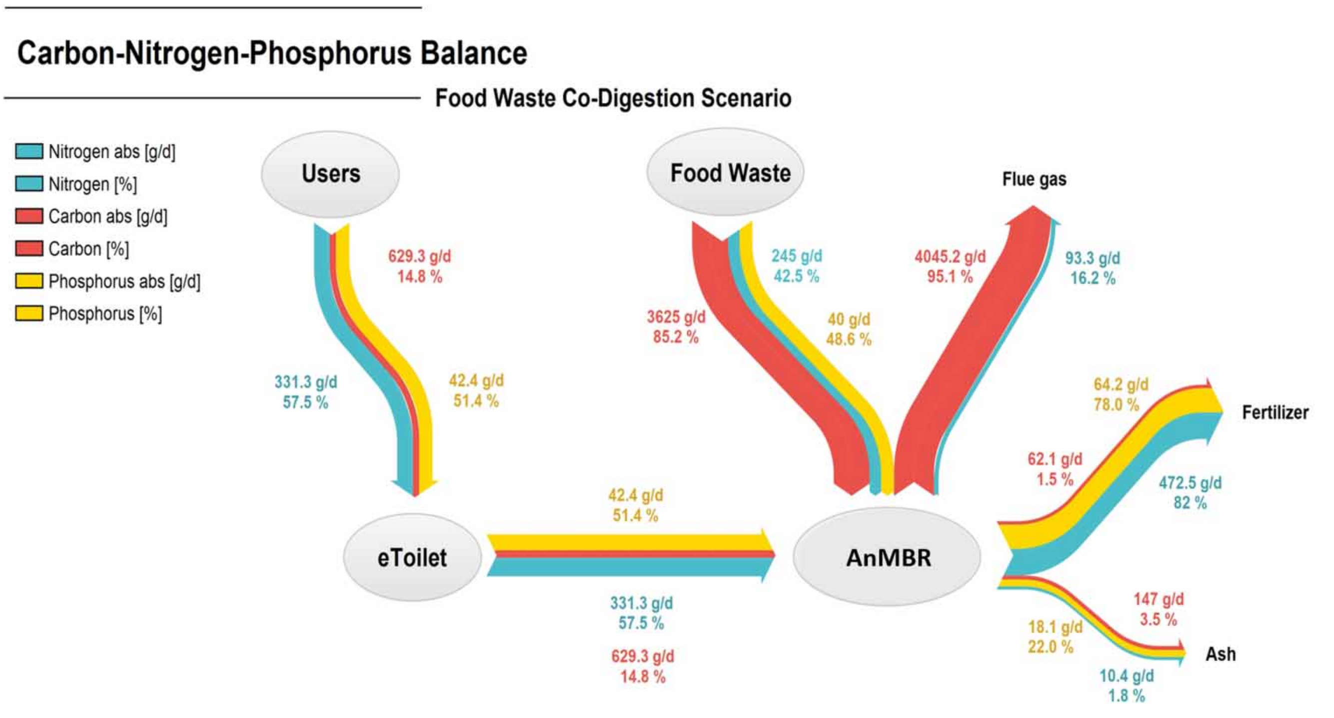

Figure 4 | Nutrient and element analysis for combined electronic toilet and AnMBR system with the addition of food waste.

While the addition of food waste has clear benefits from the perspective of energy production, it does come at the expense of larger quantities of nitrogen, phosphorus, and carbon entering the system. The amount of nitrogen exiting the system increases to 472.5 g/d while phosphorus increases to 64.2 g/d in Scenario 2. While these nutrients can be recovered using struvite precipitation and ion exchange as mentioned before, larger quantities of nutrients will require greater organizational capacity on behalf of the maintenance personnel for storing and maintaining the nutrient recovery subsystems. A summary of the carbon–nitrogen–phosphorus balance for Scenario 2 can be found in Figure 4.

Although the system is theoretically possible from an energy and water perspective, its application will be confronted with the same challenges that current sanitation technologies face, including lack of maintenance and difficulty in sourcing specialized spare parts. Many of these practical challenges can be addressed by the same model that has been adopted by the ESS. Under their model, complex systems are monitored remotely via wireless sensors and maintenance personnel and site visits are required only in the event of a technical failure. This model reduces operational costs while delivering consistent system performance. This same model reduces the burden of finding spare parts, as a direct supply chain can be established by the centralized maintenance facility and manufacturers. This will be particularly important for membrane module sourcing and replacement. The use of these systems within large cities also makes them less vulnerable to supply chain problems since transportation to large cities is usually well established.

CONCLUSIONS

By combining a public toilet with an AnMBR, what can be created is an off-grid sanitation system that serves the needs of slum dwellers. The combined system is theoretically capable of recycling its own water, so that minimal make up water would be required. In principle, this would enable the technology to be used in arid areas or in locations lacking reliable water services. Although the organic content of human faeces would be sufficient to power both systems, it is recommended to either increase the organic load entering the system using food waste, or to include photovoltaics to ensure the electricity requirements are met. According to our evaluations, nitrogen removal through either ion exchange, struvite precipitation, oxygen or plant uptake will be required to prevent ammonia accumulation within the AnMBR system. Future studies should aim at laboratory testing or piloting of the combined AnMBR and public toilet.

In summary:

- A decentralized AnMBR coupled to a public toilet is theoretically capable of producing enough energy to supply its own power requirements.
- Supplementing the AnMBR with food waste has the potential to increase the energy generated by the system.
- Our calculations indicate that ammonia accumulation needs to be addressed for multiple cycles within the combined public toilet–AnMBR system.

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